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Research Article

ASSESSING THE ENVIRONMENTAL IMPACT OF DIVERSE SLAB DESIGNS IN TIMBER, CONCRETE, AND STEEL ON THE LIFE CYCLE ASSESSMENT OF A HIGH-RISE BUILDING.

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The building and construction sector are a significant contributor to greenhouse gas (GHG) emissions, accounting for approximately 40% of global energy-related CO2 emissions. High-rise buildings, in particular, have substantial environmental impacts due to the extensive materials and energy required for their construction and operation. This study analyses the environmental impact of three different slab designs on the Life Cycle Assessment (LCA) in a high-rise building design. As example of a high-rise building, the Pontina Tower, a 128-meter concrete high-rise building in Italy, will be considered. The studied slabs are including bubble deck, steel composite and CLT—fabricated from three materials: timber, concrete, and steel. Initially, slab data is collected from catalogues, ensuring comparable characteristics and compliance with European standards by adding flooring layers. Furthermore, a parametric design was developed using Grasshopper3D software, simulating the Pontina Tower with each slab variant to analyze how changes in floor sizes affect embodied greenhouse gas (EGHG) emissions. The results demonstrate how material choice and slab design significantly influence the building's overall environmental footprint, providing crucial insights for sustainable architectural practices and material selection in high-rise construction.

1. Introduction

The building and construction sector have been identified as a significant contributor to environmental degradation in various forms. The activities involved in the process of construction, such as extraction of raw materials, manufacturing of construction products, construction work, building use, and demolition, result in various environmental challenges and pose a threat to natural resources. Environmental challenges include resource depletion and biodiversity loss due to material sourcing, such as quarrying, forestry and water use (Herczeg et al. 2014). The construction sector is a significant consumer of resources, accounting for 40% of extracted materials, particularly minerals like sand, gravel, and crushed rock, which represent 65% of the sector's total aggregates. Additionally, the construction of buildings contributes 11% of CO_2 emissions in the energy sector while consuming 6% of global energy (Herczeg et al. 2014). The global building stock is expected to double by 2060, adding over 230 billion square meters of new construction—equivalent to building the current floor area of Japan every year until then. By 2050, 66% of the global population will live in urban areas, increasing demand for taller buildings (United Nations 2019; Benedicte Kaspersen 2016). Structure's materials, particularly concrete and reinforcement steel, account for the majority of a building's total embodied energy, with values ranging from 66.73% to 59.57%. These materials contribute the largest portion compared to other elements assessed in the buildings (Dimoudi & Tompa, 2008).

Whereas buildings are accused of abundant environmental problems, tall buildings are considered as principal consumers of global energy and prodigious emitters of CO2 because they demand immense quantities of materials and variety of environmentally harmful operations (Mavrokapnidis, Lagaros, & Mitropoulou, 2019). The construction of tall buildings leads to concentrated greenhouse gas (GHG) emissions over short periods, a phenomenon referred to by Säynäjoki, Heinonen, and Junnila (2012) as a "carbon spike." These spikes are particularly severe in tall buildings, which can have up to 60% more embodied energy (EE) per unit of gross floor area compared to low-rise buildings, exacerbating their environmental impact. This increased energy demand amplifies the environmental impact of tall structures, making their carbon footprint significantly higher than that of shorter buildings (Helal, 2022; Trabucco, Wood, Vassart, Popa, & Davies, 2015; Treloar, Fay, Ilozor, & Love, 2001). However, they have also been proposed as a solution to balance urban development with limited land availability, thanks to their efficient use of land for construction. As a result, improving their design offers a significant opportunity to enhance sustainability (Ascione, et al., 2024).

2. Life Cycle Assessment

LCA is a methodology that provides a comprehensive evaluation of the environmental impact of materials and buildings using standardized metrics based on scientific principles (Bruce-Hyrkäs, Pasanen, & Castro, 2018). One of the most widely recognized metrics used in LCA is the Global Warming Potential, also known as the life-cycle carbon footprint. LCA has been employed for building performance evaluation since the late 1980s, though it has only emerged as a significant research area in recent years. The life cycle of a building consists of several stages that contribute to its environmental impact, including the production stage (A1-A3), which covers the sourcing of raw materials, transportation, and manufacturing. The construction stage (A4-A5) involves transporting materials to the site, on-site installation, and waste management. Emissions from these stages occur before the building is operational (Adams, Burrows, & Richardson, 2019). The use stage (B1-B5) addresses emissions and activities related to maintenance, repair, replacement, and refurbishment of building components. The end-of-life stage (C1-C4) involves the deconstruction, transportation, sorting, and disposal of materials (BRE Global Ltd, 2018).

