SILESIAN UNIVERSITY OF TECHNOLOGY PUBLISHING HOUSE

SCIENTIFIC PAPERS OF SILESIAN UNIVERSITY OF TECHNOLOGY 2024
ORGANIZATION AND MANAGEMENT SERIES NO. 207

CARBON FOOTPRINT MANAGEMENT BASED ON LCA CALCULATIONS IN ARCHICAD FOR A HYPERLOOP STATION

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Purpose: The purpose of this study is to determine the carbon footprint of a Hyperloop station by integrating Building Information Modeling (BIM) with Life Cycle Assessment (LCA).
Design/methodology/approach: The research quantifies carbon dioxide emissions at all stages of the Hyperloop station's life cycle—from design and construction to operation and demolition. It focuses on identifying key sources of emissions and developing strategies to minimize their environmental impact. Detailed tracking of material flows during construction allows for assessing the sustainability and durability of the building materials used. A digital model was created in Archicad, defining the environmental properties of materials. Energy performance was estimated both graphically and analytically to showcase the carbon footprint and assess environmental indicators.
Findings: The integration of BIM and LCA supports environmentally friendly decision-making throughout the project life cycle. The study identifies environmental hotspots and promotes the adoption of greener alternatives. It demonstrates that using these tools provides dynamic, real-time feedback during design stages, which is essential for minimizing environmental footprint and ensuring compliance with EU directives.
Research limitations: The research does not explicitly address potential limitations; however, the accuracy of the carbon footprint estimation may depend on the quality of data and assumptions used in the BIM and LCA models.
Practical implications: This research could influence public and corporate policy decisions by highlighting the importance of sustainable building practices. By reducing environmental impact, it contributes to improving the quality of life and aligns with broader societal benefits under EU sustainability directives.
Originality/value: The study is original in its integration of BIM and LCA for a Hyperloop station, promoting environmentally friendly decision-making throughout the project life cycle. It not only adheres to stringent environmental standards but also sets benchmarks for future sustainable infrastructure projects. This approach aids in minimizing environmental footprint and ensuring compliance with EU directives through dynamic, real-time feedback during the design stages.

Keywords: Hyperloop station, carbon footprint management, BIM, LCA, global warming potential (GWP).
Category of the paper: Research paper.

http://dx.doi.org/10.29119/1641-3466.2024.207.24

1. Introduction

The development of the Hyperloop, a revolutionary transportation system that leverages low-pressure tubes and electromagnetic propulsion (Prymon-Ryś et al., 2023), has emerged as a significant innovation, especially in the context of the 2022 energy crises. This innovation underscores the urgent need for economically viable and environmentally sustainable transportation solutions (Bhuiya et al., 2022). As such, a thorough LCA of the Hyperloop is essential to substantiate its sustainability claims and to ensure that its implementation aligns with global environmental goals.

This study employs LCA to evaluate the environmental impacts associated with building materials, transport logistics, and operational energy use, all integrated with BIM to create a dynamic framework for assessing environmental impact. This approach is in line with the European Union's Green Deal directive and adheres to standards such as EN-15804+A1 (Hollberg et al., 2020). The research reveals significant variations in GWP of different materials; for example, Aerated Reinforced Concrete and Precast Concrete contribute substantially to GWP, while Natural Stone exhibits lower impacts, and Glued Laminated Timber demonstrates carbon sequestration capabilities (Dias et al., 2020).

Operational energy, particularly from heating and lighting, is identified as a major contributor to GWP, posing challenges in meeting the EU's 2024 standards. The study also highlights the limitations inherent in relying on specific LCA databases, which may not fully reflect diverse geographic and ecological conditions (Zhang, Cai, Braun, 2022). Consequently, future research should expand to include a broader range of databases and environmental indicators. Implementing the findings of this study can significantly reduce carbon emissions in the construction and operation of Hyperloop stations. It emphasizes the necessity of sustainable construction practices and technologies, such as the use of renewable energy sources and low-carbon materials.

The integration of BIM and LCA is shown to enhance the environmental performance of construction projects, despite current software limitations (Santos et al., 2019)., Based on the LCA of the Hyperloop station conducted in accordance with the EN-15804+A1 standard, the data was implemented into the Archicad program to evaluate the environmental impact from material production to disposal or recycling (Najjar et al., 2019; European Committee for Standardization, 2019). While the Hyperloop suggests lower operational emissions compared to traditional transport systems (Shinde et al., 2019), these benefits may be offset by the emissions from all associated infrastructure.

Therefore, this study further examines the integration of BIM and LCA in the design of a Hyperloop Station to comply with the EU's stringent sustainability directives (Patz, 2022). Using Archicad, and data from the Ökobaudat (Theißen et al., 2020) and Defra (Tribby, 2023) databases, the study assesses environmental impacts across all lifecycle stages, crucial for aligning infrastructure projects with sustainability goals and improving decision-making through dynamic feedback during design. Additionally, the study investigates innovative construction materials and methods to significantly reduce the carbon footprint of large-scale infrastructure projects. Through a literature review, it evaluates materials that fulfill functional requirements while minimizing environmental effects, such as alkali-activated concrete, fiber -reinforced concrete, geopolymer concrete (Chottemada, Kar, Maeijer, 2023, Amran et al., 2019; Nematollahi) and timber-concrete composite systems, which are expected to decrease ecosystem impacts. Furthermore, the study examines the operational energy of traditional buildings, focusing on heating and ventilation, to ensure compliance with the EU's nearly zero-energy building standards and considers the operational energy's impact on overall GWP, particularly in regions with high-carbon intensity energy mixes.

