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THE INTERRELATIONS OF INTERMEDIATE FLOOR BEAM STRUCTURES, STRUCTURAL SPANS, MATERIAL EFFICIENCY AND GLOBAL WARMING POTENTIAL IN FINNISH MID-RISE TIMBER APARTMENT BUILDINGS

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ABSTRACT: The built environment is a significant contributor to climate change, and Finland aims for carbon neutrality by 2035, promoting wooden multi-story construction. Timber-structured intermediate floors are technically demanding building components, often thick and multi-layered, making them often the most carbon-intensive elements in residential multi-story timber buildings. This study investigates the interrelations of intermediate floor beam structures, longest structural spans, material efficiency and global warming potential (GWP) in Finnish mid-rise timber apartment buildings. The material efficiency and GWP were assessed per one square meter of apartment space, thus providing comparison of various case studies. This study analysed data from 21 Finnish mid-rise timber apartment buildings built between 2018 and 2022 using the 2D panel construction method. The main results of the research were: (1) for spans of 5–6 m, 6–7 m, and 7–8 m, the GWP ranged from 41.4 – 72.0, 32.2 – 57.6, and 36.8 – 56.5 ($kgCO_2e/m^2$), respectively; (2) the material volume for these spans ranged from 0.24 – 0.50, 0.22 – 0.31, and 0.24 – 0.30 (m^3), respectively. These findings indicate no clear correlation between structural spans and the GWP or material volume of the intermediate floors, likely due to variations in material choices, particularly those needed for vibration and acoustical performance. To reduce emissions, it is recommended to replace high-impact materials with low-carbon alternatives, especially those needed for vibration and acoustical performance. This study provides valuable insights for architects, engineers, and stakeholders in designing more sustainable timber floors.

KEYWORDS: timber construction, structural span, multi-storey timber, mid-rise timber, apartment building

1 – INTRODUCTION

In 2022, buildings accounted for 37% of global CO2 emissions [1]. To achieve a carbon-neutral circular economy by 2035, Finland is promoting the construction of wooden multi-story buildings, as timber is renewable and has lower embodied emissions compared to conventional materials [2]. However, transitioning to a circular built environment also requires improving energy efficiency and reducing material demand through material efficiency [3]. Addressing the environmental impacts of timber-structured intermediate floors has been identified as a key issue requiring attention [4,5]. This is because timber-structured intermediate floors are technically demanding building components, requiring designers to carefully consider fire resistance, acoustics, and vibration behavior. Among these, vibration behavior has been shown to be the most challenging criterion when designing the structural components of intermediate floors [6,7]. To ensure also high performance in fire situations and acoustic insulation, wooden intermediate floors are constructed using multi-layered structures, making them thick and often the most carbon-intensive parts of timber multi-story buildings [5]. There is limited knowledge about the interrelations of intermediate floor beam structures, longest structural spans, material efficiency and global warming potential (GWP) in mid-rise timber apartment buildings. This study seeks to address this research gap by presenting an analysis of these interrelations found in the case studies. To accomplish these objectives, data was collected from 21 buildings constructed between 2018 and 2022. The year 2018 was an important starting point for selecting case studies, as it marked the introduction of new fire regulations that came into effect on January 1, 2018. This article focuses on mid-rise (three to eight storeys) apartment blocks in timber,

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where the primary structural elements are predominantly wood or wood-based products [8]. The categorisation of mid-rise buildings by the number of floors aligns with the definition in the Finnish fire code [9].

The findings offer valuable insights and practical implications for architects, engineers, and other stakeholders, contributing to the development of more efficient and environmentally sustainable intermediate floor designs.

2 – BACKGROUND

This study examines the same 2D panel timber buildings analysed by Tuure et al. [8] , which reported that the total thicknesses of intermediate floors ranged from approximately 450 mm to 700 mm. This variation offers an opportunity to explore the material use of these buildings. The lower the emissions and the smaller the material quantities required to achieve long structural spans, the easier it becomes to construct more environmentally sustainable living spaces. Longer spans also provide greater flexibility for creating adaptable and personalised spatial and façade designs. In addition to potentially reducing the environmental impact of the intermediate floor itself, thinner floors are likely to minimise material use and the environmental impact of vertical components of the building.