This paper focuses on analyzing embodied greenhouse gas emissions (EGHGE), also known as cradle-to-gate, while excluding operational EGHGE emissions, as they are considered negligible and are omitted due to minimal maintenance and repair needs. (Helal, Mehdipanah, Stephan, Lumantarna, & Crawford, 2022).

3. **Aims and Scope**

This paper is part of a study that investigates how the choice of materials, particularly concrete versus hybrid timber-concrete systems for vertical and slab structures, impacts greenhouse gas emissions, structural performance, and flexibility in tall buildings of varying heights. The research focuses on understanding these effects across different building designs to assess the overall sustainability and efficiency of material choices.

Several studies have examined the relationship between vertical structural systems and the embodied environmental impacts in tall buildings. This study will focus on the influence of slab structures in tall buildings and their associated embodied carbon emissions.

In this framework the aim of this study is to demonstrate the influence of slab structures on overall weight and embodied carbon emissions of the building, using the Pontina Tower, a 37-floor structure, as the case study. The Pontina Tower is a residential and office building located in the Municipality of Latina, Italy, standing at a height of 128 meters. The tower features 37 floors above ground, each with a floor height of 3.10 meters. The layout of each floor is an octagon, derived from a 34.60-meter square with a 4.05-meter isosceles right triangle removed from each corner (Sgambi, 2020).

This study considers three different floor systems using timber, concrete, and composite steel materials: Bubble Deck, timber CLT, and steel composite floors. To ensure realistic results, not only the structural components of the slabs but also the flooring and finishing layers were analyzed. The specifications for these systems were sourced from manufacturer websites and evaluated under office building loading conditions, including acceptable deflection limits. Detailed information regarding each slab, such as span range, thickness, weight, acoustic properties, and fire resistance, was extracted from industrial brochures provided by the manufacturers.

In this research, embodied greenhouse gas (GHG) emissions are calculated using Global Warming Potential (GWP) indicators from the ÖKOBAUDAT platform. This platform is a publicly accessible LCA database that includes datasets for building materials, construction, transport, energy, and disposal processes. The datasets follow EN 15804+A2 standards and are derived from GaBi background data (ÖKOBAUDAT, 2024).

4. **Acoustic and Fire Resistance Considerations**

To ensure accurate measurements of acoustic insulation between rooms, current standards from the NBN EN ISO 16283 series are applied. These standards focus on two key areas: airborne sound insulation between rooms through sound pressure measurements and impact sound insulation from footsteps or other impacts on floors and stairs. For new residential buildings, a common benchmark for impact sound insulation is an L'nT,w value of no more than 53 dB, which can also serve as a reference for office buildings. For airborne sound insulation, floors should target a Rw value of 50 dB or higher to ensure comfort and privacy (ISO 16283-2:2018, 2018).

To meet the required acoustic standards for all floor systems, and to ensure compatibility between different flooring layers, additional components such as cement screed, tiles, parquet, and gypsum boards were designed and integrated to achieve the appropriate acoustic performance.

The objective of fire resistance is to minimize the fire's propagation and ensure the structural integrity, sustaining load-bearing capacity for a defined period. This is essential to facilitate the evacuation of occupants during a fire incident. In Belgium, the fire resistance requirement for floors in buildings exceeding a height of 25 meters is set at 120 minutes (GUIDES SÉCURITÉ INCENDIE, 2007). As some of the considered slabs don't have the minimum fire resistance rate, gypsum layer has been added to the systems to enhance the rate. Finishing layers will devised to align all floor systems with the specified fire resistance standard. For normal plasterboards:

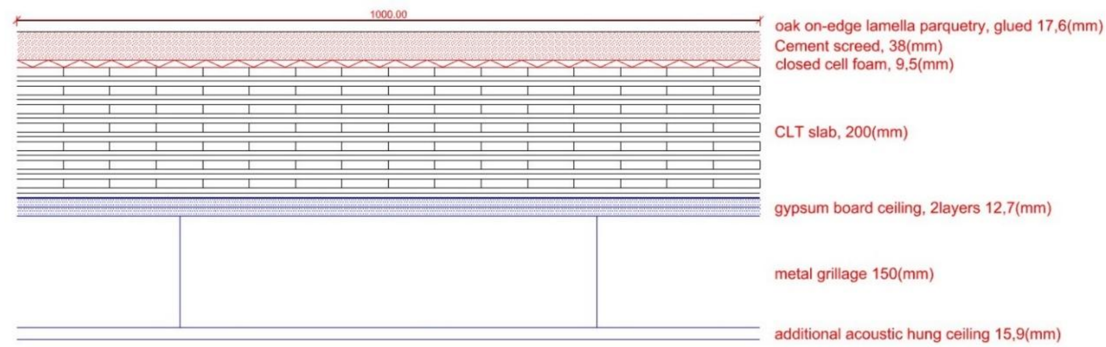
Achieving equal levels of acoustic insulation and fire resistance for all slab types has been challenging when comparing different materials—concrete, timber, and steel—in terms of thickness, weight, and CO_2 emissions. Each material has unique properties, and the interaction of each material with additional flooring and ceiling layers affects both its soundproofing and fire resistance, as these layers can either enhance or alter the material's performance in these areas. Also adding layers to enhance acoustics or fireproofing increases the thickness, weight, and CO_2 emissions, reducing efficiency and sustainability. The revised approach focuses on ensuring consistent acoustic performance (Rw over 50 dB, as per Belgian standards) and maintaining a fire resistance of at least 120 minutes across all materials.

5. **Methods and Materials**

The study considers flowing types of floor systems.

1. Cross-laminated timber (CLT), a mass timber product, is crafted by bonding layers of solid wood panels (Mass Timber Design Guide, 2019). featuring 74dB airborne (and 49dB impact) sound insulation capability and a fire resistance duration of 2 hours.

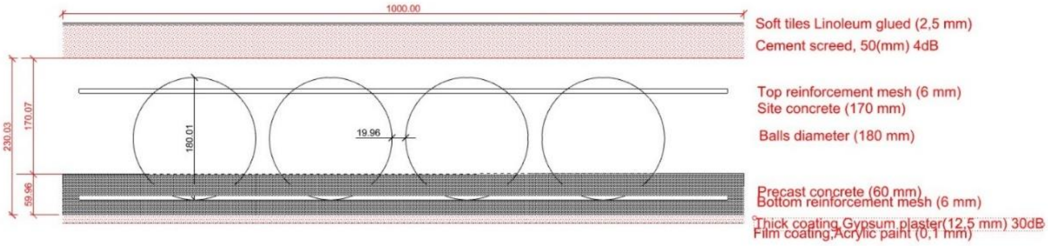
Figure 1: Cross-laminated timber slab



Source: Authors' work

2. The Bubble deck slab, (BubbleDeck Voided Flat Slab Solutions, 2008) constructed with concrete class c30/37, has a 55 to 57dB is designed to provide a level of 72-74 dB airborne sound insulation and 120 minutes of fire resistance.

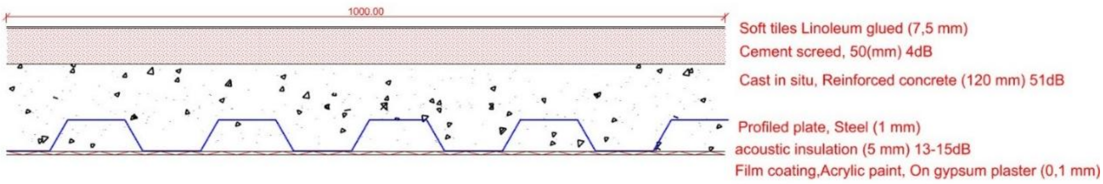
Figure 2: Bubble deck concrete slab



Source: Authors' work

3. Composite steel slab, Comprised of profiled steel decking and a reinforced in-situ concrete topping. The chosen product, using concrete c40/50 and provides spans ranging from 7,62 to 10,84 (New Millennium Building Systems, 2021), 90-180-minute RF duration and designed for 68-70 dB sound insulation by improving with not structural layers.