2. Literature review

Global climate efforts have progressed through UNFCCC COPs since 1995, with COP 26 operationalizing the Paris Agreement's 1.5°C target, driving stricter CO2 reduction in the building sector. The EU has led with directives to boost renewable energy in buildings and decarbonize by 2050 (de Oliveira et al., 2023). Influenced by Danish initiatives, the European Union implemented stringent LCA standards for sustainable construction, as emphasized by the 2021 EU Directive 2010/31/EU. This directive mandates nearly zero-energy building standards to minimize operational energy and promote sustainable construction methods (Arrigoni et al., 2020). This directive is supported by Green Public Procurement initiatives that set LCA benchmarks for construction materials and whole buildings throughout Europe (Scherz et al., 2022).

In 2019, building material production contributed 28.2 million metric tons of CO2, with concrete and steel responsible for 90% of these emissions. Timber, though only 10% of emissions, offers a significant reduction potential due to its lower carbon intensity (120 kg-CO2/m²) compared to steel and concrete. Achieving net-zero embodied carbon by 2050 is unlikely under current practices, even with low-carbon alternatives. However, increasing timber use in construction could reduce emissions by 35%, with additional reductions possible through design optimization and longer building lifespans. Increased timber demand can also enhance forest carbon uptake by rejuvenating aging forests, potentially increasing carbon sequestration by 60% by 2050 (Watari, Yamashita, Cabrera Serrenho, 2024).

Emphasizing holistic sustainability, the focus in Europe has expanded to include the entire lifecycle of building materials, from pre-use to maintenance. For instance, prefabricated timber houses in Germany have been show to exhibit lower GWP and reduced acidification impacts, contributing to sustainability from production through disposal (Ruocco, Melella, Sabatano, 2023). As shown in Figure 1, the IEA EBC Annex 72 project examines the environmental impact of a building by harmonizing Life Cycle Assessment (LCA) approaches globally. There a reference building was used to explore national discrepancies in methodology.

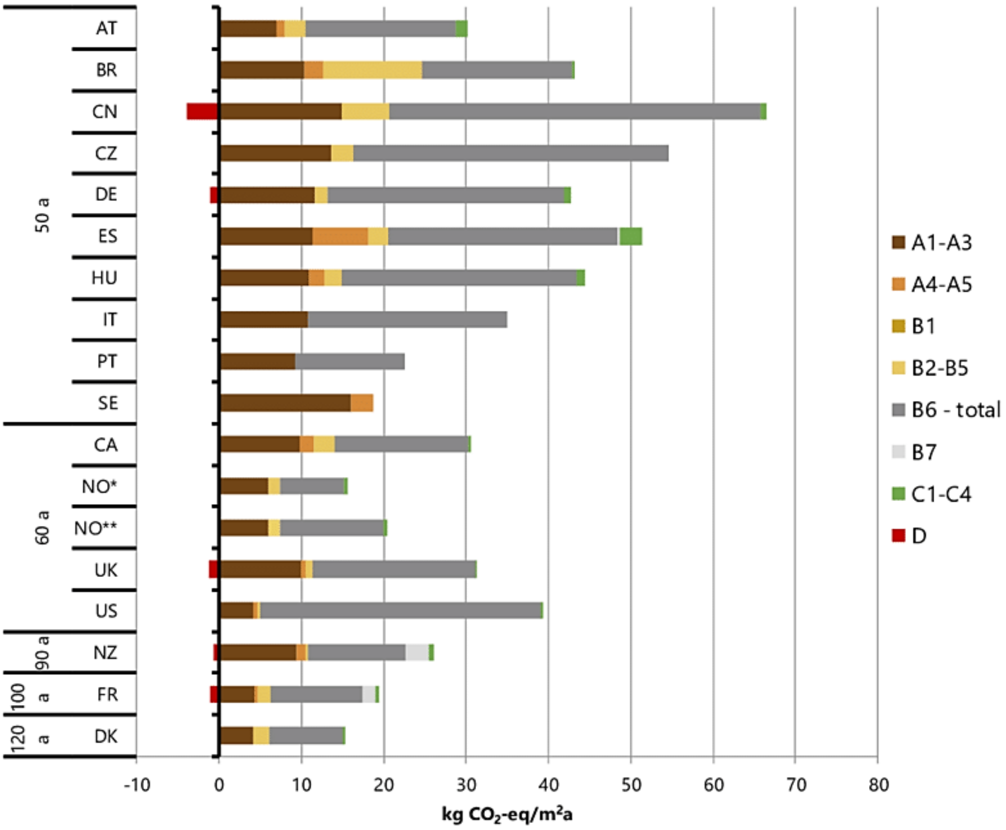

Figure 1. GHG emissions from the reference building "TJ-CSY-11," measured in kg CO2-eq per m² per year, were evaluated using the national/regional methodologies of the listed countries.

Source: (Frischknecht et al., 2020).

Figure 1 illustrates the CO2-equivalent emissions per square meter per year (kg CO2-eq/m²*a) across various countries, highlighting the environmental impact at different stages of a building's life cycle. The emissions for each country are broken down into specific modules, including material production, transportation, construction, use, and end-of-life disposal. The life cycle begins with modules A1-A3, which cover the production of building materials. This is followed by modules A4-A5, focusing on the transportation of materials and the construction process. Module B1 represents the use phase that does not involve energy consumption, while modules B2-B5 include activities such as maintenance, repair, replacement, and refurbishment. The total energy consumption during the use modules is captured under B6, while B7 accounts for water consumption during this phase. Modules C1-C4 refer to the end-of-life stage, encompassing deconstruction and disposal of materials. Lastly, modul D represents potential benefits beyond the system boundary, such as recycling or energy recovery.

