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Exploring the Impact of Span Length on Environmental Performance: A Comparative Study

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Abstract: Architects and building designers are pivotal in mitigating climate change by shaping the environmental footprint of buildings from their inception, with life cycle assessment (LCA) serving as a crucial tool for quantifying these impacts. Given that structural systems contribute significantly to embodied carbon, accounting for approximately 24% of a building's life cycle emissions, this research investigates the relationship between structural span length—a key design factor influencing material choices and construction methods—and overall environmental performance. Through a scenario-based analysis employing building information modeling (BIM) and whole building life cycle assessment (WBLCA) tools, this study evaluates various building configurations to reveal that in long-span scenarios, steel demonstrates a lower environmental impact compared to timber. This finding offers a novel, quantifiable insight for architects and designers to assess and optimize building designs, particularly in the context of emerging architectural trends featuring longer spans, ultimately contributing to more sustainable building practices.

Keywords: LCA; life cycle assessment; GWP; global warming potential; embodied carbon; structural span; steel; timber

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1. Introduction

1.1. Research Background

In recent decades, the impacts of climate change and the growing consumption of raw materials have heightened global awareness of the necessity to implement the concept of sustainable development on a worldwide scale. Architects and building designers play a crucial role in tackling climate change challenges, with the potential to greatly impact the environmental footprint of buildings, especially during the initial design phases [1]. As the global environmental crisis intensifies, professionals across these fields are increasingly recognizing the need to reduce the ecological impact of their work. This shift is particularly critical in the context of the built environment, where construction activities and the operation of buildings contribute significantly to global greenhouse gas emissions and resource depletion. Historically, efforts of both policymakers and the construction industry have largely concentrated on minimizing operational impacts, mainly energy consumption, within buildings [2]. Several policies and regulations have been established to enhance the energy efficiency of buildings. Initiatives like the EU Energy Performance of Buildings Directive (EPBD) [3] aim to promote efficient buildings by enforcing new standards for constructing nearly zero-energy buildings. With the aim of further mitigating greenhouse gas (GHG) emissions, it is now crucial to focus on other stages of the building life cycle, including the embodied impacts from manufacturing, transport, construction, upkeep, and end-of-life procedures [4]. As operational carbon emissions lessen, the proportional contribution of embodied carbon will increase, constituting a greater portion of total emissions. Embodied carbon, which encompasses the aggregate emissions from all building materials, products, and construction activities, currently accounts for approximately 20% of the building sector's total GHG emissions.

To support this shift, life cycle assessment (LCA) has emerged as a pivotal methodology for quantifying and understanding the environmental impacts associated with the construction and operation of buildings. First introduced by the ISO 14040 [5] standard in the 90s and now governed by a regulatory framework composed of various standards (ISO at the international level and EN at the European level), LCA provides a comprehensive procedure for evaluating the full range of environmental consequences throughout a building's life cycle—from material extraction and manufacturing to construction, operation, and eventual demolition or decommissioning. By offering insights into the environmental footprint of materials, construction processes, and the operational lifespan of buildings, LCA enables designers, engineers, and stakeholders to make informed decisions aimed at minimizing negative environmental impacts [6].

Through the application of LCA, it is possible to identify the most sustainable materials, construction methods, and operational strategies that can significantly reduce a building's carbon footprint. This methodology is crucial not only for assessing energy consumption and greenhouse gas emissions but also for evaluating other environmental factors, such as water use, waste generation, and resource depletion. As a result, LCA plays an increasingly vital role in the decision-making process, enabling architects and engineers to optimize their designs for both performance and sustainability. The ability to integrate LCA into the design process allows for the identification of trade-offs and opportunities for improvement, fostering more responsible and sustainable building practices that are aligned with the global goal of mitigating climate change.

As a result, the inclusion of LCA methodologies in architectural and engineering practices is vital for fostering environmentally responsible design outcomes. As awareness and urgency around climate change continue to rise, LCA will undoubtedly remain a central methodology for guiding the transition toward a more sustainable and low-carbon built environment.

In this context, building structural systems are acknowledged as significant sources of embodied carbon emissions. According to benchmarking research [7], these systems are estimated to be responsible for approximately 24% of a building's total life cycle embodied carbon emissions. Given their considerable share of a building's overall environmental footprint, structural systems are a critical focus area for reducing embodied carbon in the construction industry. Strategies such as optimizing material efficiency, selecting low-carbon alternatives, and improving design methodologies can play a pivotal role in mitigating these emissions.

The authors have already examined the impact of structural systems on embodied carbon in previous studies. In their analysis of contemporary architectural trends, they highlighted how decorative spires influence the embodied carbon of tall buildings, despite contributing only 1% to the total [8]. In 90-story buildings, these elements can increase the embodied carbon of structural systems by up to 14.2%, primarily due to the additional vertical and lateral loads they impose. This leads to a greater need for materials and an elevated embodied carbon cost linked to the increased vertical dimension ("vanity for height"). Additionally, their research has explored the role of cantilevers, which have become a defining characteristic of modern architecture. Driven by the pursuit of striking visual effects and the rise of 'vanity architecture', cantilevered structures enable dramatic overhangs and projecting volumes without visible supports. Their findings indicate that unbalanced cantilevers can lead to a 10% increase in embodied carbon compared to alternative designs that incorporate supporting columns [9]. This study aligns with that same line of research, further investigating how structural design choices shape both architectural expression and environmental impact.

Certain buildings, such as gyms, swimming pools, cultural and recreational facilities, exhibition halls, auditoriums, and theaters, have always required long spans and open-plan layouts. However, the number of such structures being built is increasing, reflecting a growing preference for expansive, flexible spaces. Additionally, new building typologies are emerging, driven by advancements in construction technologies that enable even greater spatial versatility and structural innovation. The rapid growth of digital infrastructure, in fact, driven by advancements in artificial intelligence and the development of smart cities, has introduced new challenges and opportunities. This evolution emphasizes the need for buildings designed specifically to accommodate computer servers, known as data centers, which are integral to supporting these technological innovations. These data centers, often characterized by single-story structures with large open spaces on the ground floor, pose unique sustainability challenges [10]. On the other hand, the growing demand for e-commerce is driving an increasing need for logistics centers. As online retail continues to expand, companies require larger and more advanced distribution hubs to handle inventory management, order fulfillment, and last-mile delivery more efficiently [11]. Applying LCA to these buildings can help optimize their design for reduced environmental footprints [12], addressing both their immediate construction impacts and their long-term operational efficiency. Moreover, applying LCA is strictly fundamental to making clients aware of the implications of long-span structures, ensuring informed decision-making. In this context, the role of architects and the construction industry becomes crucial in guiding this progress, promoting sustainable design choices, and balancing structural innovation with environmental responsibility.

Among the numerous design factors that influence the environmental performance of these buildings, the span length of structural elements plays a particularly significant role. Span length directly affects the choice and quantity of materials, the structural systems employed, and the associated construction methods [13]. Longer spans often necessitate the use of high-performance materials or innovative construction techniques, which can result in higher embodied carbon emissions. Conversely, shorter spans might require additional supports or increased material use, which also carry environmental trade-offs. Understanding these nuances is essential for optimizing designs that align with sustainability goals.