Figure 3: Composite steel slab



Source: Authors' work

The layers include a 1 mm profiled steel plate, topped with 120 mm of cast in situ, reinforced concrete contributing 51 dB to the sound insulation. Above this, a 50 mm cement screed layer by 4dB sound insulating and a 7.5 mm layer of linoleum tiles are applied, enhancing the acoustic damping. A 5 mm layer of acoustic insulation is integrated, contributing an estimated 13-15 dB to the slab's overall sound insulation capacity. This is complemented by a substantial 12 mm coating of gypsum plaster and a thin 0.1 mm film of acrylic paint applied to the underside, which collectively provide additional soundproofing measures

5.1. Measuring the Thickness and Weight of the Structural Systems

The slab thickness information is obtained from the manufacturer's technical documentation.

To calculate the total slab weight, the weight of the slab plus the weight of additional flooring layers—like cement screed, tiles, gypsum board, etc.—are combined. The slab's weight can be determined in one of two ways: it is either provided in the manufacturer's technical specifications or, calculating by multiplying the material's density by its thickness.

$$Weightss = \sum_{m=1}^{M} (Qm, ss \times Densitym)$$

$Q_{m,ss}$ is the thickness of material m in the structural system ss converted to a volume per unit area (m^2)

$Q_{m,ss}$ =Thickness×1 m^2

Since thickness is in meters and we're considering a per meter squared (m^2) basis, this effectively adjusts the volume calculation to align with the area-specific weight calculation.

$Density_m$ in kg/m^3.

According to the data, the concrete bubble deck system becomes significantly thicker as the span increases, while CLT shows a more gradual rise, and steel composite remains relatively consistent across different spans.

Comparing the weight-span calculation for three different systems, CLT offers the lightest solution, while bubble deck system becomes significantly heavier with larger spans, and steel composite slab provides a middle ground in terms of weight efficiency.

5.2. Measuring the embodied green house emissions of structural systems

By multiplying the material quantity ($Q_{m,ss}$) by its emissions coefficient ($EGHGE_m$), and summing for all materials, you obtain the total EGHGE for the floor system.

The EGHGE of floor systems are calculated using the following equation:

$$EGHGEss = \sum_{m=1}^{M} (Qm, ss \times EGHGEm)$$

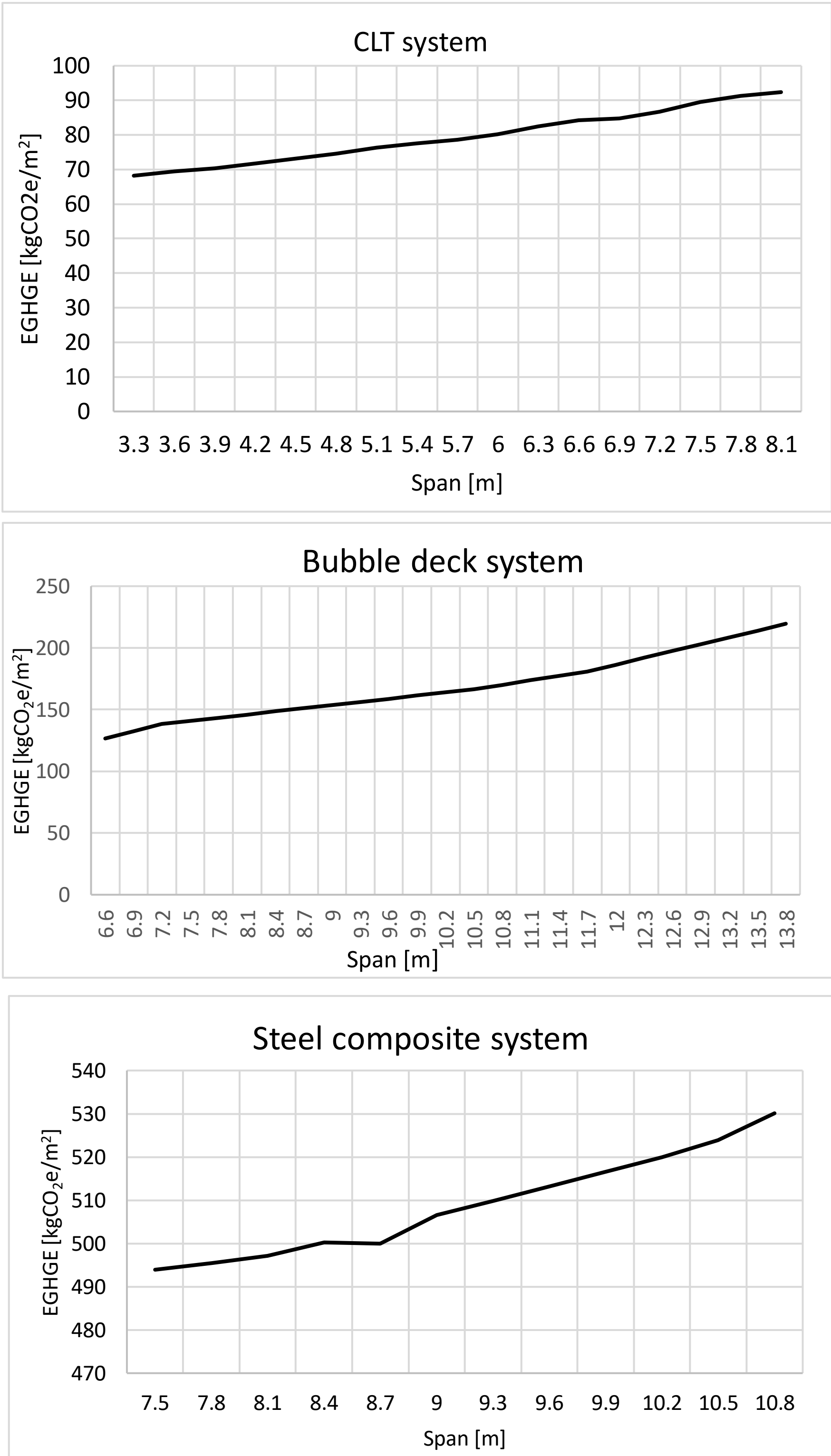
$EGHGE_{ss}$ is embodied greenhouse gas emission of structural system per net floor area in $kgCO_2e/m^2$.

$Q_{m,ss}$ is quantity of material m per floor area in structural system ss.

$EGHGE_{cm}$ = embodied GHG emissions coefficient of material m (Helal, Stephan, & Crawford, 2020).

The graphs for EGHGE/span of the studied floor systems are presented in Figure 4. For EGHGE of the compared systems, CLT has the lowest environmental, with steel composite being the most GHG-intensive system, while concrete bubble deck sits between the two.