Skaar et al. [10] conducted a study analysing the carbon footprint of four timber floor systems, each with a minimum joist span of 7.2 meters and a fire resistance requirement of at least REI 90. Their research revealed that the emissions can vary significantly based on the chosen manufacturers. Their findings indicated that selecting products from manufacturers with high reported GWP values can result in emissions more than four times higher than a similar structure using products from manufacturers with lower reported GWP values.

Westerholm [5] conducted a comparative life cycle assessment (LCA) of five newly constructed residential multi-storey timber buildings, a conventional concrete building, and their alignment with current climate targets. The study presented the distribution of embodied emissions across structural categories and building components. The findings revealed that intermediate floors and walls accounted for the largest share of emissions. Intermediate floors accounted for the largest proportion of emissions associated with the production of construction materials in timber buildings, ranging from 26% to 35%.

Nesheim, S., et al. [4] conducted a study where recent development for the accounting of manufacturing resources for timber elements was utilised to build an optimisation framework for cost and GWP minimisation of timber floor elements finalised at the factory gate. The findings indicated that glulam joists performed better than the alternatives, offering a competitive balance of cost, embodied emissions, stiffness, and availability in standard formats. Moreover, the combination of glulam and spruce-LVL-Q in flanges was generally the most effective. The study also observed a strong correlation between minimising costs and GWP, as both are directly influenced by the total material volume used.

The study by Ruuska and Häkkinen [11] explored different aspects of material efficiency, including scarcity, land use, and the environmental impacts of material production. Their findings suggested that emissions could be utilised as an indicator of material efficiency in building construction.

Fink et al. [6] examined the basic design principles and their limitations for wood structures. Their report addresses that although wood has a relatively high stiffness-to-weight ratio, which contributes to high vibration performance, this performance is reduced by the additional mass from the other necessary layers for fire and acoustic performance. This leads to the scenario where the vibration design dictates the size of the structural members of the intermediate floors.

Aspila et al. [7] demonstrated that vibration performance can be improved by focusing on three key properties of the intermediate floors: mass, span length, and the stiffness of the floor. In real construction cases stiffness is the most easily modifiable parameter as the mass is usually dictated by the use case of the floor and the necessary fire and acoustic material, and the spans are by floor layout. Stiffness of the floor can be increased by using composite structures such as steel-timber and concrete-timber composite structures but also timber-timber composites such as LVL rib slabs.

3 – PROJECT DESCRIPTION

This study employs a case study approach to investigate the interrelations between intermediate floor beam structures, structural spans, material efficiency, and GWP in Finnish mid-rise timber apartment buildings. Fig. 1 illustrates the methodology and process employed for the identification and selection of the case studies.

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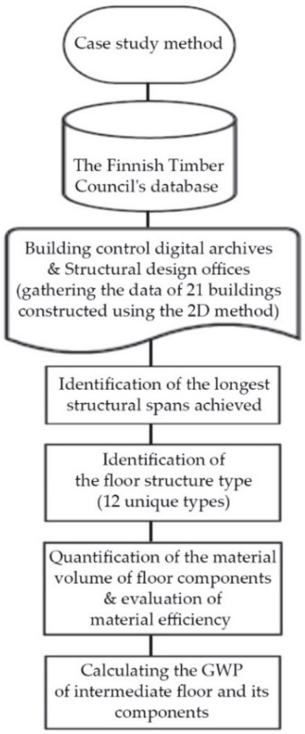

Figure 1. Flowchart of the methodology and process.