Figure 1 also highlights the differences in emissions associated with each stage, which can be influenced by national practices, building material choices, and energy mixes. For example, Denmark exhibits the highest overall emissions, primarily driven by energy consumption during the building's use phase. In contrast, countries like Austria and Brazil demonstrate a more balanced distribution of emissions across all life cycle stages. Notably, Norway and Sweden show lower emissions during the use phase, likely due to more energy-efficient buildings or a cleaner national energy mix (Obrecht et al., 2019).

The variation in greenhouse gas (GHG) emissions, such as those seen in Austria's "be2226" office building, which range from 10 to 71 kg CO2-eq/m^2*a, highlights the influence of national LCA databases that reflect unique production conditions and energy mixes (Frischknecht et al., 2020). These differences, exemplified by differences in GHG emissions per kg of building material and national electricity mix intensities, underscore the need for standardized LCA methodologies to ensure comparability across different settings.

Overall, innovative construction materials and methodologies are enhancing the construction industry's ability to build structures such as Hyperloop stations, with significantly reduced carbon footprints. While the construction industry heavily contributes to carbon emissions through material production and transportation, the use of alternative materials and designs can mitigate up to 90% of these emissions during critical phases (Sizirici et al., 2021). Life cycle assessment, especially of concrete, is essential for understanding and reducing greenhouse gas emissions across different construction phases (Arrigoni et al., 2020).

Denmark has set a progressive benchmark by aiming to limit the GWP of new buildings to 7.5 kg CO2-eq/m^2*a by 2029, a goal that could influence broader EU policies. BIM with LCA has proven to optimize environmental impact assessments in construction projects, enhancing data accuracy during the design phase. This integration is further developed by tools that assess the global warming potential of buildings, emphasizing the need for detailed environmental monitoring (Hollberg et al., 2020). For instance, the University of Seville, in collaboration with Datacomp, utilized the Advanced Reports plugin for BIMvision in the Urban BIM project to evaluate environmental efficiency of buildings. Indicators such as carbon footprint and embodied energy were used, illustrating how digital models can generate comprehensive environmental reports (Carvalho et al., 2021).

Literature review reavealed that elevators and escalators play a significant role in the overall Total GWP. Therefore it is crucial to include the carbon footprint of these elements from production to disposal. A study highlighted that the major contributors to carbon dioxide emissions were the manufacturing stage (41.31%), followed by operation and maintenance (57.32%), with installation and demolition contributing minimally (0.92% and 0.44%, respectively). On average, the annual carbon dioxide emissions were estimated at about 27.18 kgCO2 per ton·kilometer. The study emphasized that the primary factors influencing these emissions included electricity consumption, the use of various metals like low-alloy steel and chrome steel, and components like printed circuit boards (Ang et al., 2022).

3. Materials and methods

3.1. Life Cycle Analysis

The LCA was applied in this study to evaluate the Hyperloop Station, assessing environmental impacts in accordance with EN-15804+A1 standards (Vladimirov, Bica, 2019). This assessment covers all phases, from raw material acquisition to operation, including maintenance and energy use, thereby providing a comprehensive analysis of environmental impacts. The process concludes with the end-of-life phase, encompassing demolition and material recovery, utilizing Module D of LCA to evaluate net impacts (Mesa, Fúquene-Retamoso, Maury-Ramírez, 2021).

Moreover, integrating technologies such as 3D architectural software into the LCA enhances the accuracy of environmental evaluations, linking decisions during maintenance to the overall sustainability and underscoring the importance of each phase in reducing both environmental and economic impacts (Vishnu, Padgett, 2020). The formula for calculating the carbon footprint (CF) of construction projects through LCA is expressed as follows:

$$CF = \sum_{i=1}^{n} (EF_i \times AD_i) \tag{1}$$

where:

CF is the total carbon footprint,

EF_i is represents the emission factor of the i-th activity,

AD_i is the activity data for the i-th activity,

n is the number od the activities considered.

Calculating the carbon footprint of construction projects through LCA, quantifies total greenhouse gas emissions as CO2 equivalents, starting with defining scope and collecting data on material and energy use (Figure 2) (Waldman et al., 2020).

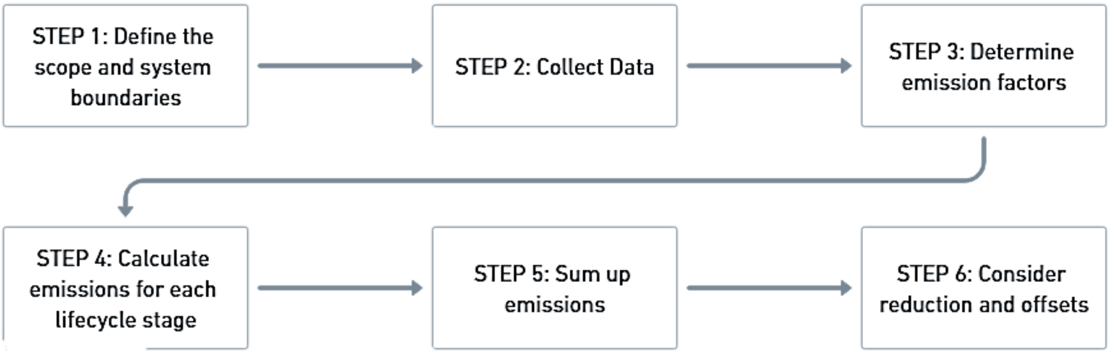

Figure 2. The stages of calculating the carbon footprint.

