

Article

Life Cycle Assessment Analysis Based on Material Selection in Sustainable Airport Buildings

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Abstract: Sustainable airport buildings aim to minimize environmental impacts through energy efficiency, water conservation, and waste management. This is achieved by employing green building materials and utilizing renewable energy sources to reduce their carbon footprint. In this study, life cycle assessment (LCA) was conducted to assess the environmental impacts of three main construction materials—concrete, steel, and wood—used in sustainable airport buildings. These materials were selected for their widespread use in eight different airport terminal buildings with sustainability certifications. The environmental impacts of these materials were calculated and compared using OpenLCA 1.9.0 software and the ECOinvent database, adhering to the standards set forth by the Environmental Product Declaration (EPD) initiative. The findings indicate that wood, as a construction material, has a significantly lower impact on global warming compared to steel and concrete, with a global warming potential (GWP) ratio of less than 60%. Steel, with a GWP of approximately 90% of that of concrete, also showed a lower impact than concrete. Additionally, other environmental impacts, such as stratospheric ozone depletion potential (ODP) and acidification potential (AP), were also examined, highlighting the trade-offs associated with each material.

Keywords: airport; building materials; life cycle assessment (LCA); project management; sustainability



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1. Introduction

Sustainability has become a critical concept in addressing the environmental challenges faced by various industries, including construction. The concept of sustainability was first discussed at the “Man and Environment” conference in Stockholm in 1972 and gained widespread recognition with the Brundtland Report, “Our Common Future”, published by the World Commission on Environment and Development in 1987 [1]. This report defined sustainable development as “the process of meeting the needs of the present without compromising the ability of future generations to meet their own needs” (World Commission on Environment and Development, 1987) [1,2]. This definition integrates environmental, social, and economic dimensions, highlighting the interconnected nature of these aspects.

The construction industry plays a vital role in sustainable development, as it utilizes a significant portion of natural resources for building structures where people live and work. The efficient management of the construction process, the use of renewable resources, and minimizing the use of natural resources by adhering to sustainable practices throughout the life cycle of buildings contribute significantly to sustainable development [3,4].

To promote sustainable practices in the construction industry, sustainability certification systems such as Leadership in Energy and Environmental Design (LEED) and the Building Research Establishment Environmental Assessment Method (BREEAM) have emerged as essential tools [4]. LEED is an internationally recognized green building rating system that encourages environmentally friendly design, construction, and operation practices. LEED-certified buildings are known for reducing environmental impacts, lowering

operating costs, and enhancing the health and well-being of occupants [3–5]. Similarly, the BREEAM is a globally accepted green building assessment and certification system that evaluates construction projects based on environmental, social, and economic sustainability. BREEAM assessments cover various areas, including energy use, water conservation, indoor air quality, material selection, waste management, and ecological impacts [4–6].

The aviation industry has seen substantial growth in recent decades, driven by rising demand for air travel and global connectivity. However, this expansion has brought significant environmental challenges, particularly in energy consumption, resource use, and carbon emissions. Airport buildings, as vital infrastructure, play a major role in these impacts. Consequently, there is a growing focus on developing sustainable airport buildings that integrate environmentally friendly practices throughout their design, construction, and operation [7,8].

Sustainable airport buildings aim to reduce their environmental footprint by enhancing energy efficiency, conserving water, and managing waste effectively. A key strategy in achieving sustainability in airport construction is the careful selection of building materials. The choice of materials affects not only the energy efficiency of the building but also its overall environmental impact, from extraction and production to use and disposal [9,10]. In this context, Life Cycle Assessment (LCA) is a crucial tool for evaluating the environmental impacts of construction materials, offering a comprehensive view of their performance across various environmental indicators.

LCA is a systematic approach that assesses environmental impacts throughout a product's life cycle, from raw material extraction to disposal. In sustainable airport buildings, LCA enables the comparison of different construction materials, offering insights into their contributions to global warming, ozone depletion, and acidification [11,12]. By using LCA, stakeholders can make informed decisions on material selection, ensuring alignment with sustainability goals.

This study evaluates the environmental impacts of three commonly used construction materials—concrete, steel, and wood—in sustainable airport buildings. These materials were chosen due to their widespread use in airport terminals, especially those with sustainability certifications [13,14]. The aim of this study is to compare their environmental impacts, focusing on global warming potential (GWP), stratospheric ozone depletion potential (ODP), and acidification potential (AP).

Using OpenLCA software and the ECOinvent database and following the standards of the Environmental Product Declaration (EPD), this study analyzed these materials in eight airport terminal buildings designed with sustainability in mind [15,16]. These buildings, previously unexamined in terms of material use, provide a unique dataset that sets this study apart. This study also examined other environmental impacts, further highlighting the trade-offs associated with each material.

This research emphasizes the importance of material selection in sustainable airport construction and provides a foundation for informed decisions that align with environmental goals, contributing to the broader objective of creating more sustainable airport buildings [17,18].

1.1. Literature Review

1.1.1. Sustainable Airport Construction

Yang and Al-Qadi [7] conducted an in-depth study on the runway example of Chicago O'Hare International Airport, focusing on the LCA of airport building materials. Their research, using a quantitative methodology and a probabilistic LCA as defined in the ISO 14040 series, revealed that designs incorporating recycled materials or hot mix asphalt technology had lower Thermoplastic Elastomer (TPE) consumption and Greenhouse Gas (GHG) emissions. This finding aligns with those of Xie et al. [13], who also evaluated the environmental sustainability of an airport building system by integrating LCA with artificial neural networks (ANN). Their study underscored the unsustainability of the energy used during construction and operation, which accounted for 92.4% of the total energy.

Building on the theme of sustainable airport construction, De la Fuente et al. [19] explored the extension of the Ferrocarrils de la Generalitat de Catalunya railway line to Barcelona El Prat Airport Terminal 1. They employed the Integrated Value Model for Sustainable Assessment (Modelo Integrado de Valor para una Evaluación Sostenible—MIVES) method, a multi-criteria decision-making approach, and concluded that concrete and fiber-reinforced concrete configurations were more sustainable. Similarly, Greer, Rakas, and Horvath [8] reviewed environmental sustainability metrics for airports globally and suggested that practices like using low-emission electricity sources and electrifying ground services can help airports achieve sustainability targets. This is further supported by AlKheder, AlKandari, and AlYatama [14], who developed sustainable evaluation criteria for choosing between asphalt and concrete for a new runway at Kuwait International Airport, concluding that asphalt was the better alternative in terms of cost, energy savings, and ease of maintenance.

Expanding on the specific materials used in airport construction, Jamshidi et al. [17] focused on concrete samples used at airports, examining their structural performance and sustainability. Their study [17] proposed scenarios for selecting concrete content based on sustainability criteria, a conclusion that resonates with the findings of the previous studies on the importance of material choice in sustainable construction.

1.1.2. LCA and Building Materials in Construction

The discussion of building materials extends into Ding's [9] examination of LCA concerning materials such as steel, concrete, aluminum, glass, and wood. Ding's findings highlight the critical role of sustainable building materials in green building design, which complements Khan and Ali's [11] analysis of concrete mixtures for sustainable construction. They recommended the use of additional improvers in concrete, citing their benefits in reducing air emissions and costs.

Further emphasizing the importance of material selection, Häfliger et al. [10] explored the sensitivity of construction materials to LCA modeling options, revealing significant variations in the overall evaluation of buildings. Their study highlights how modeling choices can dramatically impact sustainability assessments, a point also discussed by Devaki and Shanmugapriya [20]. They conducted a content-based literature analysis focusing on sustainable waste management, finding that the majority of LCA studies are concentrated in Europe, with a noted research deficiency in developing countries.

In terms of data reliability, Martínez-Rocamora, Solís-Guzmán, and Marrero [12] examined LCA database examples, concluding that the GaBi and ECOinvent databases were particularly effective in providing accurate data on construction materials. This evaluation of LCA databases is crucial, as highlighted by Carabaño et al. [21], who evaluated the environmental impact of thermal insulation materials using LCA methodology. Their study indicated the necessity of considering global commitment solutions when choosing materials, as no single product excels in all impact categories.