1.2. The Open Plan as an Architectural Trend

To provide insights on span length, this article first explores its growth in architecture. Several architectural trends, such as cantilever and open-plan layouts, have driven this rise in structural spans and have become increasingly popular in recent decades. The open-plan concept in architecture refers to spatial configurations that minimize internal partitions to create flexible, multifunctional environments. Characterized by a column-free floor layout, this approach is particularly advantageous for spaces requiring adaptability and large, uninterrupted areas [14]. It has been widely adopted in various building typologies, including offices, cultural facilities, and sports complexes, due to its ability to enhance spatial adaptability and foster social interaction [15].

In contemporary practice, advancements in structural engineering have significantly facilitated the implementation of open-plan layouts by enabling the design of long-span structures that minimize the need for internal load-bearing partitions. These developments include the use of long-span steel trusses, arches, and space frames, which efficiently distribute loads across extensive spans, creating large, unobstructed interior spaces.

Notable examples include the Sendai Mediatheque (2001) by Toyo Ito (Figure 1), which employs a system of irregularly arranged steel-tube columns to achieve structural openness (Figure 1) and the Apple Park Headquarters (2017) by Foster + Partners, where extensive use of long-span structures supports a highly flexible, column-free interior

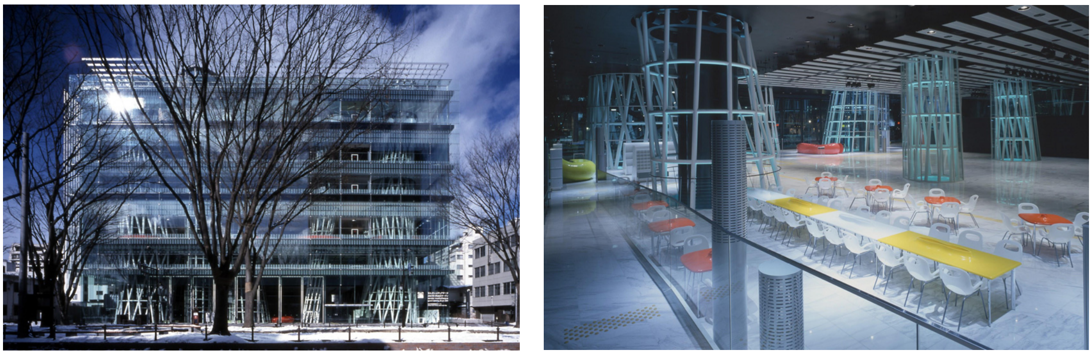

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Figure 1. Sendai Mediatheque by Toyo Ito. (**a**) Exterior view; (**b**) interior view (both by Forgemind Archimedia via flickr.com (accessed on 12 November 2024)).

The Heydar Aliyev Center (2012) designed by Zaha Hadid Architects (Figure 2), instead utilizes a complex shell structure to achieve fluid, uninterrupted interior spaces. Additionally, the selection of lightweight yet robust materials, such as high-strength steel and engineered wood products, has been crucial in managing loads and minimizing deflection in long-span designs [16]. However, while open-plan configurations offer advantages in terms of flexibility and openness, they also pose challenges related to acoustics, privacy, and thermal zoning, necessitating strategic design interventions to balance openness with functional requirements [17].

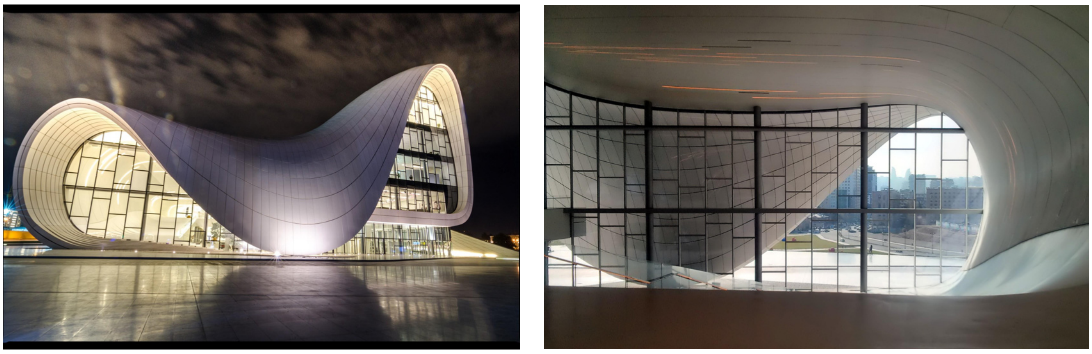

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Figure 2. Heydar Aliyev Center by Zaha Hadid Architects. (**a**) Exterior view (Brenac via commons.wikimedia.org (accessed on 12 November 2024)); (**b**) interior view (Ljubar via flickr.com (accessed on 12 November 2024)).

1.3. Literature Review on Environmental Performances

The present study builds on a previous work by the authors [18], which analyzed the GWP impacts arising from a comparison of steel and timber alternatives for tall buildings, limiting its scope to the effect of height on the two options. A further review of the literature on span length reveals certain gaps. While numerous studies have examined the influence of materials [19,20], transportation [21], and construction techniques [22] on the environmental performance of buildings, the role of structural span length remains relatively underexplored—despite its critical impact on material consumption, structural efficiency, and spatial flexibility. Existing research has mostly addressed this variable in the context of bridge engineering [23,24], where span plays an explicit structural and environmental role. In building design, however, studies addressing this relationship are sparse and often fragmented.

Among the few notable contributions, Maxineasa et al. [25] adopted a cradle-to-cradle perspective to compare GLT with conventional long-span beams, highlighting the lower environmental burden of timber. However, the focus of this work was limited to material comparison without fully isolating the effects of span length. Similarly, Van den Dobbelsteen et al. [26] emphasized that increased spans may lead to disproportionately high impacts due to the need for more resource-intensive materials, though the study's design context limited generalizability. Other works provide more qualitative insights, such as Sayhood and Mahmood's [27] analysis of the trade-offs between reducing spans to minimize slab material versus the added environmental cost of increased vertical supports—a tension that is rarely quantified. Trabucco et al. [28] extended this by showing the growing environmental weight of horizontal structures in tall buildings, yet they stopped short of systematically linking span variation to life cycle impacts. Notably, other studies [29,30] have identified a span-dependent increase in embodied carbon, particularly with steel, but lack a cross-material or performance-normalized comparison. An Australian case study [31] offers a rare, quantified result, revealing up to a 20.6% reduction in GWP per square meter based on span configuration, yet it remains an isolated case with limited replication.

These studies collectively suggest that span length has a measurable yet undertheorized impact on environmental performance. However, the lack of standardized metrics, cross-material comparisons, and reproducible methodologies limits broader conclusions.