Source: own elaboration.

This method tracks emissions from material extraction to demolition, with a focus on detailed assessments of processing and operational energy. In Figure 2, the stages of calculating the carbon footprint are illustrated, providing a detailed overview of the process from data collection to final emission calculations, further highlighting the importance of each stage in the overall reduction strategy. Strategies for emission reduction include adopting renewable energy sources and selecting low-carbon materials, with the feasibility of carbon offset mechanisms providing a comprehensive approach to mitigation. Continuous improvements in LCA methodologies, through annual evaluations and updates, enhance data precision and support effective mitigation strategies (Shekhorkina et al., 2020; Yue et al., 2022).

3.2. Tools for calculating

The design of the Hyperloop station emphasizes scalability, accessibility, and environmental sustainability, incorporating comprehensive soil and utility assessments. Drawing on traditional railway architecture, the Station features clear pathways and signage to enhance passenger flow and accessibility. Its tiered spatial layout includes accessible entrances and ample parking at ground level, facilitating efficient circulation and integrating safety measures for high traffic volumes. Additionally, an adjacent hotel offers synchronized services with the Hyperloop, enhancing traveler convenience through sustainable practices. The Station's underground levels focus on passenger safety and experience. The first underground level houses amenities and security infrastructure, while deeper levels ensure smooth transit, and the lowest level features advanced safety systems like vacuum chamber gates (Stryhunivska et al., 2020). Emergency management is well-integrated, ensuring efficient evacuation and maintaining safety in crises, with automation technologies such as biometrics boosting operational safety (Stryhunivska et al., 2020; Haack, Schreyer, 2006). This approach demonstrates a strong commitment to maintaining high safety standards and operational efficiency throughout the Hyperloop network.

BIM was implemented in this study due to its high level of interoperability, which enabled the integration of various disciplines involved in the project and all information generated throughout the building's life cycle into a single virtual model of the Hyperloop station (Sampaio, Gomes, Farinha, 2021). This station model was developed using ArchiCAD, a software that supports Building Information Modeling (BIM) technology. By integrating Life Cycle Assessment (LCA) within the BIM environment via ArchiCAD, the study achieved a more consistent and accurate evaluation process.

The workflow for the model analysis was divided into three main stages. First, the models were created using ArchiCAD in the "Plan" data format (PLN). The second stage focused on the LCA itself, utilizing a workflow where LCA was conducted using the DesignLCA plug-in within the ArchiCAD environment, focusing on accurately deriving mass balances from the model. A critical aspect of this process was the use of high-quality environmental data from the

Ökobaudat and Defra databases. These databases were integrated into the DesignLCA tool to provide precise data on CO2 emissions related to material quantities used in the project.

Ökobaudat and Defra provided comprehensive and reliable data essential for evaluating the environmental impacts of building materials. Their integration into the LCA ensured accurate and current CO2 emission data, aligning the study with international sustainability standards like Germany's BNB and DGNB (Theißen et al., 2020). This approach enabled precise assessment of the Hyperloop station's materials, emphasizing durability and supporting strategies to minimize environmental impacts and maintenance needs.

The final stage involved evaluating the results. The outputs from DesignLCA underwent a manual error analysis. Any identified issues or anomalies were documented and resolved, either by rerunning the analysis after troubleshooting or by manually incorporating any missing data using well-established methodologies. The refined results were then used to formulate both general and specific conclusions, which informed the final recommendations. The optimized computational workflow enabled by ArchiCAD ensures that LCA calculations were seamlessly integrated, leading to reliable outcomes. This approach not only enhanced the accuracy of environmental impact assessments but also improved the project's sustainability by enabling a detailed analysis of materials and processes directly within the BIM model.

The operational energy use analysis for the Hyperloop Station was conducted using ArchiCAD, focusing on precise thermal modeling of the building. Key parameters such as wall thickness, thermal conductivity, and window area were thoroughly examined to optimize energy consumption for heating and cooling. ArchiCAD facilitated the simulation of heat transfer, which is crucial for understanding energy flow within the building and adjusting systems to match real operational conditions. Integrated environmental data within the model ensured the building's compliance with sustainable construction standards. This allowed for the design of heating and ventilation systems that minimize CO2 emissions while maintaining user comfort. Additionally, the application of advanced technologies, such as triple-glazed windows and photovoltaic panels, was carefully evaluated for their effectiveness in reducing energy consumption and their impact on the overall carbon emissions balance during the station's operation.

Because module A4, the transportation of materials to the construction site, is customized for each specific location, it was necessary to calculate it independently. This calculation utilized a thorough literature review on the linear relationship between fuel consumption and cargo weight during long-distance transportation. Extensive empirical analysis was conducted using Mercedes-Benz Actros-1840 truck tractors to establish this relationship. The correlation coefficient rXY was used to identify the connection between two key variables: the mass of the transported cargo in tons (X) and the fuel consumption per 100 km (Y) in intercity transport per one truck. This coefficient, rXY, helps determine the statistical relationship between these variables. The regression equation derived from this analysis was:

$$Y = 21{,}331 + 0{,}3906X \tag{2}$$

where:

Y is total fuel consumption per one truck per 100 km of intercity transport,
X is mass of cargo that one truck is carrying.