1.1.3. Sustainable Material Evaluation Models

Moving beyond specific materials, Akadiri, Olomolaiye, and Chinyio [22] proposed a multi-criteria evaluation model for selecting sustainable materials in building projects. They provided a numerical example demonstrating that the model offers accurate sustainability assessments, which can guide building designers. This evaluation model was further elaborated in a separate study by Akadiri and Olomolaiye [23], who examined the development stages of sustainability criteria for material selection, emphasizing the model's utility in facilitating sustainable building projects.

Kylili et al. [24] expanded this discussion by integrating Building Information Modeling (BIM) with LCA to assess various materials used in water supply systems. Their study demonstrated that cross-linked thermoplastic systems significantly outperformed other materials in terms of climate change impact, aligning with the findings of Mattinzioli et al. [25]. Mattinzioli's study assessed sustainable highway design using various global rating sys-

tems like CEEQUAL and Greenroads, highlighting the strong potential of rating systems in the social evaluation of projects.

Finally, Asdrubali, D'Alessandro, and Schiavoni [18] explored non-traditional sustainable building materials made from natural or recycled products. Their LCA analysis showed that these materials could substantially reduce environmental impacts during production and waste management, echoing the earlier discussions on the importance of selecting sustainable materials.

While many studies have explored the sustainability of construction materials, especially in the context of structures like airports, the specific evaluation of green building-certified airport terminals through the lens of material use remains limited. Previous research has predominantly focused on energy efficiency, water conservation, and waste management in sustainable airport buildings, yet there is a noticeable gap in examining the environmental impacts of the materials themselves. This gap is particularly significant given the findings that material selection directly influences the overall environmental footprint of these structures, from resource extraction to end-of-life disposal.

This study sought to address this gap by conducting an LCA of three widely used construction materials—concrete, steel, and wood—within eight green building-certified airport terminals. The focus on these materials is crucial, as they represent the most common choices in airport construction, yet their environmental impacts have not been comprehensively compared within this specific context. By utilizing OpenLCA software and the ECOinvent database and adhering to the standards of the Environmental Product Declaration (EPD), this research uniquely contributes to the literature by providing a comparative analysis of these materials' impacts, including global warming potential (GWP), stratospheric ozone depletion potential (ODP), and acidification potential (AP). This research not only fills a critical gap but also provides practical insights that can guide the construction industry in making more sustainable material choices, ultimately contributing to the broader objective of reducing the environmental impact of airport buildings.

1.2. Sustainable Material Selection and Standards

An Environmental Product Declaration (EPD) is a critical component supporting sustainable development in the field of construction materials. An EPD provides a standardized, independently verified report that assesses the environmental impacts of materials across their life cycle. By offering detailed analyses of factors such as energy and water consumption and greenhouse gas emissions, EPDs serve as essential reference points for construction industry professionals, guiding material selection and promoting greener building designs [4]. The EPD plays a vital role in the decision-making process from material selection to building design, helping to reduce environmental impacts and enhance transparency and accuracy in the sustainable construction materials market. In the context of green building certifications, such as LEED and the BREEAM, EPDs contribute significantly to measuring and improving the environmental effectiveness of construction materials.

The life cycle assessment of materials often evaluates environmental impacts in various categories, including GWP, ODP, and AP. These categories are critical in understanding the broader environmental implications of material use in construction. In this study, GWP, ODP, and AP were selected as the primary categories for assessing the environmental impacts of concrete, steel, and wood used in sustainable airport buildings.

1.3. Life Cycle Assessment Approaches and Tools

LCA is a rigorous and systematic methodology used to evaluate the environmental impacts of materials throughout their entire life cycle—from raw material extraction to end-of-life disposal. By providing a comprehensive understanding of the environmental costs associated with each stage of a product's life, LCA is indispensable in sustainable development efforts. It enables stakeholders—such as engineers, designers, policymakers, and construction managers—to make informed decisions that minimize environmental footprints, optimize resource use, and contribute to long-term sustainability goals.

LCA methodologies can be categorized into various approaches depending on the scope and the life cycle stages being analyzed. The most common approaches include “cradle-to-grave”, “cradle-to-gate”, and “gate-to-gate” assessments [26]. The “cradle-to-grave” approach, which was adopted in this study, examines the full life cycle of materials, encompassing all stages from raw material extraction (cradle) to the disposal or recycling of the product (grave). This comprehensive approach ensures that the analysis captures the total environmental impact of materials, including those associated with production, transportation, use, and end-of-life processes.

The effectiveness and reliability of an LCA heavily depend on the tools and databases employed. Among the most widely recognized LCA tools are OpenLCA, GaBi, and SimaPro, with each offering different functionalities and strengths. OpenLCA, selected for this study, is an open-source platform known for its flexibility and compatibility with various databases, making it accessible to a broad range of users, from academic researchers to industry professionals. Its open-source nature, coupled with its comprehensive environment for analyzing environmental impacts across different life cycle stages, makes it a suitable choice for diverse LCA applications. GaBi 2022.2, another leading software, is extensively used in industry due to its advanced modeling capabilities and extensive library of datasets, which are particularly useful for handling complex LCA studies involving large-scale industrial systems. Similarly, SimaPro is valued for its detailed inventory data and strong capabilities in conducting scenario analysis and sensitivity studies, making it a popular choice in academic and research settings for addressing various environmental impact categories [27].

In this study, the combination of OpenLCA software and the ECOinvent database was employed to conduct the LCA. The ECOinvent database, widely recognized for its extensive and reliable environmental data, provides crucial inputs for LCA, covering the production, use, and disposal phases of construction materials. This combination ensures that the environmental impacts of the materials analyzed—concrete, steel, and wood—are accurately modeled and calculated, adhering to the standards set forth by the EPD initiative.

Moreover, this study’s approach using OpenLCA and the ECOinvent database allows for a detailed assessment across five key life cycle modules: production, application, use, end-of-life, and remanufacturing. Each of these modules is subdivided into specific processes that contribute to the overall environmental impact. For instance, the raw material supply phase (A1) includes the extraction and initial processing of raw materials required to produce the construction materials, while the transportation to the manufacturer phase (A2) accounts for the environmental impacts associated with transporting these materials to production facilities. The production phase (A3) covers all processes related to manufacturing the materials, including energy use and emissions, and the application and use phases (B1–B5) encompass the installation of materials in construction projects, their operational life, and maintenance activities. Finally, the end-of-life phase (C1–C4) captures the final stages of the life cycle, including demolition, waste processing, recycling, and disposal.

By adopting this cradle-to-grave approach and utilizing these detailed life cycle modules, this study provides a robust and holistic assessment of the environmental impacts of the three materials in question. This comprehensive approach is critical for identifying the trade-offs associated with different materials, offering valuable insights for sustainable construction practices. The findings from this study contribute to a deeper understanding of how material selection can influence the sustainability of airport buildings, ultimately guiding more informed and responsible decisions in the construction industry.

2. Objective

2.1. Examination of Sustainable Airport Structures

In order to determine the environmental effects of the materials used in airport structures, it is necessary to first determine the airport samples, and the materials used. For this purpose, airports that have received international green building certification and

important information about these airports are shared in the tables below (Tables 1–4). This information starts with the name of the building and includes its location, climate, year of completion, sustainability certificate, and construction materials. The materials used in the buildings will be discussed in the following sections.

Airports have been selected from all over the world, and the tables are shared below.

Table 1. Sustainable airports (İstanbul, Shenzhen).