3.1 Case Study Selection and Data Collection

The 21 buildings included in this study were chosen based on the following criteria:

1. Timeframe: Buildings constructed between 2018 and 2022
2. Building type: Apartment buildings.
3. Number of storeys: Mid-rise buildings (three to eight storeys).
4. Fire class: P2 (with a fire resistance requirement of REI 60.)
5. Structural materials: timber floor and wall components, with a focus on floors constructed using engineered wood products.
6. Construction method: 2D panel construction method

In Finland, the P2 fire class permits timber apartment buildings up to 8 storeys and a maximum height of 28 meters, with structures required to maintain their load-bearing capacity for at least 60 minutes (R60) in the event of a fire. Additionally, the minimum airborne sound insulation rating is 55 dB (R'w), while the maximum impact sound level is 53 dB (L'n,w) for such buildings. Moreover, for these types of buildings, vibration criteria in the National Annex of Finland specify that the lowest natural frequency must be above 9 Hz, and the deflection from a 1 kN point load must be less than 0,5 mm, to ensure good vibration behavior. The National Annex also accounts for the live load in the form of an additional 30 kg/m² load on the floor structure [12]. Data for each case study was obtained from publicly accessible digital resources, including construction permit drawings and structural design documents sourced from building control services, or structural designer. As all Päivänsäde case buildings featured identical floor systems, and similarly, all Vuoreksen Kuusikko case studies had identical floor systems, a total of 12 different floor systems were identified across all case studies. General information is provided in Table 1.

Table 1: *General information of each case study.*

Building name	**City**	**completion year**	**# of storeys**	**Floor structure type**
Jyväskylän Vuorihelmi	Jyväskylä	2021	5	glulam beams
Nurmeksen Yhteisöpihan puukerrostalo	Nurmes	2020	3	LVL beams
Turun Linnanfältin Lyhdynkantaja	Turku	2019	5	LVL beams
Päivänsäde 3 Building C	Turku	2020	4	semi-open LVL rib slab
Päivänsäde 3 Building D	Turku	2020	3	semi-open LVL rib slab
Päivänsäde 4 Building A	Turku	2021	3	semi-open LVL rib slab
Päivänsäde 4 Building B	Turku	2021	4	semi-open LVL rib slab
Goliathin Salmi Building A	Turku	2019	4	semi-open LVL rib slab
Goliathin Salmi Building B	Turku	2019	4	semi-open LVL rib slab
Turun Hirvensalon Kirsikka	Turku	2022	4	semi-open LVL rib slab
Tampereen Pähkinä	Tampere	2022	5	semi-open LVL rib slab
Turun Linnanherra	Turku	2022	3	semi-open LVL rib slab
Tuuliniitty 3	Espoo	2020	5	semi-open LVL rib slab
Vuoreksen Kuusikko (A-Kruunu Oy) Building A	Tampere	2022	4	semi-open LVL rib slab
Vuoreksen Kuusikko (A-Kruunu Oy) Building B	Tampere	2022	5	semi-open LVL rib slab
Vuoreksen Kuusikko (A-Kruunu Oy) Building C	Tampere	2022	5	semi-open LVL rib slab

Vuoreksen Kuusikko (TA-Asumisoikeus Oy) Building A	Tampere	2022	6	semi-open LVL rib slab
Vuoreksen Kuusikko (TA-Asumisoikeus Oy) Building B	Tampere	2022	5	semi-open LVL rib slab
Vuoreksen Kuusikko (TA-Asumisoikeus Oy) Building C	Tampere	2022	4	semi-open LVL rib slab
Wood City Building A	Helsinki	2019	8	semi-open LVL rib slab
Wood City Building B	Helsinki	2019	8	semi-open LVL rib slab

4 – DESIGN PROCESS

This study focuses on intermediate floors in dry spaces of apartment units, excluding surface materials specified by the architect as they don't affect floor performance. Beams at the edges of floor elements were also excluded for more generalised evaluations, as variations in floor element sizes and apartment layouts are not considered. Additionally, potential cross-bracing between beams affecting vibration performance was excluded due to lack of information in the design documents.The following steps were undertaken:

1. Structural Analysis:

- Identification of the longest structural spans achieved by the floor structures in the case studies. Due to the unavailability of detailed floor element drawings, the structural span was determined based on the center-to-center distance of the load-bearing timber components in the structural walls.