It demonstrates a linear relationship, with the confidence test affirming the statistical significance of the correlation coefficient (Khabibullozoda, Goriaev, 2021). The assessment of additional space needed for the packaging of building materials is a crucial component in counting emissions. This study employs a model to estimate the total packaging volume, calculated based on study showcasing the amount of packaging waste generated during construction activities. Predominantly the types of packaging materials which were identified were cardboard, plastic, and wood. These are often found in mixed waste containers upon the completion of construction (Narcis et al., 2019). Them the proportionate increase in the volume of packaging associated with the use of prefabricated materials, as well as the enhanced packaging of traditional materials, is quantified.

To accurately estimate the required additional space for these materials, a ratio is derived from the total construction area to the volume of packaging waste. Specifically, for the Hyperloop Station with a surface area of 29,352.02 m², and a comparison construction work area (CW1) covering 15,065.51 m², the total waste volume from CW1 was 2534 m³ (Sáez et al., 2019).

1. Calculate total mass of cargo:

$$M = \left(\frac{V_{CW1}}{A_{CW1}} \times A_{HS}\right) \times \sum_{i=1}^{n} (\rho_i \times q_i) \tag{3}$$

2. Determine number of truck trips:

$$N = \frac{M}{W_{avg}} \tag{4}$$

3. Fuel consumption calculation:

$$Y = \left(21.331 + 0.3906 \times W_{avg}\right) \times N \tag{5}$$

where:

V_{CW1} is Total waste volume from CW1.
A_{CW1} is Area of CW1.
A_{HS} is Area of the Hyperloop station.
ρ_I is Proportion of each material type in the total volume of waste.
M is Total mass of transported cargo in tons.
N is Number of truck trips required to transport all materials.
Y is Total fuel consumption for all trips in liters per 100 km.

The estimated volume of waste for the Hyperloop Station is calculated to be 4937 m^3. This estimate serves as the basis for determining the proportion of packaging materials, which is crucial for calculating the final mass of the packaging within the total waste volume. According to the literature, the average density of materials such as wood in pallets is 496.12 kg/m^3 (Schweinle et al., 2020), plastic (based on an average of 176 types) is 1306.75 kg/m^3, and cardboard is 970 kg/m^3 (Rudenko, 2019).

The next step in the calculations involves determining the total mass of cargo that needs to be transported. This mass is derived by scaling the waste volume from a comparison construction work area (CW1) to the area of the Hyperloop station and then multiplying it by the sum of the proportions of each material type within the total waste. After establishing the total mass, the number of truck trips required for transportation is calculated by dividing the total mass by the average weight capacity of a truck. Finally, the fuel consumption for all trips is calculated using a formula that accounts for both a base fuel consumption value and an additional factor related to the truck's average weight capacity, multiplied by the number of trips. This comprehensive approach provides an accurate estimation of the resources required for transportation, including the total mass, logistics, and fuel consumption.

4. Results

The study demonstrated that the Hyperloop Station requires significant quantities of materials, leading to substantial environmental impacts. It was found that materials such as Aerated Reinforced Concrete and Precast Concrete have high Global Warming Potential (GWP), contributing significantly to the station's overall carbon footprint. In contrast, materials like Natural Stone and Expanded Clay hollow blocks were shown to have lower GWPs. Additionally, the use of Concrete ECOPact was highlighted for its reduced GWP, indicating progress in sustainable building practices (Zīmele et al., 2019).

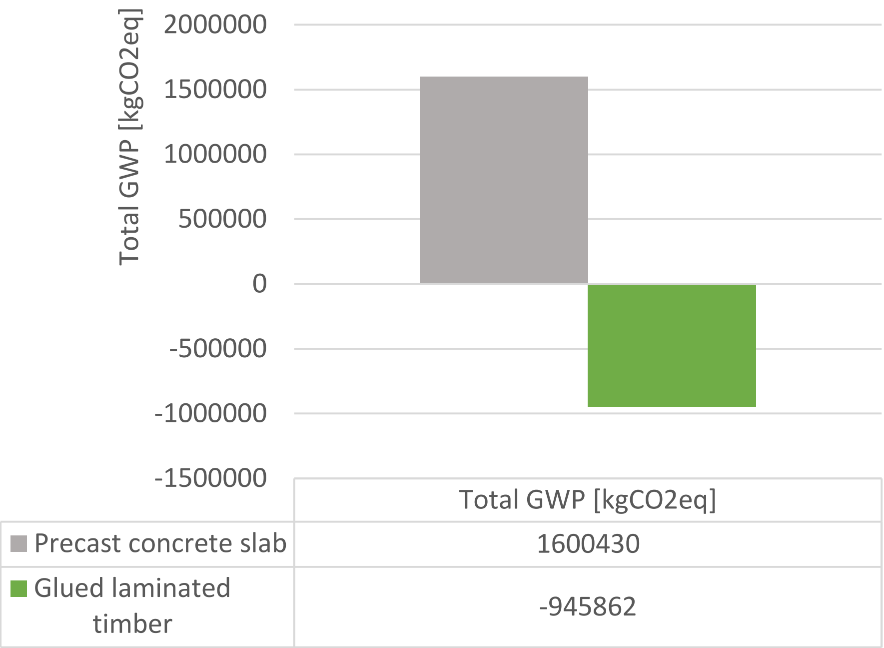

Figure 3. Potential GWP Offset using glued laminated timber.

Source: own elaboration.

Moreover, Glued Laminated Timber demonstrates a potential for carbon sequestration (Figure 3), drastically reducing the industry's overall carbon footprint and driving global demand for sustainable timber (Balboni, 2022).