Code			1	2
Name			İstanbul Airport	Shenzhen Bao'an International Airport
Using For			Terminal Building, International Flights, Departures and Arrivals Floor	Terminal Building, All Flights, Departures and Arrivals Floor
Const. Area (sqm)			1,294,082 sqm	500,000 sqm
Opening			2018	2013
Location			Türkiye/İstanbul	China/Guandong/Shenzhen
Climate			Temperate Climate	Monsoon Climate
Sustainable Certificate			LEED GOLD	LEED CERTIFIED
Materials Used in Construction	Structural Materials	Facede	Steel, Glass, Wood	Steel, Glass
		Walls	Concrete, Brick	Steel, Concrete
		Columns	Steel, Concrete	Steel, Concrete
		Bean	Steel, Concrete	Steel
		Flooring	Concrete	Concrete
		Roof	Steel	Steel
	Detail Materials	Floor Cladding	Granite, Marble, Wood, Carpet, Ceramic	Ceramic, Vinyl, Wood
		Wall Cladding	Wood, Metal, Plasterboard, Glass	Metal, Glass, Wood
		Ceiling	Steel, Metal, Plasterboard, Wood	Steel, Plasterboard

Table 2. Sustainable airports (California, İzmir).

Code			3	4
Name			San Francisco Airport	Adnan Menderes Airport
Using For			Terminal Building, International Flights, Departures and Arrivals Floor	Terminal Building, Domestic Flights, Departures and Arrivals Floor
Const. Area (sqm)			55,747 sqm	200,000 sqm
Opening			2011	2014
Location			USA/California	Türkiye/İzmir
Climate			Mediterranean Climate	Mediterranean Climate
Sustainable Certificate			LEED GOLD	LEED SILVER
Materials Used in Construction	Structural Materials	Facede	Steel, Metal, Glass	Steel, Metal, Glass, Wood
		Walls	Concrete, Brick	Concrete
		Columns	Concrete	Steel
		Bean	Concrete	Steel
		Flooring	Concrete	Concrete
		Roof	Concrete	Steel, Glass
	Detail Materials	Floor Cladding	Vinyl, Ceramic, Wood	Granite, Wood, Ceramic
		Wall Cladding	Wood, Ceramic, Plasterboard	Marble, Glass, Plasterboard, Wood, Carpet
		Ceiling	Plasterboard	Steel, Glass

Table 3. Sustainable airports (Changi, Beijing).

Code			5	6
Materials Used in Construction	Name		Jewel Changi Airport	Beijing Daxing International Airport
	Using For		Terminal Building, International Flights, Departures and Arrivals Floor	Terminal Building, International Flights, Departures and Arrivals Floor
	Const. Area (sqm)		135,700 sqm	700,000 sqm
	Opening		2019	2019
	Location		Singapore/Changi	China/Beijing
	Climate		Tropical Climate	Monsoon Climate
	Sustainable Certificate		LEED CERTIFIED	LEED PRECERTIFIED PLATINUM
	Structural Materials	Facede	Steel, Glass	Steel, Glass
		Walls	Concrete, Brick	Steel
		Columns	Concrete	Steel
		Bean	Concrete	Steel
		Flooring	Concrete	Concrete
		Roof	Steel, Glass	Steel, Glass
	Detail Materials	Floor Cladding	Granite, Ceramic, Natural Stone, Wood	Granite, Natural Stone, Wood, Carpet, Ceramic
		Wall Cladding	Natural Stone, Plasterboard, Wood	Plasterboard, Glass, Wood
		Ceiling	Steel, Glass, Plasterboard	Metal, Glass

Table 4. Sustainable airports (London, Vantaa).

Code			7	8
Materials Used in Construction	Name		Heathrow Airport—Teminal 2A	Helsinki—Vantaa Airport—Terminal 2
	Using For		Terminal Building, International Flights, Departures and Arrivals Floor	Terminal Building, International Flights, Departures and Arrivals Floor
	Const. Area (sqm)		56,000 sqm	43,000 sqm
	Opening		2014	2021
	Location		England/London	China/Beijing
	Climate		Tropical Climate	Monsoon Climate
	Sustainable Certificate		LEED CERTIFIED	LEED PRECERTIFIED PLATINUM
	Structural Materials	Facede	Steel, Metal, Glass	Steel, Metal, Glass, Wood, Plywood
		Walls	Metal, Concrete	Steel, Concrete
		Columns	Steel	Steel
		Bean	Steel	Steel
		Flooring	Concrete, Steel	Concrete
		Roof	Steel, Glass	Steel, Wood
	Detail Materials	Floor Cladding	Ceramic, Wood	Ceramic, Wood
		Wall Cladding	Plasterboard, Glass, Wood	Wood, Plywood
		Ceiling	Steel, Metal, Glass	Wood, Plywood

2.2. Identification of Construction Materials Used in Airport Buildings

Figure 1 shows the building materials used in these sustainable airports. Following the airport numbers, the points where the materials are located in the structure were added to the figure based on the accepted quantities. This figure shows the materials of eight environmentally friendly airport structures located in regions with different climatic conditions and designed for the same purpose. These numbers were collected for all the

airports to reach the total number. Accordingly, concrete, steel, and wood were determined to be the most used materials. Following this stage, LCA was performed for concrete, steel, and wood, and the environmental impacts of the materials were calculated.

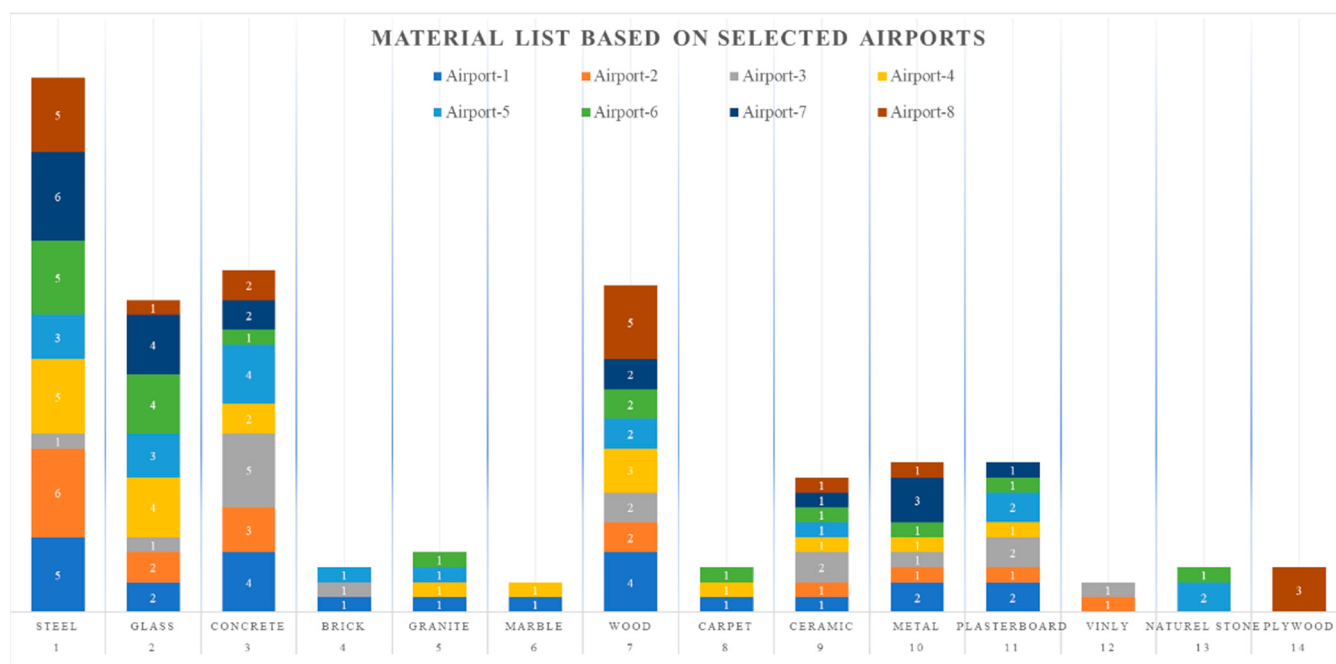


Figure 1. Some materials used in the eight different sustainable airports and their number of points of use.

3. Method

OpenLCA is a powerful tool that simplifies complex LCA calculations. The working principle of OpenLCA generally follows the basic steps of the LCA methodology. These are, respectively, target and scope determination, life cycle inventory analysis, and life cycle impact assessment and interpretation. Situation visuals of the ECOinvent database running on OpenLCA software are shared in Figures 2 and 3.