1.4. Aim and Scope of the Research

Building on the current lack of systematic and quantitative analyses regarding the influence of span length on the environmental performance of buildings, this research addresses this gap by evaluating the environmental consequences of span variation across multiple structural systems within a controlled LCA framework. The aim is to determine whether a measurable and consistent relationship exists between structural span and life cycle environmental impacts. In doing so, the study develops an analytical tool that not only enhances our understanding of span-related environmental implications but also supports design decisions aligned with evolving architectural trends and functional requirements. Ultimately, it contributes to the broader discourse on how structural efficiency and environmental responsibility can be jointly optimized in contemporary building design.

This is achieved by evaluating several building scenarios designed to closely reflect real-world examples while maintaining sufficient abstraction to enable meaningful comparisons and yield informative results. The scenarios are first modeled using building information modeling (BIM) software (Autodesk Revit v. 2022) and then assessed for their GWP impact using a whole building life cycle assessment (WBLCA) tool.

The primary objective of this paper is to investigate the impact of structural span lengths on embodied carbon in buildings. By analyzing this specific aspect, the research aims to offer valuable insights into how span length variations influence the embodied carbon of structural systems, thereby informing more sustainable design decisions.

1.5. Study's Structure

The current section, Section 1, presents the research background and objectives. The subsequent two sections outline the study's approach and facilitate the interpretation of its findings. Notably, Section 2, structured into four chapters, details the research methodology. The first three subsections correspond to the LCA process, covering the study's goal and scope, the scenario design process, and the LCA inventory analysis. Furthermore, it discusses the methodology and execution of the impact assessment phase, along with additional methodological aspects, including the assumptions forming the basis of the comparative framework. In Section 3, the LCA results for each scenario are analyzed to assess the impact of design choices at both the overall and phase-specific levels throughout the life cycle. This section also includes an in-depth discussion and interpretation of the findings, providing greater insight into the study's outcomes. Lastly, Section 4 outlines the study's limitations, offering a critical perspective on the results.

2. Methodology

The methodology of this study is based on the LCA framework defined in EN 15978 [32], which was applied to eight scenarios representing single-story buildings. The analysis focused on examining the open-plan layout and the structural use of steel and mass timber, either independently or in combination, while also considering different span lengths. For mass timber, glued laminated timber (GLT) and cross-laminated timber (CLT) were included, whereas other options, such as laminated veneer lumber (LVL) and nailed laminated timber (NLT), were excluded from the scope due to their relatively lower prevalence in mass timber construction at present [33]. The objective is to assess the environmental impacts of choosing one structural solution over another. The research also includes a market comparison, assuming the construction of buildings in two distinct locations: France and the United States of America. These locations were chosen because Europe, specifically the Alps region, is where mass timber was first introduced, and North America serves as the natural commercial counterpart.

Following the LCA approach (Figure 3), this study is organized into three main steps. The first step was to define the goal and scope of the LCA. Next, building scenarios were modeled using BIM software. The third step involved running a life cycle impact assessment (LCIA) using a specific WBLCA tool. These three main activities were accompanied by the interpretation of the results from each step, with the aim of identifying significant issues and providing conclusions and recommendations. The three main steps are described as follows.

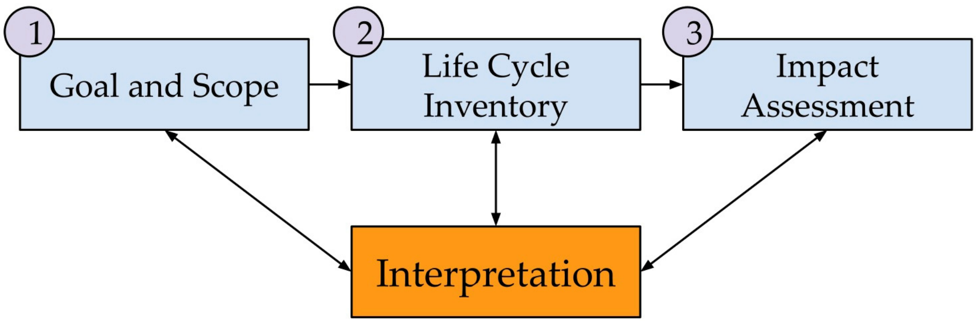


Figure 3. Steps of a life cycle assessment based on ISO 14044 [34] (source: authors).

2.1. Goal and Scope

In accordance with the ISO 14044 standard [34], the study adopts a 'cradle to grave' system boundary approach, covering the entire life cycle of building materials. Consequently, the boundaries encompass all phases from A1 to C4 (refer to Figure 4). Notably, the use stage (B1–B7), which includes building operation and maintenance, is explicitly excluded from the assessment, as structural elements do not have impacts during this phase. This exclusion applies over the building's lifespan, which is assumed to be 50 years. Indeed, since structural elements remain intact without requiring repairs or replacements, no substantial maintenance is expected. It should be noted that periodic inspections may be required to check the integrity of the fireproofing layer on steel components and to monitor potential moisture-related issues—such as runoff, leakage, or condensation—that could impact wooden elements. However, the environmental impact of these inspections is expected to be under 1% and unlikely to affect the overall assessment results [35]. In conclusion, this study specifically evaluates the environmental impacts associated with the production phase (A1–A3), the installation process (A4–A5), and the end-of-life phases (C1–C4) of the building's life cycle.

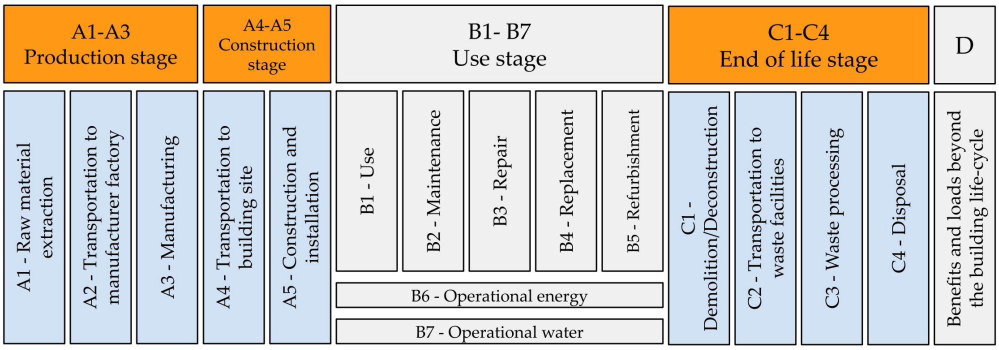


Figure 4. Modules within the scope of the study (shown in light blue), based on EN 15978 [32] (source: authors).

The functional unit for this study focuses solely on the structural framework. Specifically, it is defined as 1 square meter of the building, calculated according to the IPMS 4.2 standard [36], and includes the structural columns, beams, and roof slabs. Finishing layers, such as thermal insulation, waterproofing membranes, and envelope elements like roof tiles, were excluded from the assessment due to the wide variety of available typologies for single-story buildings, as selecting only a few would have been overly restrictive. Moreover, these typologies result in significantly different environmental impacts, further complicating a consistent evaluation within the study's scope. Likewise, foundations fall outside the study's scope. While they generally have a significant influence on a building's structural integrity, environmental impact, and cost efficiency [37], their effects can vary greatly depending on factors such as soil composition, seismic requirements, and site-specific conditions [38].