- Identification of the timber-based floor structure type (product)

- Identification of the products used in the intermediate floors and their thickness, and the measurement of the total intermediate floor thickness.

2. Material Efficiency Calculation:

- Material efficiency was defined as material volume per sqm area of apartment space.

- Material volumes were calculated using material data sourced from the generic structural type list compiled by the structural designer. The spacing and exact dimensions of beams were identified from the floor structure plans.

- To facilitate comparisons between different projects, the materials used in the intermediate floors were categorised into the following groups:

(1) Structural timber materials, including beams, engineered wood-based boards, and engineered wood-based panels, all of which are directly connected to the beams themselves to form load-bearing or stiffening action; (2) Cement screed; (3) Gypsum, including gypsum boards and gypsum screed; (4) Insulation; and (5) Other, including steel profiles, non-structural timber battens, and steel reinforcements in the cement screed.

3. Global Warming Potential (GWP):

- Finland intends to regulate construction via Life Cycle Assessment (LCA) requirements in the construction permit process by the year 2026 and is currently in the process of establishing carbon budgets. The LCA in this paper adheres to the methodology established by the Ministry of the Environment Finland and utilises the national co2data database developed for the permit application process [13,14]. The database is open-source and provides conservative and average GWP values and other necessary data for LCA for most common construction materials.

- In cases where products specified in the intermediate floor lack an equivalent in the database, we use Environmental Product Declarations (EPDs). Materials that use EPD data are insulations with densities much higher than those in the database.

- For materials found in the CO2data database, we use average values instead of conservative values (conservative value conversion factor: 1.2) typically used in the permit application processes. Using conservative values would make the products for which we use EPDs appear more environmentally friendly compared to conventional materials found in the database.

- GWP is assessed per square meter of floor area. Total emissions and emissions of each material category in each floor system are reported separately.

5 – RESULTS

Table 2 presents the floor structure types of the case studies, which included semi-open LVL rib slabs, LVL beams, and glulam beams. Semi-open LVL rib slabs are typically supplied to construction sites as prefabricated elements (Fig. 2).

Table 2: Identified floor structure types in the intermediate floor of each case study.

Floor structure types	Semi-open LVL rib slab	LVL beams	Glulam beams
# of case studies	9	2	1

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Fig. 3 presents sectional drawings of the intermediate floors with the longest spans in the dry areas of the apartment units.

Figure 2. Semi-open LVL rib slab.