As a result of the inputs provided to the OpenLCA program, the ECOinvent database automatically supplies the necessary calculation values to the OpenLCA software. The modeling process within the program is depicted in the accompanying image. The life cycle assessment process, comprising five distinct steps, is detailed below:

Determination of Materials and Construction Processes for Life Cycle Assessment:

This step involves identifying and selecting the specific materials and construction processes to be analyzed. For this study, concrete, steel, and wood were chosen due to their widespread use in sustainable airport buildings. The choice of these materials is crucial, as they represent the primary components in the construction of such infrastructure.

Selection of Software and Database Infrastructures: In this step, the appropriate software and database infrastructures necessary for conducting the LCA are selected. For this study, OpenLCA software and the ECOinvent database were chosen. OpenLCA is a widely recognized tool for LCA, known for its flexibility and comprehensive features. The ECOinvent database provides extensive and reliable data on environmental impacts associated with various materials and processes, making it ideal for this analysis.

Determination of Material Values and General Assumptions: This step involves entering the specific material values into the software and database for calculation. General acceptance figures are determined for materials where limited data are available. These values are critical as they form the basis for the environmental impact calculations. Accurate data input ensures the reliability of the LCA results, particularly when assessing the sustainability of different building materials.

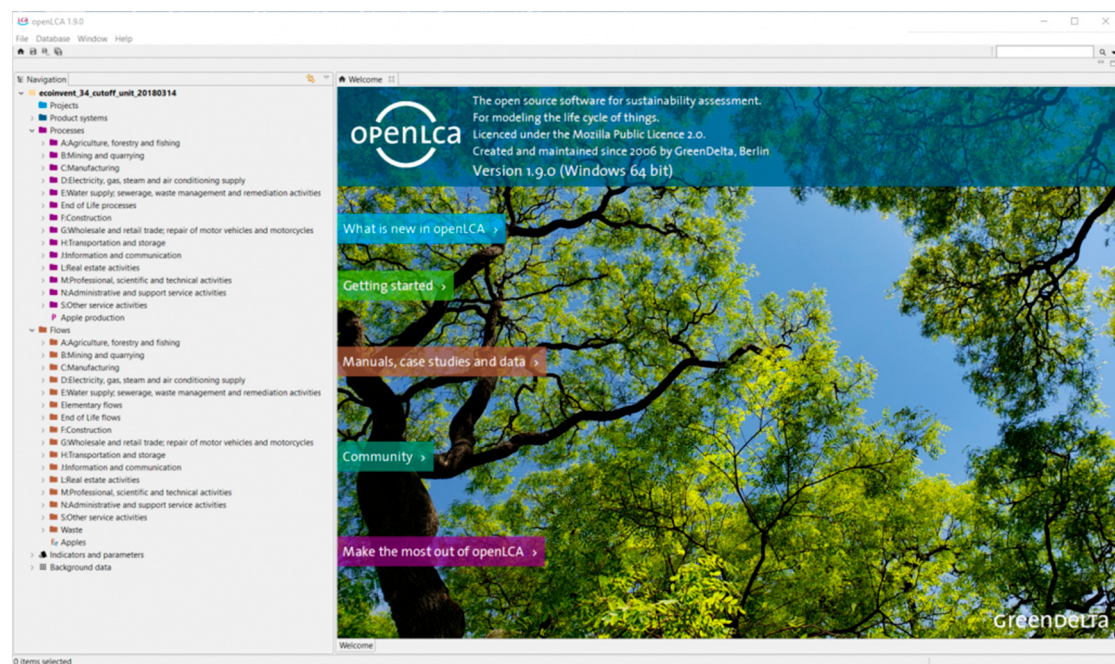


Figure 2. Open LCA.

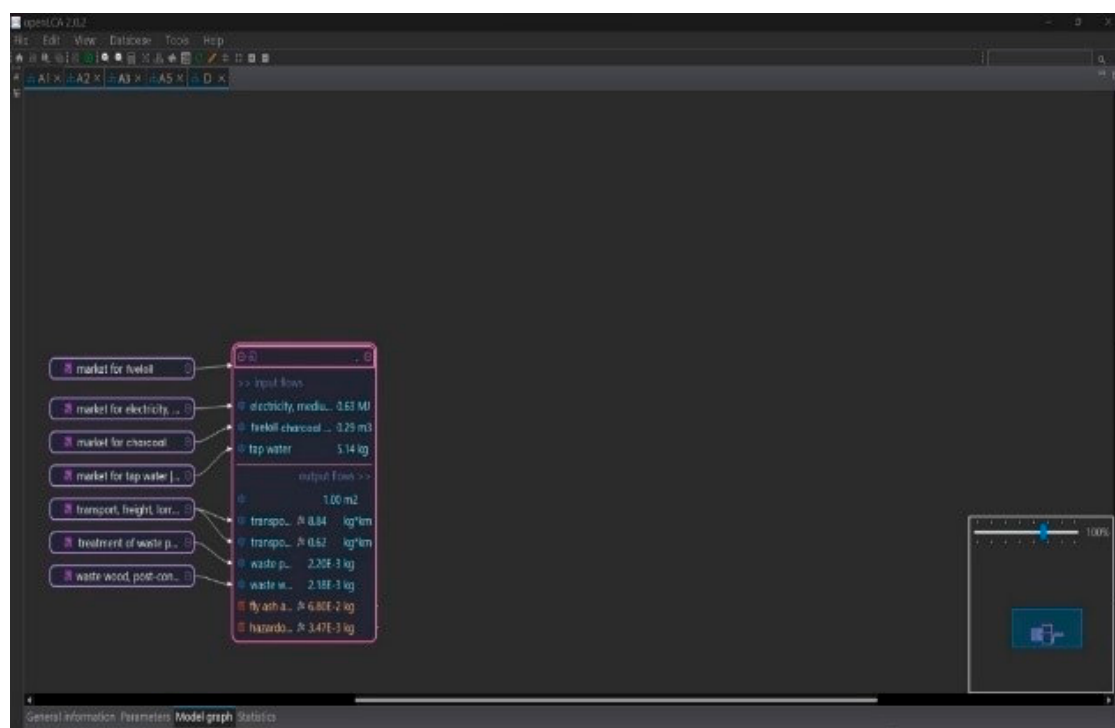


Figure 3. Ecoinvent database.

Life Cycle Assessment Calculations: In this step, life cycle assessment calculations are performed for the three selected building materials—concrete, steel, and wood. These calculations assess the environmental impact of each material across its entire life cycle, from raw material extraction to end-of-life disposal. The LCA considers various factors, including energy consumption, emissions, and waste generation, to provide a comprehensive evaluation of each material's environmental footprint.

Measurement and Reporting of Environmental Impact Values: The final step involves measuring and reporting the environmental impact values obtained from the LCA. This

includes quantifying impacts such as GWP, ODP, and AP. The results are then documented, providing valuable insights into the environmental performance of the materials analyzed. These findings can guide decision-making in material selection for sustainable construction projects.

3.1. Life Cycle Assessment of Concrete, Steel, and Wooden Materials

3.1.1. Concrete

During the production phase, the raw material of the concrete material, the extraction of the raw material from the source and its transportation to the production facility, and the details of the production process in the production facility were examined.

The primary energy input for the concrete life cycle stages, other than raw materials, is electricity. The data for electrical input were obtained from the meter. The secondary energy inputs were defined as coal and fuel oil. The coal and fuel oil data were obtained with fuel flow meters. The water used in the LCA process was groundwater in the field. The groundwater was measured with a water meter. The quantities entered into the OpenLCA program for the LCA process of 1 ton of concrete material are shown in the table below (Table 5).

As a result of these inputs, the database automatically provided the calculation values to the OpenLCA program.

Table 5. Inputs for concrete material.

Name	Value	Amount
Electricity	201.24	kWh
Coal	94.107	kg
Fuel (Fuel oil)	0.36	L
Groundwater	110	m ³

The LCA results obtained as a result of the calculations were converted into a report and shared (Table 6). The values resulting from the calculations were turned into a percentage chart via OpenLCA (Figure 4).

Table 6. Life cycle assessment results for concrete.