2.2. Life Cycle Inventory (LCI)

Eight single-story buildings were analyzed as scenarios, each designed with one of four distinct structural frameworks by a team of structural engineers, simulating the actual process typically followed in professional practice.

Each scenario refers to an 8-m-tall building and includes both a short-span (8 × 15 m) and a long-span (15 × 25 m) version. The scenarios are named using a code that specifies their composition, with the first letter representing the columns, the second the beams, and the third the decks. They are structured as follows:

Scenario 1 features timber columns, beams, and decks with a short span and is named "TTT" (Figure 5a).

Scenario 2 is the long-span version of Scenario 1 and is therefore named "TTTL" (Figure 6a).

Scenario 3 features steel columns, beams, and decks with a short span and is named "SSS" (Figure 5b).

Scenario 4 is the long-span version of Scenario 3, featuring steel joists, and is named "SSSL" (Figure 6b).

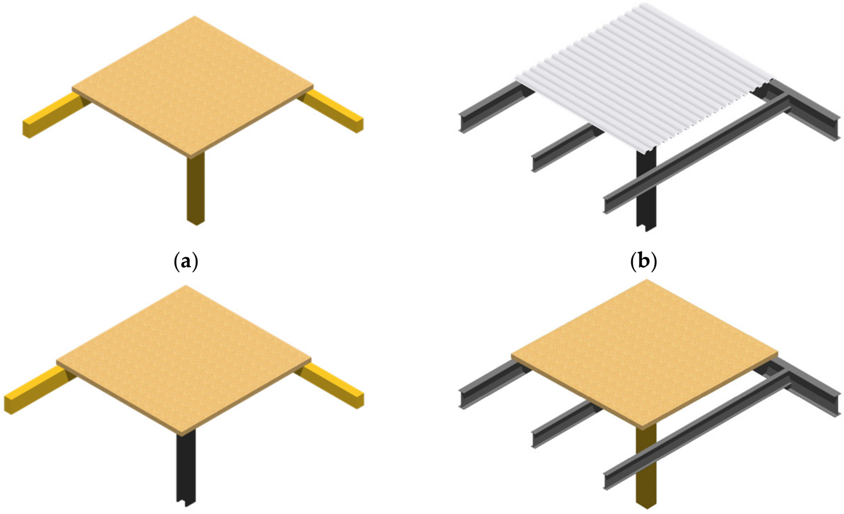
Scenario 5 consists of steel columns and timber beams and decks with a short span and is named "STT" (Figure 5c).

Scenario 6 is the long-span version of Scenario 5 and is therefore named "STSL" (Figure 6c).

Scenario 7 features timber columns, steel beams, and timber decks with a short span and is named "TST" (Figure 5d).

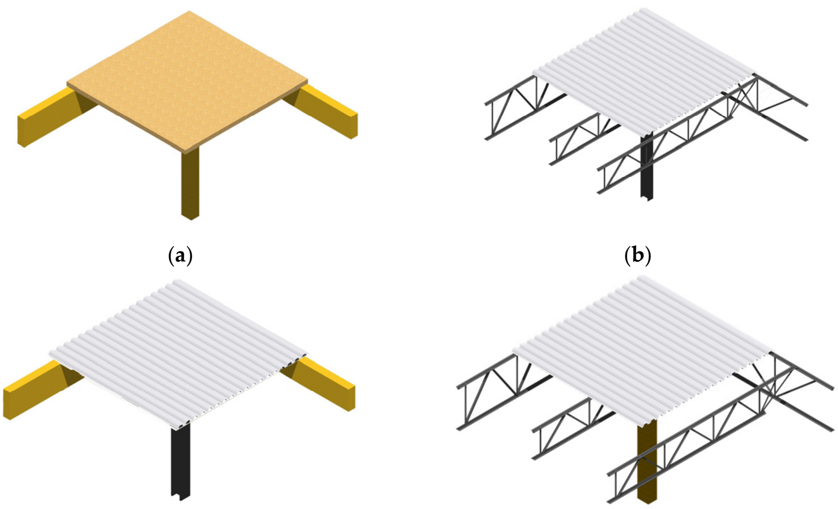
Scenario 8 is the long-span version of Scenario 7, making use of steel joists, and it is consequently named "TSTL" (Figure 6d).

Both steel columns and beams are selected from the W series, while timber columns and beams are made of GLT elements, with dimensions varying depending on the scenario. Steel joists and girders are taken from the LH-Series and G-Series, according to the Steel Joist Institute (SJI) standards. Steel roofs consist of a 7.6 cm thick metal deck, whereas timber roofs are composed of a 5-layer CLT deck (17.6 cm thick), both without concrete topping. Nodes and materials of the structural elements used in the various scenarios are presented in Figures 5 and 6.



(**a**) (**b**) (**c**) (**d**)

Figure 5. Nodes and materials of the structural elements used in the short-span scenarios: (**a**) scenario TTT; (**b**) scenario SSS; (**c**) scenario STT; (**d**) scenario TST.



(**a**) (**b**) (**c**) (**d**)

Figure 6. Nodes and materials of the structural elements used for the long-span scenarios: (**a**) scenario TTTL; (**b**) scenario SSSL; (**c**) scenario STSL; (**d**) scenario TSSL.

The nominal area of the short-span version is 3600 square meters, featuring 48 columns, while the nominal area of the long-span version is 13,500 square meters, with 52 columns. The IPMS 4.2 standard [36] was used to calculate the impact per surface unit, subtracting the area of structural elements and partition walls from the nominal area. Notably, the larger sections required for timber elements result in a slightly smaller IPMS 4.2 area. The features of the scenarios are summarized in Table 1.

Table 1. Geometric characteristics and materials of each scenario.

Scenario	Structural Frame	Span Dimensions (m)	Plan Dimensions (m)	IPMS 4.2 Area (m^2)
TTT	Timber columns, beams, and decks	8 × 15	120 × 30	3594
TTTL	Timber columns, beams, and decks	15 × 25	180 × 75	13,494
SSS	Steel columns, beams, and decks	8 × 15	120 × 30	3599
SSSL	Steel columns, trusses, and decks	15 × 25	180 × 75	13,499
STT	Steel columns, timber beams and decks	8 × 15	120 × 30	3599
STSL	Steel columns and decks, timber beams	15 × 25	180 × 75	13,499
TST	Timber columns and decks, steel beams	8 × 15	120 × 30	3594
TSSL	Timber columns, steel trusses and decks	15 × 25	180 × 75	13,494

This analysis also considers the steel connectors used to join various elements. While connectors for steel components are already factored into the 'fabrication' calculation, those for timber components can have a significant effect on both material usage and the environmental impact of the construction process. The quantity of steel fasteners for timber was determined based on the advice of structural engineers, who assessed the required amount to meet safety and performance criteria for the specific timber components. These recommendations considered aspects such as load transfer, joint integrity, and overall structural stability. As a result, an average of 10 kg of steel fasteners was required per cubic meter of CLT components, and 20 kg per cubic meter of GLT components was considered.

Another aspect advised by the engineering consultants was compliance with a 2 h fire-resistance rating for these structures, in accordance with the provisions of the International Building Code [39] and EN 1991 [40]. This requirement resulted in a 5 cm-thick coating of fireproofing plaster sprayed on the steel components, while timber elements were over-designed to guarantee fire resistance.