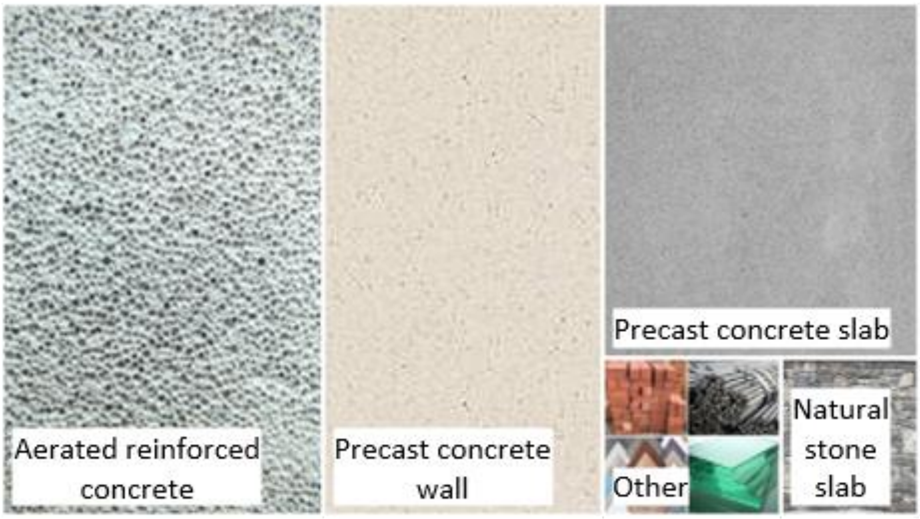

Figure 4. Visualization of the total impact on GWP of the most polluting segments of Hyperloop Station.

Source: own elaboration.

Materials like Aerated Reinforced Concrete provide structural solutions with lower environmental impact, while Natural Stone and Expanded Clay blocks contribute both aesthetic and functional benefits with minimal ecological footprints (Figure 4). The use of advanced materials like Concrete ECOPact exemplifies significant strides in reducing ecological impacts while enhancing building performance.

Based on the methodology outlined in the previous section, the estimated volume of waste for the Hyperloop Station was calculated to be 4937 m^3**.** This estimation was derived using the ratio of total construction area to the volume of packaging waste, as detailed in the Materials and methods section. Furthermore, the transportation logistics of these materials are analyzed based on data from 237 truck courses, which revealed an average cargo weight of 11.61 tonnes. By dividing the total mass of building materials, including their safety packaging, by this average cargo weight, the number of truck excursions required to transport all materials to the construction site is calculated. These calculations are then integrated into a linear regression model. The entire regression model is multiplied by the amount of truck trips, while parameter X equals the average cargo weight. It was presumed that materials would be transported from an average distance of 100 km from the construction site. However, it is important to note that this distance could substantially vary due to the diverse locations of warehouses and manufacturing facilities for building materials.

Operational energy consumption greatly impacts the global warming potential (GWP) of buildings, pointing to the necessity of holistic environmental assessments that consider all lifecycle phases to avoid transferring burdens elsewhere (Kim et al., 2022). Poland's high carbon intensity at 1.0595 kgCO2-eq per kWh is mainly due to its reliance on coal and limited renewable energy sources, which significantly affect its emission rates (Balaras et al., 2023). In the case of the Hyperloop Station, operational energy, especially from heating, hot water and ventilation systems are major contributors to its total GWP, highlighting the need for energy-efficient solutions in design and operation (Figure 5).

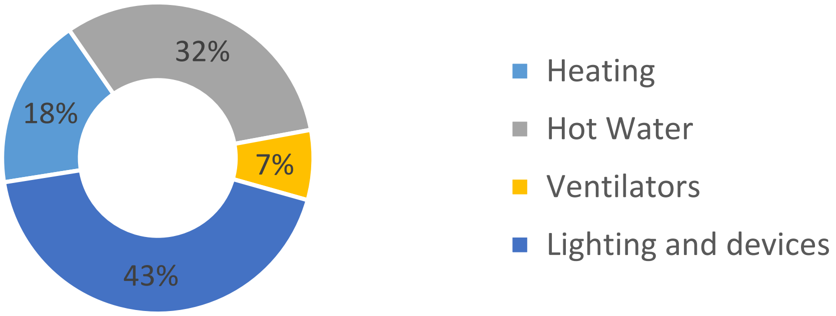

Figure 5. Utilization of Operational Energy at the Hyperloop Station.

Source: own elaboration.

A study on the Hyperloop Station's carbon footprint showed that elevators and escalators, based on a dataset of 400,000 annual rides, emit 393,457 kgCO2eq. This figure combines with the station's other operational energies for a total of 916,221 kgCO2eq. Integrating renewable energy and efficient systems into such transportation hubs could drastically lower these emissions.

The study analyzes Total GWP in respect to Cradle to Grave (A1:D) (Bhatt, Bradford, Abbassi, 2019) method for various building lifecycle stages, including Product stage (A1:A3), use phase (B1:B5), end of life (C1:C4) and benefits (D), construction process (A4, A5), operational energy use (B6), normalized per area per year to establish an LCA threshold (Figure 6).