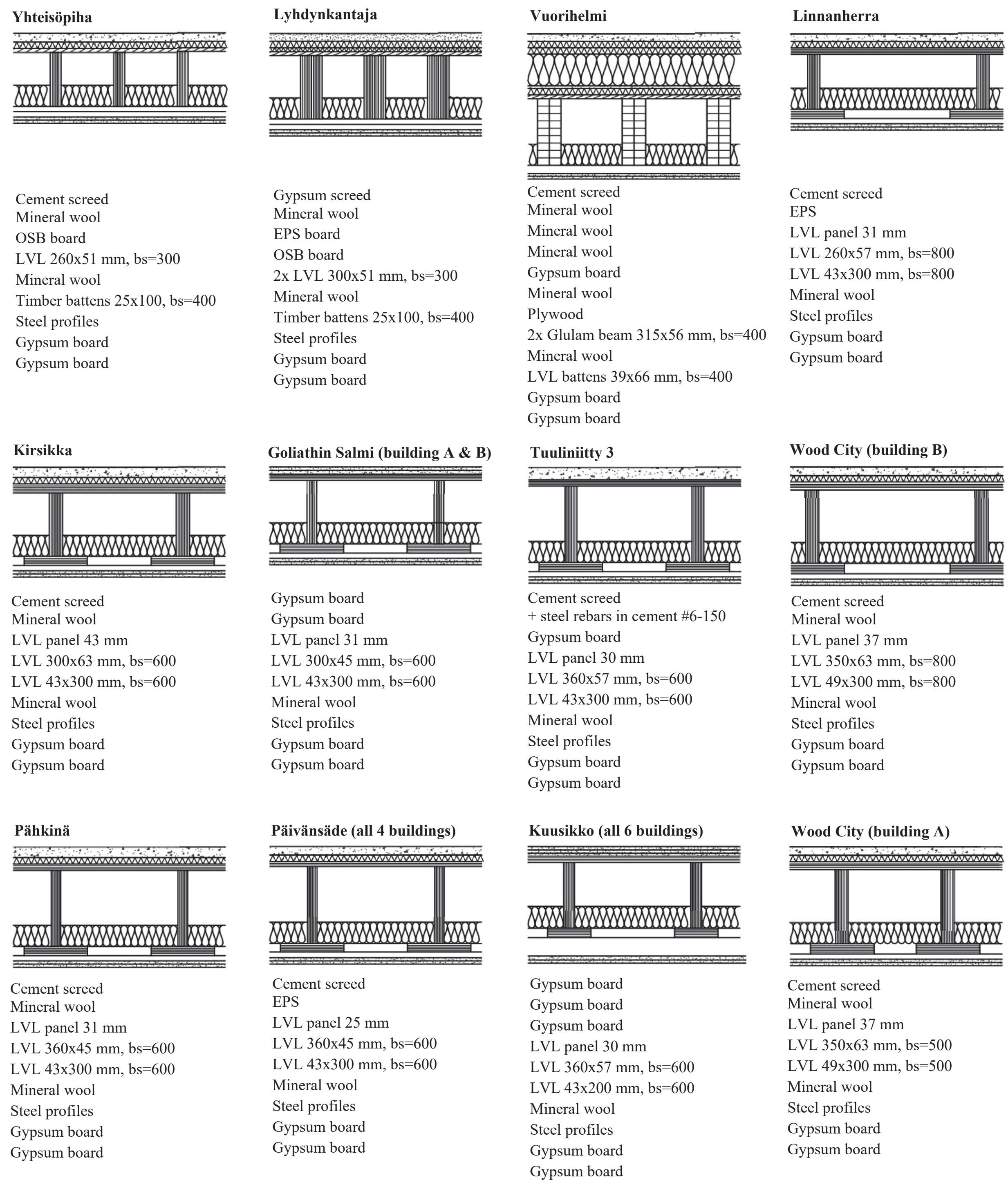

Figure 3. Sectional drawings of the intermediate floors of the case studies

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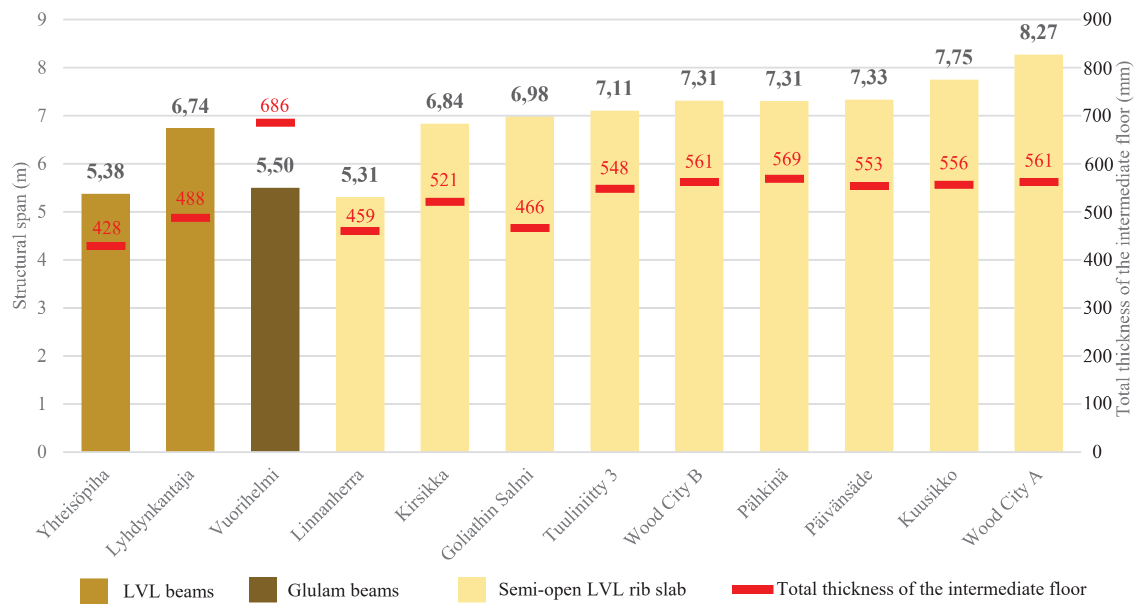