The bill of quantities (BoQ), crucial for the subsequent life cycle impact assessment (LCIA) phase, was derived from modeling the scenarios designed by the engineering team using Autodesk Revit (v. 2022) BIM software. In Autodesk Revit, the project was set up with metric units, one modeling phase, and shared levels and grids for each case study. View templates and standard base materials ensured consistency. Custom families with shared parameters were created for slab beams and joists. Material schedules were used to refine models, but due to counting and overlap issues in Revit, One Click was mainly used for quantity extraction. The model was developed to a LOD 300, aligning with the BIM Execution Plan. This activity is fundamental for accurately assessing the actual quantity of materials used in construction, as it accounts for potential overlaps between structural elements, such as beams, columns, and roof slabs. These overlaps can lead to discrepancies in material estimation, making it essential to model the scenarios precisely to ensure reliable quantity calculations. A full inventory of materials can be found in Table 2.

Table 2. Inventory of total materials used, as produced by the BIM software.

Scenario	Columns		Beams		Roofs	
TTT	GLT	47 m^3	GLT	283 m^3	CLT	637 m^3
TTTL	GLT	50 m^3	GLT	2553 m^3	CLT	2374 m^3
SSS	W series	30 ton	W series	93.7 ton	Steel deck	40.4 ton
SSSL	W series	39.7 ton	LH-G s.	235 ton	Steel deck	151.6 ton
STT	W series	30 ton	GLT	339 m^3	CLT	637 m^3
STSL	W series	50 ton	GLT	2295 m^3	Steel deck	151.6 ton
TST	GLT	45 m^3	W series	114 ton	CLT	637 m^3
TSSL	GLT	48 m^3	LH-G s.	235 ton	Steel deck	151.6 ton

2.3. Life Cycle Impact Assessment (LCIA)

For the LCIA phase, One Click LCA v. 0.35 was selected after evaluating various WBLCA tools, as it was found by the authors to be the easiest to use for assessing the environmental impacts of building materials and construction processes. This software is widely recognized for its effectiveness in evaluating such impacts, thanks in part to the comprehensive array of LCA databases it employs. Notably, it bases its assessments on both public and generic databases—such as Environmental Product Declarations (EPDs), country-specific average data, and generic materials data—as well as licensed databases, including Ecoinvent and IMPACT. The material quantities defined for each scenario were input into the software, which automatically assigned unitary environmental impact values to the total quantities based on in-built datasets and EPDs. This approach maintained uniformity and precision in impact calculations across all scenarios.

Among the various impact categories that an LCA can assess, this study focused on GWP, as it is the most commonly evaluated metric in the building sector due to its relevance in climate change assessments. GWP quantifies the impact of greenhouse gas emissions on global warming by converting different gases into a common unit, measured in kilograms of carbon dioxide equivalent (kg CO_2e). This metric allows for a direct comparison of materials and design choices in terms of their contribution to climate change, supporting informed decision-making for sustainable construction practices. The assessment of GWP in this study supports international initiatives to curtail greenhouse gas emissions, notably those outlined in the Paris Agreement [41], which seeks to restrict global temperature rise to significantly below 2 °C, and ideally to 1.5 °C, relative to pre-industrial temperatures. By selecting low-GWP materials and optimizing design choices, the construction industry can play a significant role in meeting these critical climate targets.

Two alternatives were evaluated for each scenario: a baseline case and a best case, to assess the environmental impact across a range of potential construction choices. The baseline case was determined using average GWP values from reliable datasets and EPDs available for both European and North American locations. These datasets provide typical impact values based on standard practices and materials, offering a realistic representation of the environmental impact in conventional construction scenarios.

In contrast, the best case was assessed using the lowest available impact values, which represent an idealized scenario where the least environmentally harmful materials and methods are employed. This scenario assumes the use of low-impact materials that minimize carbon emissions and other environmental impacts. By comparing these two alternatives, the study highlights the potential range of impacts that can result from different material choices and design decisions, emphasizing the importance of selecting sustainable options for reducing the environmental footprint of construction projects.

2.4. Methodological Considerations

While assessing impacts throughout each LCA phase, it is essential to clarify several parameters to ensure the clarity and comprehensibility of the research. Here, the most important ones are listed:

For the transportation methods, including their payload and fuel efficiency, as well as the distances used in the A4 and C2 phases, the software (One Click LCA v. 0.35) primarily relies on country-specific databases, and the specific values adopted are shown in Table 3.

Table 3. Default values provided by the WBLCA software for material transportation distances, transport modes, payload, and fuel efficiency for the construction materials used.

Material	Transportation Distance (km)		Transportation Mean	GWP Value ($kgCO_2e$/tonkm)		Fuel Consumption (liters/tonkm)	
	EU	US		EU	US	EU	US
GLT and CLT	220	380	Trailer combination, 40 ton, 100% fill rate	0.0383	0.0398	0.013	0.018
Structural steel, rebars, and decks	370	380					

The deconstruction/demolition phase (C1) is assessed using average market values depending on the building's structural frame.

The end-of-life choices for each material are determined based on the industry's most common scenarios: recycling for steel, combustion with heat recovery for timber, and landfill for plaster, which is classified as an inert material.

An important consideration must be made regarding the assessment of carbon content in timber products. Like many other organic materials, wood can absorb carbon dioxide from the atmosphere during its growth through chlorophyll photosynthesis. Carbon dioxide is thus broken down into oxygen, which bonds with hydrogen to form water, and carbon, which is stored within the lignin of timber fibers. This carbon, commonly known as "biogenic carbon", is theoretically permanently stored in wood and consequently in timber products. This extended carbon retention can reduce the overall greenhouse gas impact compared to materials that do not sequester carbon [42].

Because of its ability to sequester carbon, timber is widely recognized as an environmentally sustainable material, and timber-based construction is gaining consensus as a greener alternative to conventional building methods [43]. However, the projected end-of-life treatment of timber products is a critical factor when assessing their environmental impact through EPDs. Incineration—either with or without energy recovery—is the most commonly assumed disposal method, whereas large-scale reuse and recycling of mass timber components remain rare. Several challenges limit these practices, including a lack of clear guidelines on deconstruction responsibilities, inadequate recycling infrastructure, and low market demand for reclaimed structural elements, except in specialized applications such as antique columns or beams.

From an LCA standpoint, the biogenic carbon stored in timber products plays a crucial role at two key stages. During raw material extraction (A1), trees absorb atmospheric CO_2 as they grow, effectively capturing and storing carbon. However, at the end-of-life stage, particularly in phases C3 and C4, this stored carbon is released back into the atmosphere when the wood decomposes in landfills or is incinerated. Even when timber elements are repurposed or recycled, EN 15804 [44] classifies these processes as a transfer of carbon beyond the LCA system boundaries.