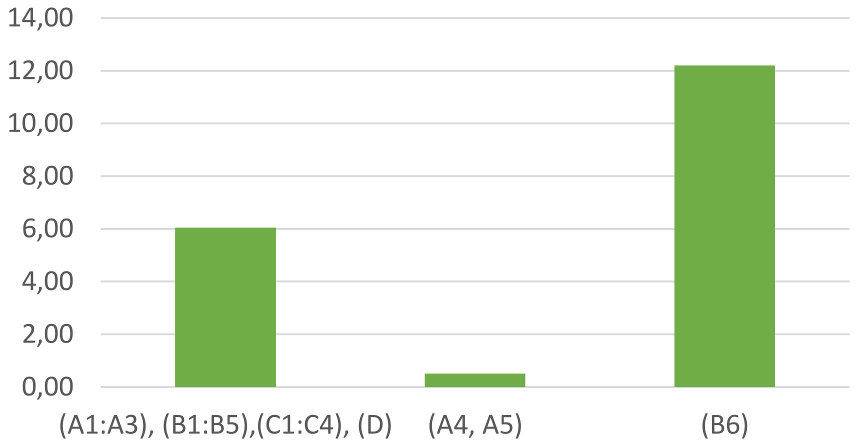

Figure 6. Total emissions during LCA phases.

Source: own elaboration.

The total GWP threshold is identified at 18.77 kg CO2-eq/m²*a, with operational energy use being the most impactful at 12.21 kg CO2-eq/m²*a, underscoring its significance during the building's operational phase. Other components collectively add 6.05 kg CO2-eq/m²*a and transportation and construction processes contribute minimally with 0.54 kg CO2-eq/m²*a (Figure 7).

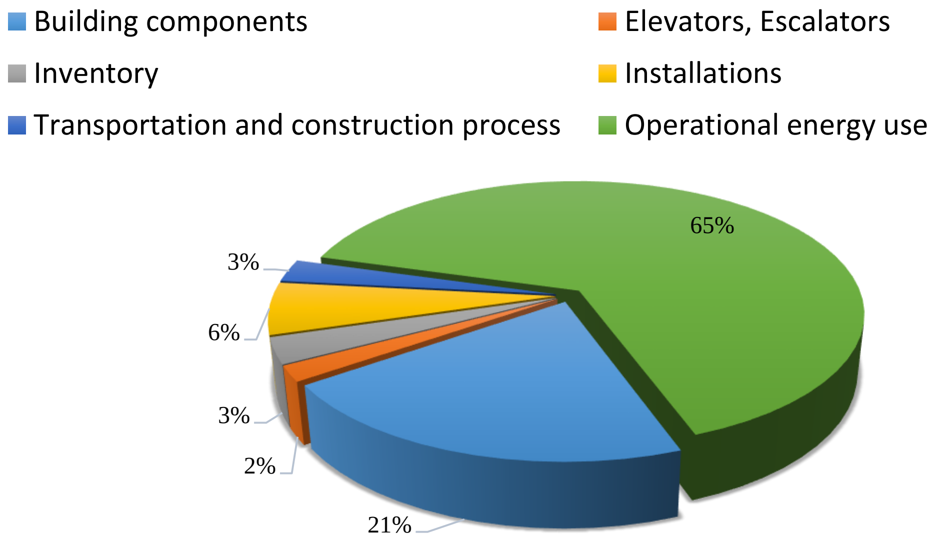

Figure 7. Total emissions from individual sources.

Source: own elaboration.

In Europe, LCA requirements for buildings are defined by guidelines and standards focused on enhancing construction sustainability. The European construction product directive mandates the quantification of environmental performance, integral to European Standards or Technical Assessments, and emphasizes Environmental Product Declarations for building certification across EU countries (Rosario et al., 2021). Additionally, the European Union guidelines mandate that from 2021 onward, new buildings must adhere to nearly zero-energy standards, thus placing a higher relative importance on the impacts of construction, disposal, and embodied emissions throughout the entire life cycle of a building (Weissenberger et al., 2014). This shift highlights the need for LCA to not only focus on operational energy but also to encompass a broader environmental assessment, as shown in Figure 8.

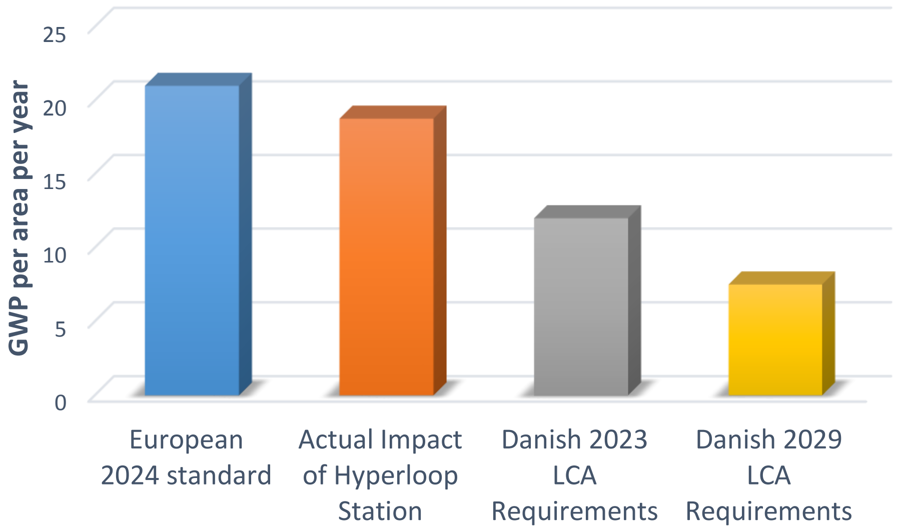

Figure 8. Comparison of the LCA threshold of the Hyperloop Station to various requirements.

Source: own elaboration.