Figure 4: EGHGE/Span trend for the considered floors



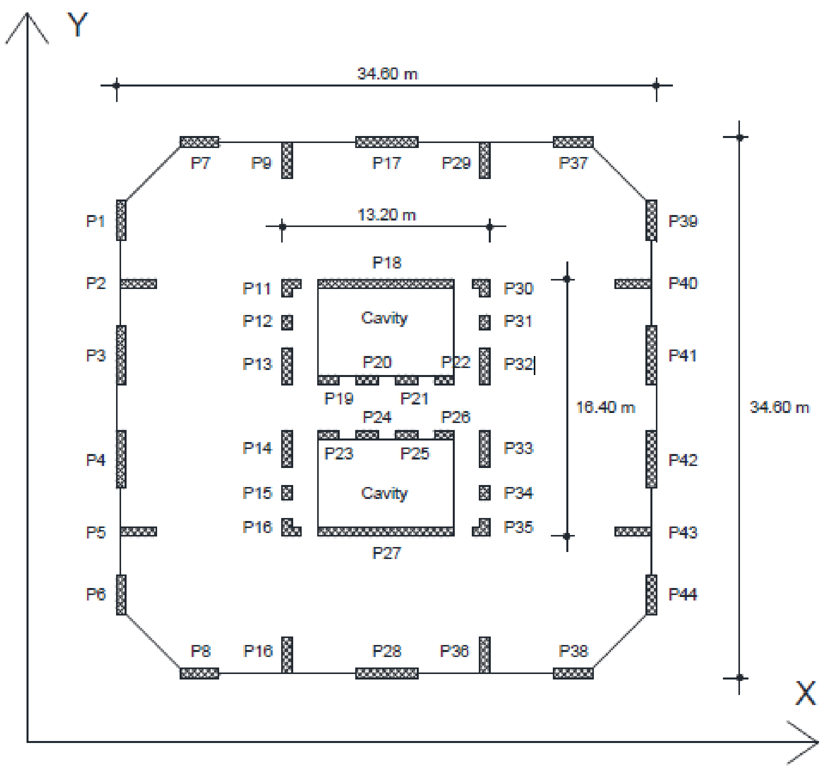
Source: Authors' work

6. **Parametric modeling and results**

The reference tower analyzed in this paper is Pontina tower, a residential building of 38 floors built in Italy. Its structural plan is showed in Figure 5. The tower is modeled using finite element techniques within the Grasshopper environment. The model features a concrete central core which includes the shafts for elevators, stairs and services, concrete rigid frame structure and slabs. The model has been designed to be fully parametric, enabling flexible adjustments to various key parameters such as the plan dimensions, height, number of floors, and other structural elements. This flexibility allows for a wide range of configurations to be explored, providing a robust basis for analysis and comparison of different structural design options.

The structural floor is composed by a system of beams that connect the central core to the peripheral pillars, and slabs that are carried by the beams. The system of beams divides the floor plan (in Figure 5) into a set of rectangles within which the slabs are supposed to be placed. On each rectangle, the shortest side are treated as the slab spans. Once the span of each slab is determined, it is possible to estimate the required slab thickness, weight, and total amount of EGHGE.