Biogenic carbon accounting in building LCA can be made following two main opposite approaches. The "0/0" approach entirely excludes biogenic carbon from the assessment, disregarding both its sequestration and subsequent release in the calculations. In contrast, the "−1/+1" method accounts for the temporary storage of biogenic carbon. It assigns a negative value (−1) during the A phase of the product's LCA, reflecting the carbon sequestered from the atmosphere. This carbon is then released during the C phase, resulting in a corresponding positive value (+1).

Several uncertainties still exist regarding the assessment of biogenic carbon sequestration in timber products:

- Large inconsistencies exist in how biogenic carbon content in timber elements is evaluated across EPDs and available databases [45,46].
- The overall environmental impact of timber can vary considerably due to factors such as forestry management techniques, transportation logistics, and the methods used during its manufacturing, utilization, and end-of-life treatment [47].
- The management of biogenic carbon over time continues to be a point of discussion in life cycle assessment studies. Research like that of Levasseur et al. [48] emphasizes that the timing of carbon emissions and the possibility of its reuptake through future vegetation growth introduce challenges in precisely evaluating its environmental effect. This line of research has led to the development of the so-called "dynamic approach" [49], which attempts to account for the time-dependent nature of carbon sequestration and release in the context of life cycle assessments [50].

Building on these premises, the 0/0 approach was adopted for this study, as it provides a practical solution for ensuring consistency and comparability across various life cycle assessments and aligns with the methodology outlined in the EN 15804 standard.

2.5. Comparative Framework

To establish a uniform basis for the findings, a further analysis was conducted, centered on assessing whether the steel materials and their corresponding EPD information were comparable between the two regions. As per the EN 15804 standard [44], European EPDs use a modular approach, dividing the process into raw material extraction (A1), transport (A2), and profile production (A3). Unlike their European counterparts, North American EPDs for steel products commonly combine raw material acquisition and manufacturing phases under module A1, designate A2 as transport to a fabrication facility, and restrict A3 to final processing steps like cutting, punching, drilling, bending, and welding, prior to building installation. A "fabrication factor" (81.22 kg CO_2 eq/ton), derived from the average of North American A3 modules, was applied to European EPDs to improve structural steel product comparability between markets.

The comparison of general GWP values necessitated a theoretical assumption of comparability between the EPDs generated in the two locations, in spite of the utilization of disparate impact assessment techniques: TRACI [51] for North America and CML [52] for Europe. These methodologies underpin the ISO 21930 [53] and EN 15804 standards, respectively. Studies [54,55] suggest that although TRACI and CML diverge in their assessment of certain parameters, the variation in their GWP evaluations is negligible, thus reinforcing the reliability of this assumption. Both frameworks utilize a globally standardized approach for GWP characterization factors, which maintains uniformity in impact assessment. The global nature of this approach enables a consistent GWP evaluation, regardless of geographical location or methodology. As a result, the assumption that EPDs from the two regions are comparable is supported, given methodological alignment, allowing for a robust comparison of environmental impacts based on GWP.

3. Results of the Life Cycle Impact Assessment

3.1. Baseline Cases

Using the One Click LCA tool, the GWP impacts of each life-cycle phase for the different scenarios, as well as their total impacts, were calculated and then normalized using the IPMS 4.2 surface standard. The total LCA impacts of the baseline case scenarios for both locations, expressed in GWP terms, are shown in Table 4.

Table 4. Results of LCA of baseline case scenarios for the two locations (GWP in $kgCO_2e/m^2$).

Span Dimensions (m)	Scenario	North America	Europe
8 × 15	TTT	96.31	88.02
	SSS	98.77	95.18
	STT	107.70	94.19
	TST	115.79	107.25
15 × 25	TTTL	124.25	112.95
	SSSL	70.56	69.80
	STSL	102.09	96.45
	TSSL	79.66	77.72

Among the short-span scenarios, the all-timber configuration (TTT) has the lowest environmental impact, followed closely by the all-steel scenario (SSS), a trend consistent across both locations (Table 4). When examining the two hybrid scenarios that combine steel and timber as structural elements, scenario TST exhibits a higher impact than scenario STT. This highlights that the combination of timber columns with steel beams results in greater environmental impacts compared to steel columns with timber beams. This difference is primarily due to the fact that, for the same timber deck weight, timber columns and beams must be proportionally wider than steel ones.

However, these findings differ significantly when examining the long-span scenarios. In this case, the increase in span results in a substantial increase in the size of the timber elements, particularly the beams. This effect is much more pronounced for timber than for steel, as steel joists used in longer spans do not require significantly larger profile dimensions to achieve the same structural strength. As a result, the all-timber scenario (TTTL) and the steel column/timber beam scenario (STSL) have higher total impacts than those using steel joists (SSSL and TSSL), which show the lowest impacts overall.

Comparing each short-span scenario with its respective long-span counterpart, differences in GWP impacts emerge depending on the material used for the beams. Notably, when timber is the primary structural material, the short-span scenario (TTT) exhibits approximately 29% lower GWP impact per square meter compared to its long-span counterpart (TTTL), for both locations. Since the timber columns maintain the same dimensions in both cases, this increase is entirely attributable to the beams, whose cross-sections rise significantly from approximately 31 × 99 cm to 46 × 297 cm in the long-span configuration. Examining the structural design parameters for the beams, the span-to-depth ratio is the key factor to consider, given that the superimposed dead load remains unchanged across the scenarios. In the TTT scenario, the span-to-depth ratio shows an optimal value of 15.15, while the beams in the TTTL scenario present a lower ratio of 8.42. Although both scenarios are structurally safe, the former reflects a more efficient balance between stiffness, deformation control, and material use, whereas the latter suggests an excessively massive and material-intensive solution. This highlights the necessity for a more efficient structural approach when dealing with long timber beams.

Conversely, an opposite trend is observed in the steel alternative. Despite the increase in both the number (from 48 to 52) and size of the columns (profile changes from a W14 × 64 to a W14 × 71), the long-span scenario (SSSL) demonstrates approximately 30% lower GWP impact per square meter compared to the short-span version (SSS) in both North America and Europe. This reduction can be primarily attributed to the use of steel joists, which consist of smaller steel profile elements that contribute less to the overall environmental impact. Comparing the span-to-depth ratios of the two alternatives reveals a higher ratio for the SSSL scenario (58.3) compared to the SSS scenario (42.1). This indicates that the use of a joist provides a more efficient balance between stiffness and material use.

When looking at the hybrid scenarios, the same trend is confirmed in the short-span TST scenario, which features timber columns and decks with steel beams. This scenario exhibits a higher GWP impact—31% in North America and 27.5% in Europe—compared to its long-span counterpart TSSL, where steel replaces timber in the decks and steel joists substitute standard steel beams.

Minor contradictory deviations are observed in the other hybrid scenario. The STT scenario, which features steel columns along with timber beams and decks, exhibits a differing total impact across the two locations when compared to the long-span STSL scenario, where only the decks are replaced with metal slabs. While STSL shows a 5% lower GWP impact in the North American market, it results in a 2% higher impact in the European market. These small discrepancies in this particular combination of elements are attributed to the metal decks used in the STSL scenario. For this building product, an American EPD was used for both locations due to the lack of availability in the European market. As a result, GWP impacts for metal decks are lower in the North American alternative compared to the European one.