Parameter	Unit	A1	A2	A3	A5	D
		Raw Material Supply	Shipping to Manufacturer	Production	Installation Indoors	Recycle
GWP	[kg CO ₂ -Eq.]	3.37×10^2	3.39×10^1	1.97×10^2	2.31	2.31
ODP	[kg CFC11-Eq.]	1.64×10^{-6}	2.41×10^{-10}	4.84×10^{-10}	7.76×10^{-12}	7.76×10^{-12}
AP	[kg SO ₂ -Eq.]	1.25×10^{-1}	3.90×10^{-2}	1.74	8.75×10^{-4}	8.75×10^{-4}

GWP = Global warming potential; ODP = Depletion potential of stratospheric ozone layer; AP = Acidification potential of land and water.

The results only include the quantification of life cycle impact category parameters based on accepted values. The accepted production unit of this LCA study was one ton of concrete. When the environmental impact values are examined on the graph, the points where the concrete material has the most impact on the environment during its life cycle are determined.

Accordingly, the GWP values were examined: it was determined that the environmental impact is highest at the A1, raw material supply stage, with 59.31%, and the lowest environmental impact is at the A5, i.e., installation inside the building stage, with 1.02%. Then, the ODP values were examined: it was determined that the environmental impact is the highest at the A1, the raw material supply stage, with 99.96%, and is less affected at other stages. In AP values, it was seen that the environmental impact value is highest at A3, i.e., the production stage, with a rate of 91.37%.

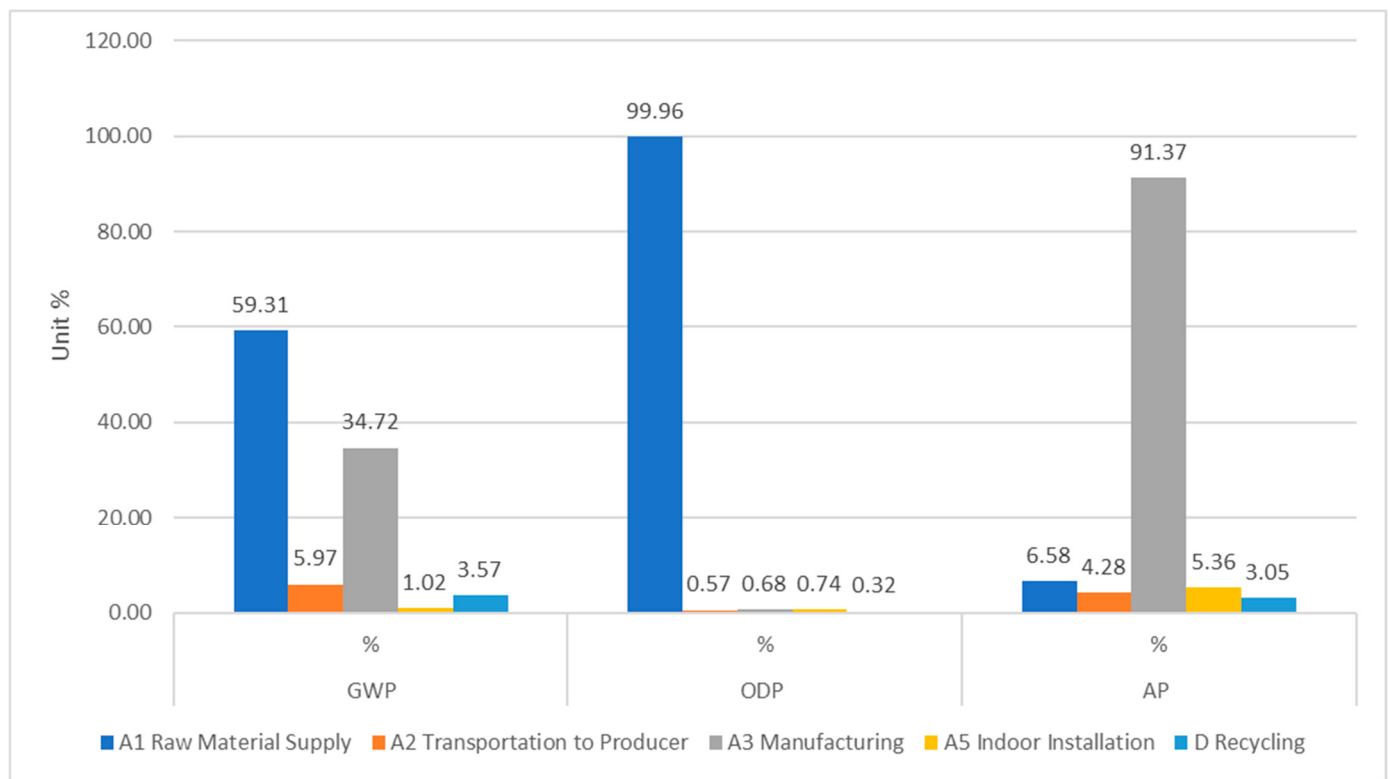


Figure 4. Life cycle assessment results for concrete.

3.1.2. Steel

Electricity, natural gas, liquefied petroleum gas (LPG), and groundwater are used as primary energy inputs in bare steel pipe production. Since each unit in the production area has its own energy meter, energy consumption is measured separately for each unit. On the other hand, water is used to cool the heated product during steel pipe production. Since this water is in circulation in the system, water consumption results only from evaporation. Water consumption is determined by measuring mains water with water meters.

In this LCA study, the results include only the quantity of life cycle impact category parameters based on the accepted unit. The accepted unit of this LCA study was one ton of steel pipe. As a result of these inputs, which are stated in Table 7, the program performed the necessary calculations based on the values provided by the database and converted them into a report. As a result of these inputs, the ECOinvent database automatically provided the calculation values to the OpenLCA program.

Table 7. Inputs for steel material.

Name	Value	Amount
Electricity	20	kWh
Natural Gas	4.14	m ³
Liquefied Petroleum Gas (LPG)	0.24	L
Groundwater	3	m ³

The LCA analysis results obtained as a result of the calculations were converted into a report and shared (Table 8). The values resulting from the calculations were turned into a percentage chart via OpenLCA (Figure 5).

Table 8. Life cycle assessment results for steel.

Parameter	Unit	A1	A2	A3	A5	D
		Raw Material Supply	Shipping to Manufacturer	Production	Installation Indoors	Recycle
GWP	[kg CO ₂ -Eq.]	2.92×10^3	1.51×10^1	1.52×10^1	2.62	-5.77×10^2
ODP	[kg CFC11-Eq.]	2.07×10^{-4}	1.08×10^{-10}	1.17×10^{-11}	2.68×10^{-11}	1.84×10^{-5}
AP	[kg SO ₂ -Eq.]	3.43×10^1	3.67×10^{-2}	1.76×10^{-1}	1.78×10^{-2}	-1.37

GWP = Global warming potential; ODP = Depletion potential of stratospheric ozone layer; AP = Acidification potential of land and water.