Figure 4. Longest structural spans identified from the case studies categorized by intermediate floor structure types.

5.1 Longest structural spans

Fig. 4 presents the longest structural spans categorised by intermediate floor structure type. The columns represent the structural spans in meters, while the red lines indicate the total thickness of the intermediate floor in millimeters. The structural spans varied from 5.31 m to 8.27 m and the thicknesses of intermediate floors varied from 428 mm to 686 mm. For spans between 7 and 8 meters, the semi-open LVL rib slabs have an average total thickness of 550 mm.

Semi-open LVL rib slabs were used in most cases, particularly for longer structural spans. This is due to the construction of the semi-open LVL rib slab, where the main LVL beam is glued between the top and bottom flanges to form a composite action (Fig. 2). This design significantly enhances the structural stiffness and other properties of the floor, enabling a relatively slim floor construction even in longer spans.

In terms of span analysis, some case buildings feature intermediate floors with varying beam sizes and beam spacing, particularly on the top floor. Additionally, two different intermediate floor thicknesses were identified in some cases for the dry spaces of the apartments. However, for this study, the floor structure with the longest span was selected for examination in each case study as it is the most signific factor when designing wooden intermediate floors [6,7].

5.2 Material Efficiency of the intermediate floors

Structural timber accounted for 22-39% of the total material volume, with an average contribution of 31%. Fig. 4 and 5 show that moving from on-site construction (LVL beams, or glulam beams) to prefabricated modular floor construction, in this case, semi-open LVL rib slabs, results in a slight reduction in the material volume of the structural timber. On the other hand, the volume of structural timber in semi-open LVL rib slabs increases as the span length increases from approximately 5 to 6 meters and from approximately 7 to 8 meters. This is a reasonable outcome since all twelve cases are apartment buildings, meaning the overall design criteria for the floors are the same, but the span length increases. Overall, there was a relatively consistent structural timber volume across spans of approximately 7 to 8 meters.

Fig. 5 shows the material volume per square meter by product category in the intermediate floors. The material volume per square meter of the intermediate floors varied from 0.22 – 0.50 (m^3). Among the 12 distinct floor systems, 9 featured a cement screed, which accounted for 8%-22% of the material volume per square meter, with an average share of 16%. In floors of Goliathin Salmi and Kuusikko, where gypsum boards were used instead of screed to add the required mass to ensure acoustical