Figure 5: Structural plan of the high-rise building considered



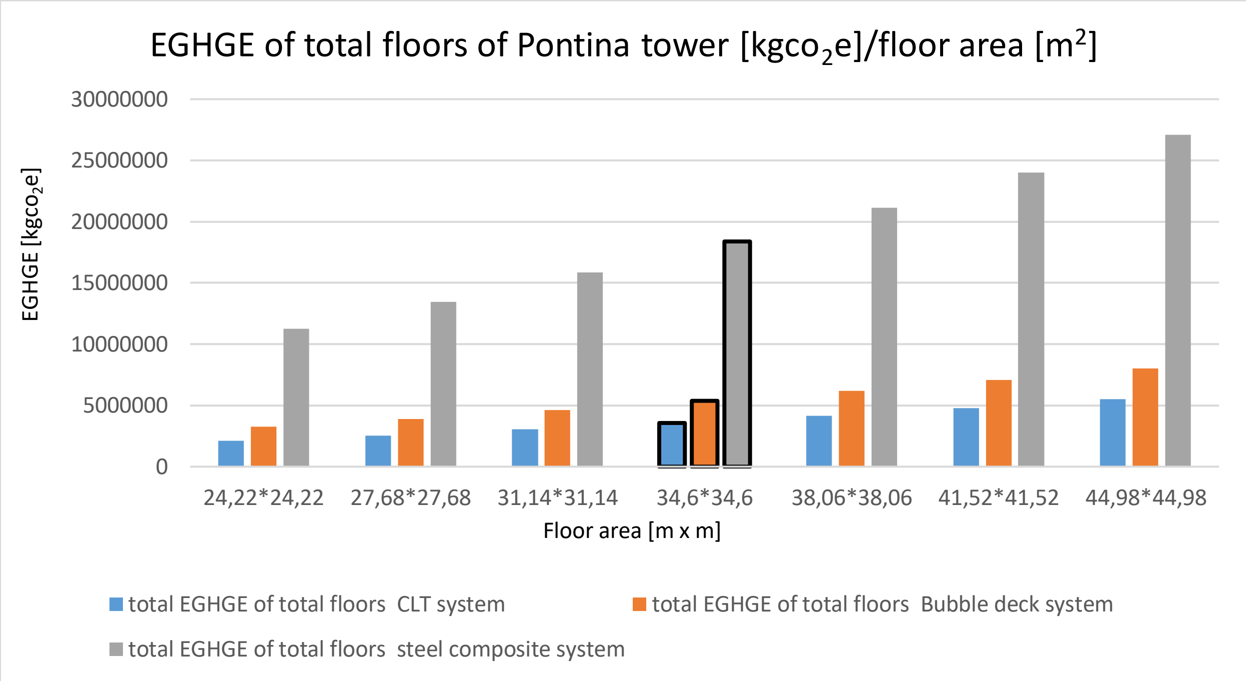
Source: Authors' work

Using Grasshopper plugin, it is possible to model the tower parametrically and use the presented graphs to study the variation of total EGHG of the tower as certain parameters change.

Parametric modeling is further used to analyze different floor sizes of the tower, facilitating a comparison of total embodied greenhouse gas (EGHG) emissions for three different slab designs. The initial floor layout of the tower is 34.6m x 34.6m (Figure 5), and to assess the building's EGHGE across different floor sizes, these initial dimensions are multiplied by factors of 0.7(24.22m x 24.22m), 0.8(27.68m x 27.68m), 0.9(31.14m x 31.14m), 1.0(34.6m x 34.6m), 1.1(38.06m x 38.06m), 1.2(41.52m x 41.52m), and 1.3(44.98m x 44.98m).

This variation allows for a comprehensive evaluation of how changes in plan dimensions affect the total EGHGE of the building for each slab design.

Figure 6: Comparing EGHGE of total floors of the reference tower with different floors sizes



Source: Authors' work

According to the chart as the floor area increases, the total EGHGE for each slab system increases. As was logical to expect, that larger spans and floor areas contribute to higher emissions, but the material type used for the slabs has a significant influence on the overall EGHGE.

7. Conclusion

This study highlights the significant influence that slab designs—composed of timber, concrete, and steel—have on the environmental footprint of tall buildings, with a specific focus on the Pontina Tower. Using Life Cycle Assessment (LCA) to determine the Embodied Greenhouse Gas Emissions (EGHGE) of different slab systems, we find that material choice and slab design greatly affect both the sustainability and efficiency of the building. Cross-laminated timber (CLT) emerges as the most environmentally friendly option, having the lowest emissions and weight per square meter, but there are trade-offs in structural performance. While the steel composite slab is more material efficient in terms of thickness and spanning capability, it has higher values of EGHGE compared to concrete bubble deck system which is heavier showing moderate environmental impact. Moreover, the acoustic and fire resistance characteristics of each slab system significantly influenced the final results.

It reveals that adding extra layers to meet these criteria can significantly alter a material's sustainability profile. This highlights the need to find a balance between structural efficiency and functional requirements, as enhancing acoustic and fire performance often results in greater embodied emissions.

This exercise effectively highlights the capabilities of parametric modeling in analyzing how variations in floor dimensions impact environmental performance. Larger floor spans lead to increased embodied emissions for all materials, but the choice of slab is a key factor that governs this effect.

Ultimately, this research contributes critical insights for architects and engineers working towards sustainability in high-rise buildings. Choosing materials with lower embodied emissions, such as timber, and designing efficient floor systems can substantially reduce a building's environmental footprint. However, it's important to balance these systems with factors like sound insulation, fire safety, and structural strength to ensure a design that is both sustainable and functional.

8. Limitations of the study

This study is limited by the scope of its material selection and case study approach. The analysis focuses on Bubble Deck, CLT, and Steel Composite slab systems, and disregaring other potential slab technologies that might offer different environmental outcomes. Additionally, the study focuses on embodied greenhouse gas emissions while excluding operational emissions, which could provide a more comprehensive understanding of the building's total environmental impact. Differences in construction methods, regional supply of building materials, and energy resources availability are also left out, which might limit the scope of the conclusions.

9. Recommendations for future studies

Future research could expand on this work by exploring additional slab systems and hybrid material combinations to identify more sustainable design alternatives. Moreover, incorporating a full cradle-to-grave analysis, including operational energy use and end-of-life disposal strategies, would provide better evaluation of environmental impacts. With particular regard to high-rise building construction, a comparative study focusing the effect of climatic conditions and geographic sourcing of structural and architectural elements may further enhance sustainability measures.

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