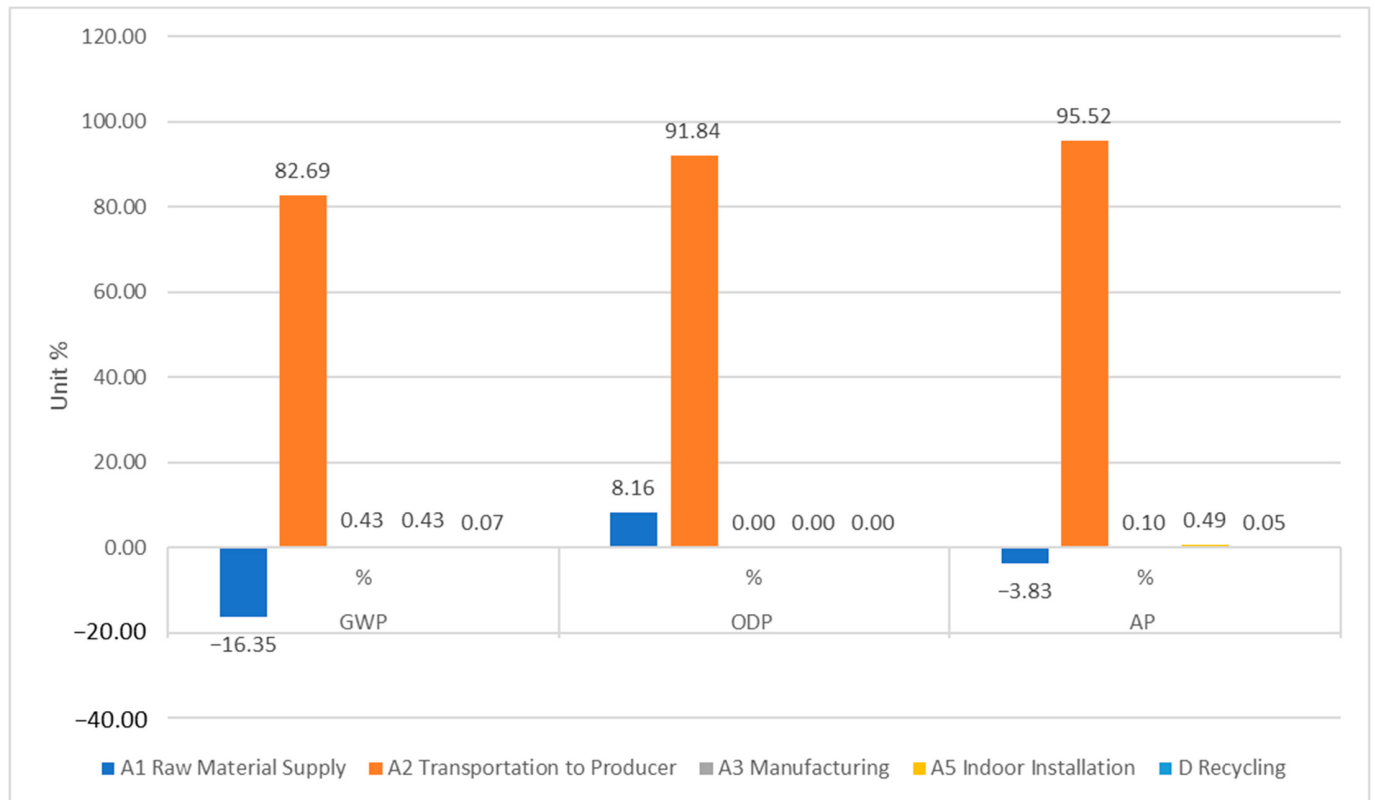


Figure 5. Life cycle assessment results for steel.

When the environmental impact values are examined on the graph, the points where the steel material has the most impact on the environment during its life cycle are determined.

Accordingly, the GWP values were examined: it was determined that the environmental impact is the highest in A2, that is, the transportation phase to the manufacturer, with 82.69%, and that the environmental impact is not high in other living modules, since the environmental impact is below 1%. Then, the ODP values were examined: with 91.84%, it was observed that the environmental impact in ODP, as in GWP, was highest in the A2 module, that is, transportation to the manufacturer. When AP values were examined, as in other impact categories, the A2 module was found to have the highest environmental impact.

3.1.3. Wood

Wood consists of 50% cellulose, 23% hemicellulose, 20% lignin, and 7% other organic compounds called extractives. Heat treatment removes the resin, other extractives, and their attached OH (Hydroxyl) groups from the wood. This process reduces swelling and shrinkage while increasing rot resistance by reducing the water absorption of wood. Another factor contributing to the high durability of wood is the crystallization of cellulose.

The change in hemicellulose increases durability. Hemicellulose breaks down into furfural and carboxylic acid. The heat-induced caramelization of lignin results in a darker color [28].

In this LCA study, the results include only the quantity of life cycle impact category parameters based on the accepted unit. The accepted unit of this LCA study was one ton of wood. As a result of these inputs, the program performed the necessary calculations based on the values provided by the database and converted them into a report. Only electricity and water are used as the energy source in wood production. Energy consumption is measured separately for each unit, and each unit has its own energy meter. During wood production, water is used to shape the product. Water consumption is determined by measuring mains water with water meters.

As a result of these inputs specified in Table 9, the ECOinvent database automatically provides the calculation values to the OpenLCA program.

Table 9. Inputs for wood material.

Name	Value	Amount
Electricity	140	kWh
Water	0.6	m ³

The LCA analysis results obtained as a result of the calculations were converted into a report and shared (Table 10). The values resulting from the calculations were turned into a percentage chart via OpenLCA (Figure 6).

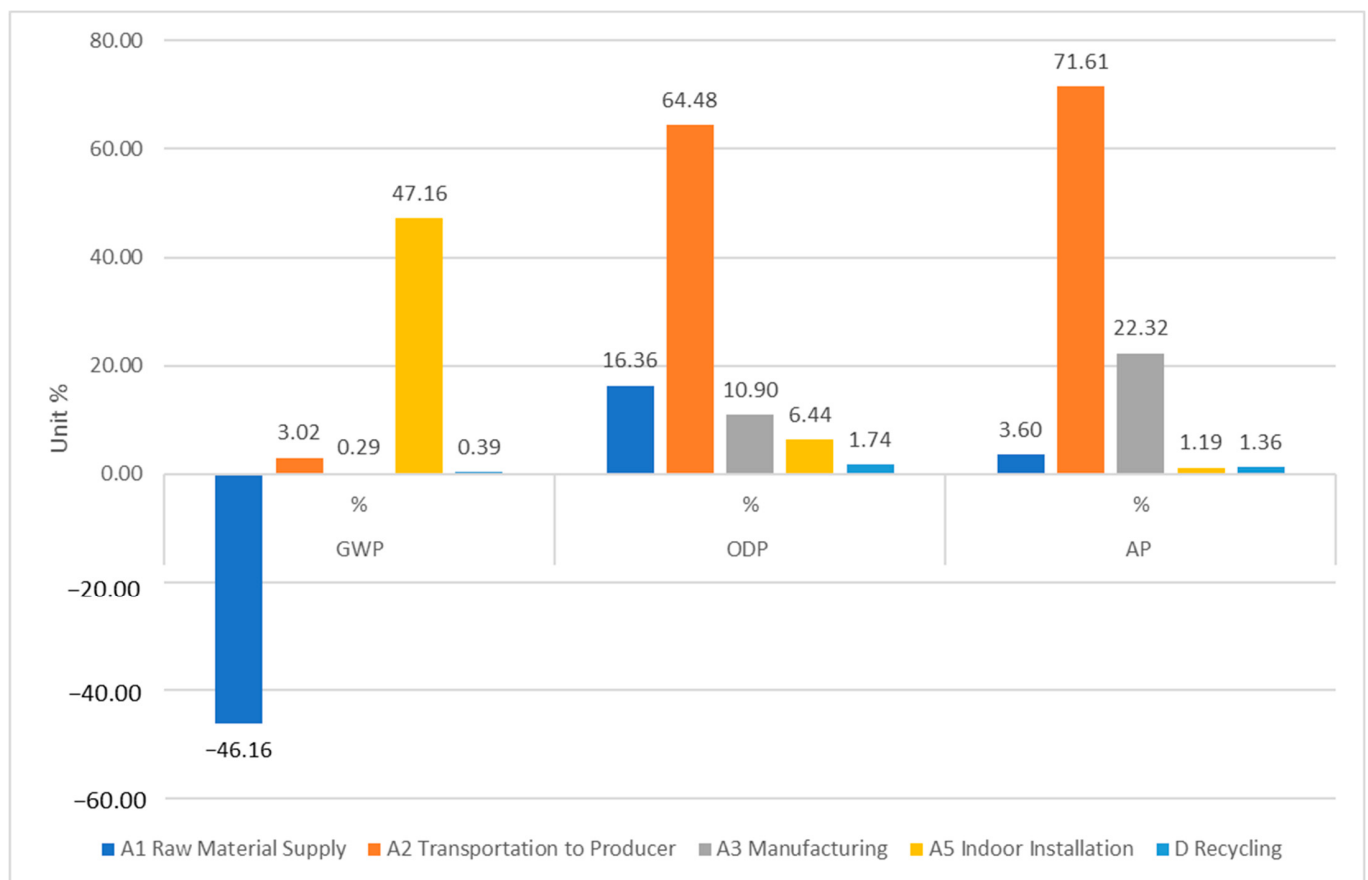


Figure 6. Life cycle assessment results for wood.