Overall, the results indicate that European alternatives have, on average, slightly more than 8% lower impacts than those in the U.S. for short-span scenarios and approximately 5.5% lower for long-span scenarios. The greatest difference is observed in the STT scenario, where European impacts are nearly 12.5% lower than in North America. Table 5 compares each stage of the LCA for the STT scenario between the two regions.

Table 5. Results of each stage of LCA of baseline case scenario STT for the two locations (GWP in $kgCO_2e/m^2$).

	A1–A3	A4	A5	C1	C2	C3	TOT
NA	61.41	7.61	30.29	5.36	0.99	1.91	107.70
EU	55.85	1.33	28.62	5.36	0.99	1.91	94.19

The primary differences between the two regions can be attributed to the production and transportation stages. In the production stage (A1–A3), the lower impacts observed in Europe are primarily due to the use of cleaner energy sources and stricter regulations that govern manufacturing processes. These regulations, in turn, push the market toward greater availability of EPDs for building products, which typically feature lower environmental impacts. Additionally, transportation methods in Europe are generally more efficient in terms of fuel consumption and pollutant emissions compared to those in the U.S., contributing further to the reduced overall impact in the transportation phase (A4). The installation phase (A5) has a slightly higher impact (6%) in the North American alternative compared to the European one, primarily due to material wastage and transport, which are a direct consequence of more impactful production and transportation phases.

3.2. Best-Case Alternatives

The best-case alternatives were determined by selecting the least impactful product available for each material in the BoQ. Each material had a best alternative for each location, except for steel decks, which had only one available product used in both locations.

As expected, for the best-case alternatives, the all-timber scenario has the lowest impact among the short-span scenarios in both locations (Table 6). Comparing each short-span scenario with its respective long-span counterpart, the trends observed in the baseline cases are also confirmed in the best-case scenarios. Even the STSL scenario, which showed contradictory deviations in the baseline cases, has higher GWP impacts compared to the STT scenario in both locations.

Table 6. Results of LCA of best-case scenarios for the two locations (GWP in $kgCO_2e/m^2$).

Span Dimensions (m)	Scenario	North America	Europe
8 × 15	TTT	76.29	60.55
	SSS	94.46	86.57
	STT	82.14	64.33
	TST	96.21	78.99
15 × 25	TTTL	124.25	112.95
	SSSL	70.56	69.80
	STSL	102.09	96.45
	TSSL	79.66	77.72

By examining the best-case versions of the various scenarios, it is evident that all of them show lower GWP impacts due to the use of less impactful materials. The reductions are more pronounced in the short-span scenarios (Figure 7) where, in proportion to the surface area, the quantities of materials are higher, and major decreases are achievable as a consequence.

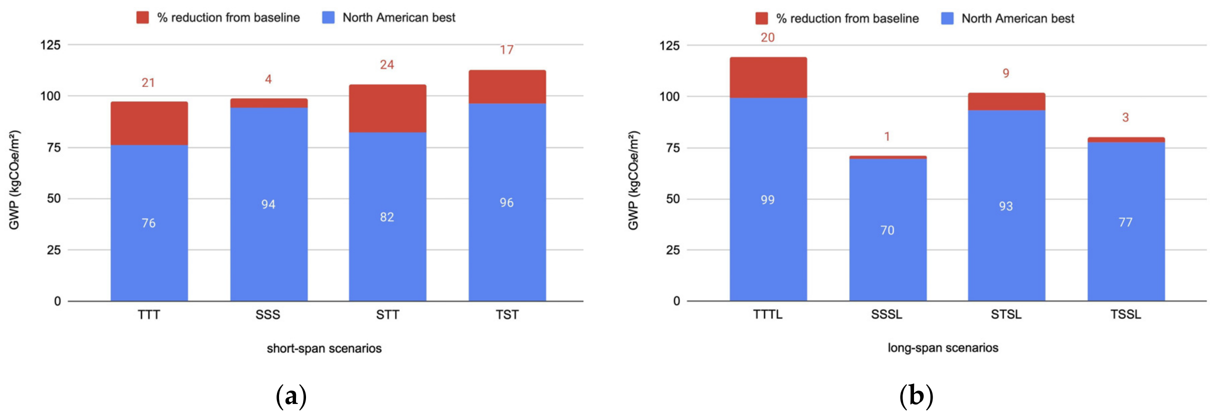
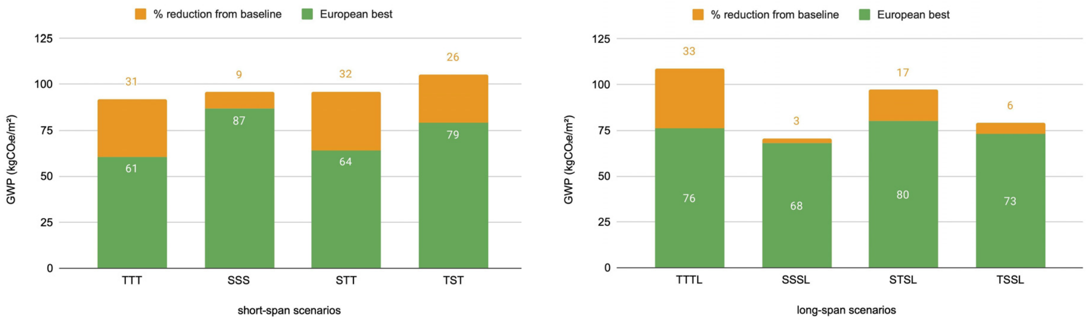


Figure 7. North American best-case alternatives and reduction from the baseline cases. (**a**) Short-span scenarios; (**b**) long-span scenarios.

It is possible to identify varying rates of reduction, with the North American scenarios reporting an average decrease of 16.5%, while the European scenarios achieve a 25.5% decrease (Figure 8).

For both locations, the highest decreases are registered for scenarios involving large quantities of timber, such as the TTT and STT scenarios. This is likely due to the better availability of timber products with very low impacts. However, the baseline scenarios incorporated steel products with 97% recycled material, and the change to 100% recycled material in the best-case scenarios resulted in an insignificant difference. In absolute terms, the STT scenario achieved the highest decreases, which are shown below in Table 7.



(**a**) (**b**)

Figure 8. European best-case alternatives and reduction from the baseline cases. (**a**) Short-span scenarios; (**b**) long-span scenarios.

Table 7. Results for each stage of the LCA of the best-case scenario STT for Europe (GWP in $kgCO_2e/m^2$) and its reduction compared to the baseline case.

	A1–A3	A4	A5	C1	C2	C3	TOT
EU	30.29 −45.8%	1.27 −4.8%	24.51 −14.4%	5.36 -	0.97 −2.8%	1.82 −4.9%	64.33 −31.7%

The production stage (A1–A3) shows the greatest decrease, driven by the significant difference in GWP between the least impactful timber element and the average one. The transportation phase (A4) exhibits a minor reduction (4.8%). Influenced by these two phases, the installation phase (A5) also shows a notable decrease (14.4%). Smaller differences are observed in the end-of-life stage (7.7%), with the demolition/deconstruction phase (C1) remaining the same for both alternatives.