Notably, the Hyperloop Station, with its GWP of 18.77 kg CO2-eq/m²*a, starkly exceeds Danish requirements and barely fits below EU 2024 standard (Figure 8). This underscores significant challenges in aligning cutting-edge infrastructure projects with national environmental targets. This highlights the urgent need for improved construction practices and technologies that can meet stringent LCA criteria without compromising the functional and structural integrity of innovative transport solutions.

5. Discussion

Integrating BIM with LCA from the design phase is crucial for aligning projects like the Hyperloop Station with EU sustainability directives, facilitating real-time feedback for environmentally friendly choices and early hotspot identification. This approach, adhering to standards like EN-15804+A1, promotes greener alternatives throughout the project lifecycle, yet the study reveals a GWP of 18.77 kg CO2-eq/m²*a for the Hyperloop Station. This figure underscores the significant challenges in meeting the EU's stringent CO2 emission standard of 21 kg CO2-eq/m²*a by 2024, particularly in light of Denmark's even more ambitious 2029 target of 7.5 kg CO2-eq/m²*a.

The unexpectedly high GWP, even with sustainable materials, necessitates re-evaluating construction material choices, as Aerated Reinforced Concrete still contributes significantly to emissions despite its eco-friendly marketing. This finding highlights the need to explore alternatives like alkali-activated and glass fiber-reinforced concrete, though their absence in environmental databases like Ökobaudat reveals a critical assessment gap. Materials such as Glued Laminated Timber, with negative GWP due to carbon sequestration, are emerging as essential in sustainable construction, potentially reducing carbon footprint through timber-concrete composite systems and plant fiber blocks. Operational energy consumption remains a significant factor in a building's environmental impact, emphasizing the need for integrated life cycle assessments balancing both operational and embodied energy to optimize sustainability.

The study of Hyperloop Stations reveals limitations due to potential inaccuracies in reflecting diverse geographic and ecological conditions. The assumed average material transport distance of 100 km, which can vary widely, impacts the accuracy of environmental assessments. Additionally, the focus on structural elements in the digital twin model in Archicad overlooks other contributors to the carbon footprint, such as electronics and decor. Future research should include diverse LCA databases and broader geographic assessments to enhance the validity and applicability of the findings.

Moving forward, exploring alternative, sustainable materials and integrating a broader range of environmental indicators will be crucial for enhancing the environmental performance of infrastructure projects like the Hyperloop Station. Expanding LCA databases to include regional variations and conducting longitudinal studies on energy use and material durability will improve the accuracy and relevance of sustainability assessments. Additionally, developing and standardizing tools that combine BIM, LCA, and sustainability metrics will enable comprehensive and consistent assessments, facilitating real-time design optimizations.

Collaboration among policymakers, industry stakeholders, and researchers is essential for adopting sustainable practices in construction. Utilizing the BIM-LCA framework in pilot projects with innovative materials will showcase the practical benefits of these approaches, encouraging wider adoption. Effective dissemination of findings through industry platforms will further accelerate the uptake of sustainable technologies. Additionally, integrating natural lighting, efficient waste management, and environmentally friendly materials, alongside certifications like BREEAM and LEED, can enhance sustainability credentials. The incorporation of 4D technology for infrastructure management can further optimize maintenance and reduce carbon footprints, positioning projects like the Hyperloop Station as leaders in sustainable transit solutions.

6. Conclusion

This study quantifies the environmental impact of Hyperloop Stations through the integration of BIM and LCA, revealing significant differences in GWP among building materials. Notably, materials like Aerated Reinforced Concrete and Precast Concrete were identified as having high Global Warming Potential (GWP), significantly contributing to the station's carbon footprint. In contrast, materials such as Natural Stone and Expanded Clay hollow blocks exhibited lower GWPs, presenting more sustainable alternatives. The use of Concrete ECOPact, which demonstrates reduced GWP, was highlighted as a significant advancement in sustainable building practices. Additionally, Glued Laminated Timber offers carbon-negative benefits through potential carbon sequestration, further reducing the industry's overall carbon footprint.

While building materials were a notable factor in the station's overall environmental impact, the operational energy consumption of the station, particularly for heating, hot water, and ventilation systems, emerged as a major contributor to GWP. This issue is exacerbated by Poland's high carbon intensity, complicating compliance with EU sustainability standards. The Total GWP was calculated at 18.77 kg CO2-eq/m^2*a with operational energy being the most significant contributor at 12.21 kg CO2-eq/m^2*a. This figure exceeds Danish requirements and barely meets the EU 2024 standards, underscoring the challenges in aligning cutting-edge infrastructure projects with national environmental targets.

The integration of BIM with LCA facilitates real-time environmental decision-making throughout the project lifecycle, ensuring adherence to EU directives and setting a benchmark for sustainable infrastructure projects. The research underscores the necessity of adopting renewable energy sources and energy-efficient designs to achieve meaningful reductions in carbon emissions. Future research should expand LCA databases and environmental indicators to improve assessments across diverse geographic and ecological contexts. Additionally, exploring more sustainable construction materials and recycling techniques can enhance the environmental performance of Hyperloop and similar infrastructure projects, aligning with sustainability goals and reducing the environmental impact of large-scale construction. By addressing the environmental challenges of both construction and operational phases, this study provides practical insights into sustainable construction practices, emphasizing the critical role of integrated technologies in developing eco-friendly infrastructure.

Acknowledgements

This research was funded by AGH University of Krakow, Faculty of Management. The authors wish to extend their heartfelt gratitude to those who provided invaluable support and expert consultation in areas pertinent to this publication. Special thanks are due to Professor Paweł Bogacz, Dr. Eng. Rafał Rumin, the Transpeed AGH organization and the Envirly company.

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