Table 10. Life cycle assessment results for wood.

Parameter	Unit	A1	A2	A3	A5	D
		Raw Material Supply	Shipping to Manufacturer	Production	Installation Indoors	Recycle
GWP	[kg CO ₂ -Eq.]	-1.17×10^3	7.63×10^1	8.52×10^1	0.00	0.00
ODP	[kg CFC11-Eq.]	3.22×10^{-6}	1.27×10^{-5}	2.17×10^{-6}	0.00	0.00
AP	[kg SO ₂ -Eq.]	7.12×10^{-2}	1.42	4.42×10^{-1}	0.00	0.00

GWP = Global warming potential; ODP = Depletion potential of stratospheric ozone layer; AP = Acidification potential of land and water.

When the environmental impact values are examined on the graph, the points where the wood material has the most impact on the environment during its life cycle are determined. Accordingly, the GWP values were examined: it was determined that the environmental impact is highest at the A5, i.e., installation stage inside the building, with 47.16%, and that the environmental impact is not high in other living modules, as the environmental impact is below 1%. When the ODP values were examined, it was observed that the highest environmental impact, with 64.48%, was in the A2 module, that is, transportation to the manufacturer. When the AP values were examined, as in the ODP impact category, the A2 module was found to have the highest environmental impact.

4. Results and Discussion

The LCA of concrete, steel, and wood materials used in green building-certified airports provides crucial insights into the environmental impacts associated with these widely utilized construction materials. By analyzing GWP, ODP, and AP values across various life cycle stages, this study not only quantifies the environmental footprint of each material but also highlights key areas for improvement in sustainable construction practices.

4.1. Environmental Impact Analysis

The data presented in Tables 6, 8 and 10, along with Figures 4–6, reveal the distinct environmental profiles of concrete, steel, and wood. These findings are contextualized within the broader framework of sustainable construction, emphasizing the importance of informed material selection. The situation in which the ECOinvent database was run on OpenLCA software is shared in the chart below (Figure 7).

Concrete: Concrete demonstrates a significant environmental impact during the raw material supply stage (A1), where the GWP reaches 337 kg CO₂-Eq., accounting for approximately 59% of the total impact. This stage also registers the highest ODP value, indicating substantial environmental challenges during the extraction and processing of raw materials. The production stage (A3) is marked by a high AP value of 1.74 kg SO₂-Eq., reflecting the acidification potential associated with concrete manufacturing. These results align with previous studies indicating that the early stages of concrete production, particularly raw material extraction, are critical contributors to its overall environmental footprint [9,10].

Steel: The environmental profile of steel is dominated by the transportation stage to the manufacturer (A2), where the GWP is particularly high at 2920 kg CO₂-Eq., representing nearly 83% of its total impact. This phase also exhibits the highest ODP and AP values, which can be attributed to the energy-intensive nature of transporting steel over long distances. These findings underscore the importance of considering logistics and transportation efficiency when assessing the sustainability of steel in construction [7,8].

Wood: Wood, often regarded as a more sustainable alternative, exhibits a unique environmental profile. The raw material supply stage (A1) shows a negative GWP value of -1170 kg CO₂-Eq., highlighting wood's potential as a carbon sink during its growth phase. However, the installation stage (A5) presents the highest GWP impact, accounting for 47% of the total. Additionally, the transportation phase (A2) contributes significantly to the ODP and AP values, reflecting the environmental costs associated with moving wood to construction sites. These findings are consistent with the literature, which emphasizes

wood's dual role as both a sustainable material and one that requires careful management throughout its life cycle [13–18].

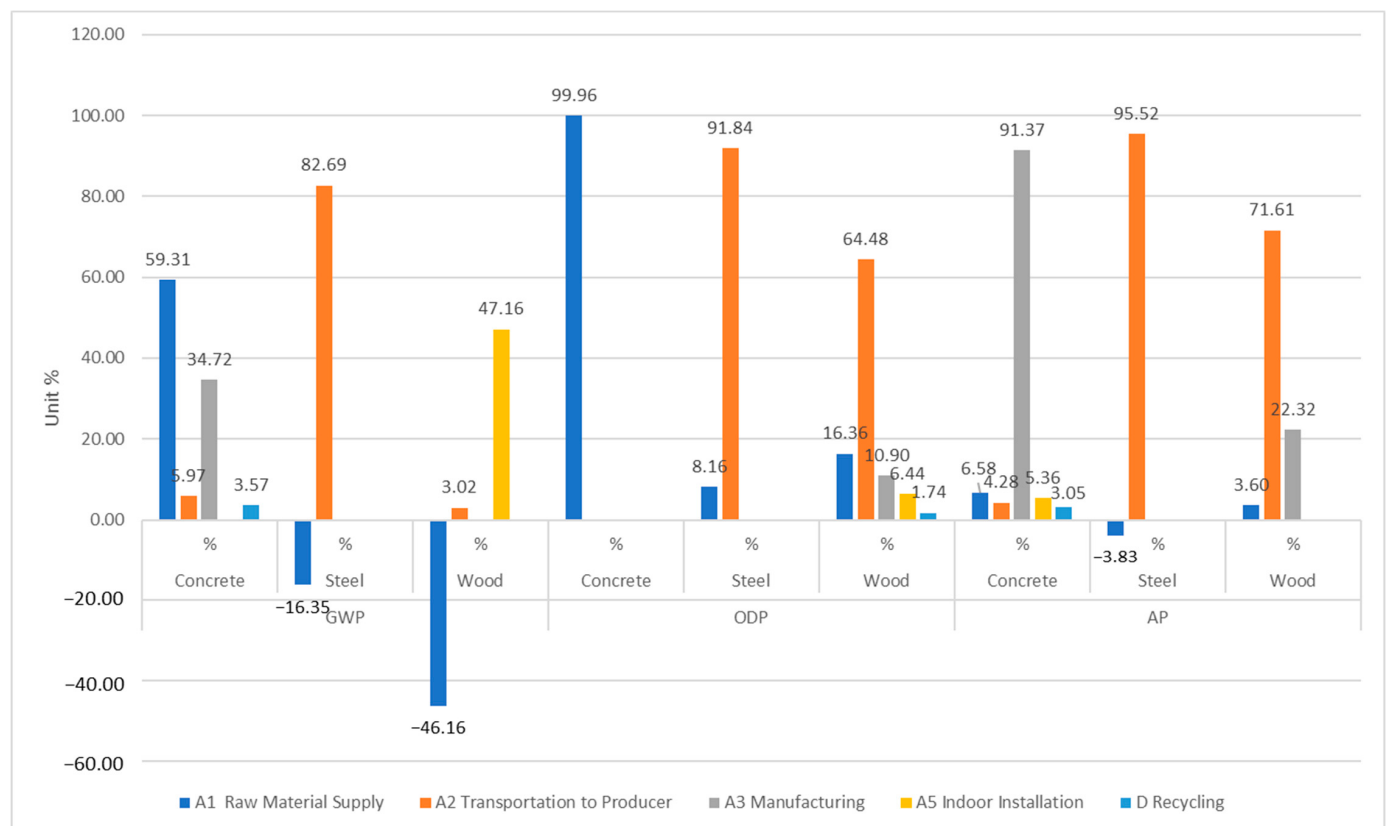


Figure 7. Life cycle assessment results for concrete, steel, and wood materials.

4.2. Interpretation of Findings

The comparative analysis of these materials reveals distinct environmental strengths and weaknesses, each shaped by specific life cycle stages. The findings suggest that while concrete and steel are integral to modern construction due to their structural properties, they also carry significant environmental burdens, particularly during the extraction and transportation stages. Conversely, wood offers substantial environmental benefits, particularly as a carbon sink, but its sustainability potential is contingent upon effective management during transportation and installation.