In general, while other scenarios show significant differences between the baseline and best-case alternatives for both locations, the SSSL and TSSL scenarios—both incorporating steel trusses—produce very similar results (Figure 9). Moreover, excluding the European best-case of the short-span scenarios involving a huge quantity of timber elements (TTT and STT), these two scenarios emerge as the least impactful overall. This consistency underscores the effectiveness of steel trusses in long-span applications, demonstrating their reliability and efficiency in reducing environmental impacts while maintaining structural performance across different contexts.

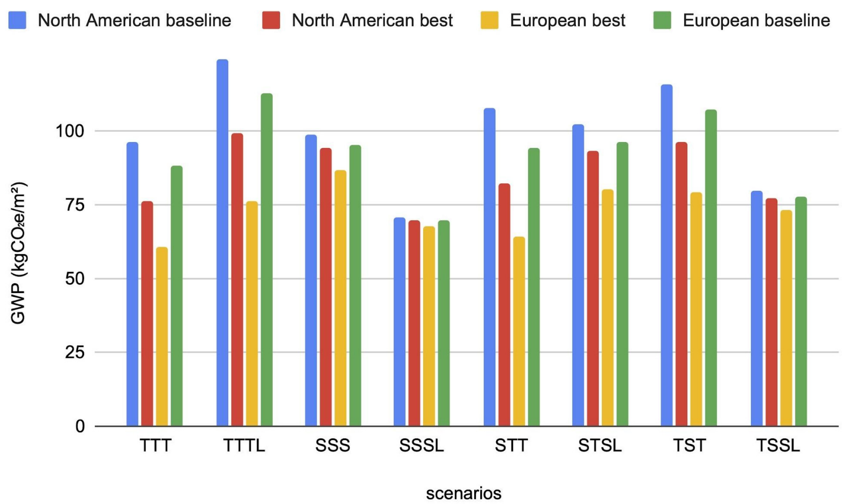


Figure 9. General overview of GWP impacts for various alternatives across different scenarios and locations.

4. Study Limitations

The study aimed to assess the impact of span length using fixed combinations of materials across eight scenarios, with only two plan arrangements and their respective spans considered. In addition, the structural elements assessed in the study consist of a single material, whereas advancements in technology have introduced beams and columns made of a steel–timber composite, whose environmental impacts should be explored as well. Future research should assess a wider range of structural element combinations, as well as additional plan configurations and span variations, to provide a more comprehensive understanding of their impact.

The environmental impact of the buildings was evaluated solely through the lens of GWP as the principal metric. However, a comprehensive LCA would need to consider a broader range of critical environmental factors. These include toxicity, resource depletion, water usage, and other potential impacts, such as air and water pollution, as well as the broader ecological consequences. Including these additional factors would provide a more holistic view of the environmental footprint of the buildings and enable more informed decision-making regarding sustainable design practices.

A further potential limitation of this study is the exclusion of LCA Phase B, encompassing the use stage. This assumption was made because the functional unit of the assessment is the structural system. Given that the structural system is not expected to undergo significant maintenance or refurbishment during the 50-year service life considered and that the study excludes the building envelope and other systems, the GWP from Phase B is anticipated to be negligible or non-existent. However, if interventions on the structure are expected during the service life, Phase B should be included to avoid underestimating the overall environmental impact.

The study adopted a conservative approach to the assessment of biogenic carbon of timber products. To avoid the complexities of assigning uncertain carbon benefits to timber [56], the 0/0 approach was employed, streamlining calculations and ensuring adherence to established norms. Nevertheless, this approach fails to account for the carbon sequestration potential of timber during its growth phase, potentially leading to an underestimation of its environmental merits relative to non-renewable materials such as steel or concrete, which do not possess such carbon-capturing capabilities [57]. Although the 0/0 approach offers a practical solution for maintaining uniformity and comparability across life cycle assessments, further investigations should explore alternative assessment frameworks for biogenic carbon.

Hybrid steel–timber structures can face challenges in fire safety due to the distinct behaviors of steel and timber in the event of a fire. Meeting the strict fire resistance specifications of building codes poses a significant challenge for hybrid structures. In this research, we simplified the assessment by examining the fire performance of individual material components, rather than analyzing their combined behavior. The connections between the materials also pose a potential weakness, thus increasing the difficulty in assessing fire performance. However, studies have focused on improving the performance of connections between steel and timber elements, such as the development of innovative joint systems that enhance the overall fire resistance of hybrid structures. For example, recent work by Akoutah et al. [58] explored the use of advanced fireproof coatings and passive fire protection materials that improve the fire resistance of timber-steel connections, making them more robust under fire exposure. Similarly, advancements in fire-resistant technologies, including the use of intumescent coatings and fire-resistant treatments for timber, are progressively improving the safety of hybrid systems. According to a study by Malaska et al. [59], the application of fire-resistant materials can significantly delay the ignition and combustion of timber, allowing for better fire safety performance of hybrid structures.

5. Conclusions

This study aimed to provide insights into the relationship between long-span architectural layouts and environmental impacts. With this focus, the study examined four different building scenarios with different structural frames and compared them with their long-span counterparts.

The main finding of the study is the sensitivity of timber-based systems to span length, as their performance declines with increasing spans due to the material's inherent characteristics. Longer spans necessitate wider resistant sections, resulting in material-intensive solutions and higher environmental impacts. In contrast, steel joists demonstrate a strong combination of material optimization and mechanical resistance, offering greater versatility across a broader range of spans. This is further confirmed by the comparative analysis of span-to-depth ratios, which reaffirms the structural efficiency of steel solutions over timber, particularly in long-span applications. While timber beams tend to require significantly increased depths for longer spans, leading to less efficient sections, steel elements maintain more favorable proportions, achieving a balanced relationship between stiffness, deformation control, and material utilization. These findings validate the superior performance and efficiency of steel as a structural strategy for long-span scenarios.

Given that this is an applied, non-parametric study, the results are specific to the selected case studies. However, they are consistent with a broader experimental trend indicating that larger span lengths tend to result in increased GWP in timber structures, especially for GLT. While different contexts and load conditions may influence the absolute values, they are unlikely to alter the relative positioning of steel and timber in terms of environmental performance.

Alternatives using timber materials demonstrate a considerably reduced impact during the production phase, leading to a lower overall impact in short-span configurations. Even when the 0/0 approach for accounting biogenic carbon is applied—meaning that no credit is given for the carbon stored in timber—timber-based construction still results in lower carbon emissions compared to conventional materials [60]. This is because timber production generally involves less fossil fuel combustion, further reinforcing its potential as a more sustainable alternative.

The research underscores the importance of a comprehensive architectural design strategy, where span length is considered a critical factor in pursuing environmentally sustainable results. By employing case study analysis and parametric evaluations, this paper demonstrated the influence of diverse span lengths, thereby aiding in the creation of more ecologically sound architectural designs.

A key recommendation for enhancing sustainable design is to determine the building's aesthetic shape only after conducting an environmental assessment of alternatives using LCA. Further studies on achieving the desired span length and aesthetic should consider the adoption of steel–timber hybrid beams.

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