Concrete: The environmental impact of concrete, particularly its high GWP and AP during raw material extraction and production, suggests a need for innovations in sourcing and processing methods. The integration of supplementary cementitious materials, such as fly ash or slag, could mitigate some of these impacts, aligning with the broader goals of sustainable construction [4–11].

Steel: Steel's environmental profile is heavily influenced by transportation logistics. Sourcing steel locally or optimizing transportation methods could significantly reduce its environmental footprint. This finding highlights the broader implications of logistics in sustainable construction, where transportation efficiency plays a critical role in the overall sustainability of the material [12–25,29].

Wood: Wood's potential as a sustainable material is evident, particularly in its role as a carbon sink during growth. However, the environmental benefits of wood are not guaranteed; they depend on how the material is managed throughout its life cycle. Sustainable harvesting practices, efficient transportation, and careful installation are essential to maximizing wood's environmental advantages [14,15].

4.3. Implications for Sustainable Construction

The insights derived from this LCA study are critical for guiding sustainable construction practices, particularly in large-scale infrastructure projects such as airports. Understanding the specific environmental impacts of each material across different life cycle stages enables more informed decision-making, aligning with the goals of reducing the overall environmental footprint of construction activities.

Concrete: To mitigate the environmental impact of concrete, it is essential to explore alternative materials and enhance production processes. This study's findings suggest that early-stage interventions, such as optimizing raw material extraction and incorporating supplementary cementitious materials, could lead to substantial reductions in environmental impact [9–17].

Steel: For steel, the focus should be on logistics and transportation. By improving transportation efficiency and exploring local sourcing options, the environmental burden associated with steel can be significantly reduced, making it a more sustainable option for construction [7,8].

Wood: Wood's sustainability potential is vast, but it requires careful management. Ensuring that wood is sustainably harvested, efficiently transported, and installed with minimal environmental impact can position it as a cornerstone of sustainable construction. The findings emphasize the importance of considering the entire life cycle of wood to fully leverage its environmental benefits [13–18].

Incorporating these insights into the planning and execution of construction projects can lead to significant reductions in environmental impact, contributing to the broader goal of sustainable infrastructure development. As materials and technologies evolve, the regular updating of LCA models and databases is essential to ensure that decision-makers have access to the most accurate and relevant information.

4.4. Practical Applications and Future Research Directions

Practical Applications

The results obtained from this life cycle assessment study offer valuable insights for construction professionals, policymakers, and sustainability consultants engaged in large-scale infrastructure projects, such as airports. By understanding the environmental impacts associated with different materials—concrete, steel, and wood—across their life cycles, stakeholders can make more informed decisions that align with sustainability goals.

Material Selection: This study's findings highlight the significance of selecting materials based on their environmental impact across different life cycle stages. For instance, the high GWP of concrete during raw material extraction suggests that alternative materials or supplementary cementitious materials could be more sustainable options. Similarly, optimizing logistics to reduce the environmental burden of steel transportation could make steel a more viable option in regions where transportation distances are significant [12–25,29]. Wood, with its ability to act as a carbon sink, could be prioritized in projects focused on minimizing carbon footprints, provided that its transportation and installation are managed efficiently [13–18].

Sustainable Design and Construction: Insights from this study can inform the design and construction phases of airport projects. Incorporating more sustainable practices in material sourcing, such as using locally available resources, can significantly reduce environmental impacts. The findings support the adoption of green building certifications like LEED and BREEAM, which promote the use of materials and practices that reduce environmental footprints [7,8].

Policy Development: Policymakers can use the results of this study to develop regulations and incentives that promote the use of sustainable materials in construction. For example, policies could be introduced to encourage the use of low-impact materials like sustainably sourced wood or to incentivize the reduction in emissions associated with material transportation [7,8].

5. Conclusions

Three of the building materials used in eight different airport terminal buildings, which are officially certified as sustainable buildings with a green building certificate, were systematically selected and examined in this study. Among the materials used in the construction of these eight different airports located in different climatic regions, three common materials were identified. The accepted values of the selected materials were provided as input to the OpenLCA program and calculated using the ECOinvent database. The results obtained reveal the sustainability values of the materials in terms of their environmental impacts. Thus, sustainable construction materials for airport structures were measured. As a result of the research, it was seen that materials have a great potential in terms of the sustainability of buildings and that this potential can be used effectively in construction.

The findings of this study show parallelism with the previous study by Asdrubali et al. [30] in terms of sustainability. They examined sustainability assessment tools of buildings at the early design stage [30]. Similarly, the method has progressed through SQL (Structured Query Language)-based software and the ICE database. As a result of this study, it has been found that it can help decision-makers in choosing the optimal building material combination in terms of environmental and economic sustainability [30,31].

When the environmental impact values, which differ according to living modules, are examined on average, it seems that concrete material is a relatively high-impact material that can be preferred in sustainable airport structures. The durability of concrete and its easy availability to local users are the reasons why this material is widely used. This may increase the environmental impact potential of the material. Of the eight different airports where construction materials were shared, San Francisco Airport was found to use concrete materials the most.

When the environmental impact values of steel material are examined, it is seen that the rates are at medium levels compared to the other two materials, concrete and wood. Steel stands out with its high strength and recyclability. However, due to the energy intensity in the production process, its environmental impacts are balanced. Of the eight different airports where construction materials were shared, Heathrow Airport was determined to be the one that used steel materials the most.

According to the environmental impact values of wood materials, it has the lowest values among the materials examined. However, due to it being a renewable resource and recycling capacity, wood needs to be carefully evaluated in sustainable airport structures. Of the eight different airports where construction materials were shared, Helsinki Vantaa Airport was found to use wooden materials the most.

Talking about the limits of this study, care was taken to ensure that the airport buildings selected here were only terminal buildings with internationally valid sustainability certificates. The environmental impact value data of the building materials for which LCA was performed here are based on the accepted values for one ton of material. Subsequent researchers need to pay attention to the comparability of the selected materials and the accepted values for these materials. For similar studies, the sample can be enlarged, different building materials can be selected, or a different program and database combination can be used. In this study, the materials were evaluated only by considering their environmental impact; cost, material life, and human health categories were excluded.

This analysis emphasizes that environmental impacts should be considered in the selection of materials used in sustainable airport structures. The advantages and disadvantages of each material must be evaluated in terms of both its technical properties and environmental impacts. Sustainability should be achieved not only based on category values such as GWP, ODP, and AP, but also by considering broader criteria such as the cost of the material and its impact on human health. The design and construction of sustainable airport structures should aim to create less environmentally harmful and more durable infrastructures for future generations.

6. Future Research Directions

The research method employed in this study—using LCA with OpenLCA software and the ECOinvent database—provides a robust framework for evaluating the environmental impacts of construction materials. This method can be extended and refined in several ways:

Broader Material Analysis: Future research could expand the range of materials analyzed, including emerging materials like recycled composites, advanced polymers, or bio-based materials. Comparing these with traditional materials would help identify even more sustainable alternatives for construction [9–20].

Regional Specificity: Environmental impacts can vary based on geographic location due to differences in transportation logistics, energy sources, and local environmental conditions. Future studies could focus on region-specific LCAs, which would help in developing tailored sustainability strategies for different regions [8–17].

Integration with BIM: Integrating LCA with BIM could provide real-time environmental impact assessments during the design phase of construction projects. This integration would allow designers and engineers to visualize the environmental consequences of their material choices and construction methods more effectively [6–24].

Life Cycle Cost Analysis (LCCA): Incorporating life cycle cost analysis alongside LCA would provide a more comprehensive understanding of both the environmental and economic impacts of different construction materials. This would enable the evaluation of trade-offs between environmental sustainability and financial feasibility [4–9].

Longitudinal Studies: Conducting longitudinal studies that track the environmental performance of materials over time would provide valuable data on the durability and long-term sustainability of various construction materials. This approach could help identify materials that perform well not just initially but throughout the entire lifespan of a building [16–25,29].

By applying these methods in future research, we can continue to refine our understanding of sustainable construction practices and develop new strategies to reduce the environmental impact of infrastructure projects globally.

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