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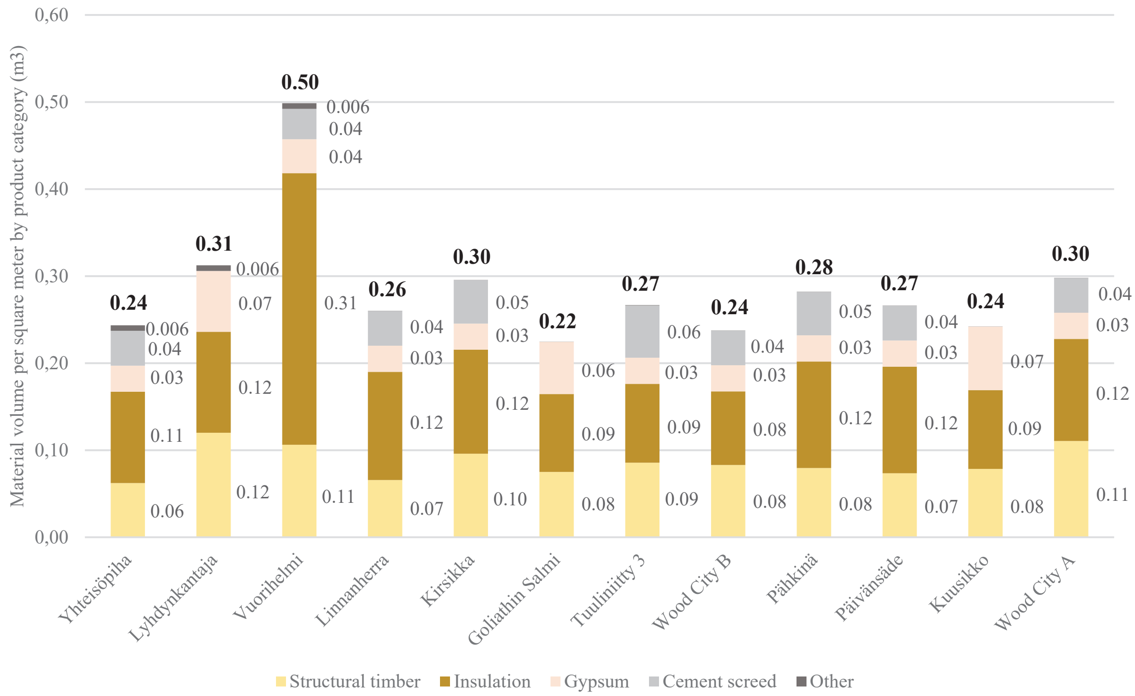

Figure 5. Material volume per square meter by product category in the intermediate floors.

performance, the cases had the lowest material volumes of all the case studies. In Vuorihelmi, insulation accounts for 62% of the total material volume. In the other case studies, insulation comprises between 33% and 46% of the total material volume, with an average of 40%. Vuorihelmi was the only building to utilise glulam beams, which contained nearly twice the volume of structural timber compared to the Yhteisöpiha case, despite both having similar span lengths. However, Vuorihelmi's structural timber GWP is lower than that of Yhteisöpiha, likely due to the lower emissions associated with glulam compared to LVL [15]. Table 3 shows that no clear correlation was identified between increasing structural spans and the material volume in the intermediate floors. This is likely influenced by the choice of materials, especially in selecting those used to achieve the required floor mass and insulation.

Table 3: Interrelation of the longest structural spans and material volume per square meter

Structural Span Range (m)	Material Volume Range (m³)
5–6 (3 cases)	0.24 – 0.50
6–7 (3 cases)	0.22 – 0.31
7–8 or more (6 cases)	0.24 – 0.30

5.3 GWP of intermediate floors and the product categories they consist of

Structural timber accounted for 16-48% of the total GWP, with an average contribution of 35%. Establishing a scientifically valid correlation between different floor structure types and their impact on GWP was not feasible, mainly because the floor structures were predominantly composed of semi-open LVL rib slabs. However, Vuorihelmi with its glulam floor had one of the highest amounts of structural timber, yet its structural timber GWP was the lowest. In floors where gypsum was used instead of cement screed to add the required mass, either as gypsum screed, as in Lyhdynkantaja, or as multiple gypsum boards, as in Goliathin Salmi and Kuusikko, gypsum accounted for 26-39% of the floor's total GWP. Partly due to the use of gypsum boards instead of cement-based screed, the intermediate floors of Goliathin Salmi and Kuusikko have the lowest emissions of the studied buildings. Although Lyhdynkantaja has a gypsum screed with emissions comparable to cases using multiple gypsum boards to add the required mass, it is not among the projects with the lowest GWP. This is because Lyhdynkantaja's load-bearing structure has a 49-56% higher GWP than those of Goliathin Salmi and Kuusikko.

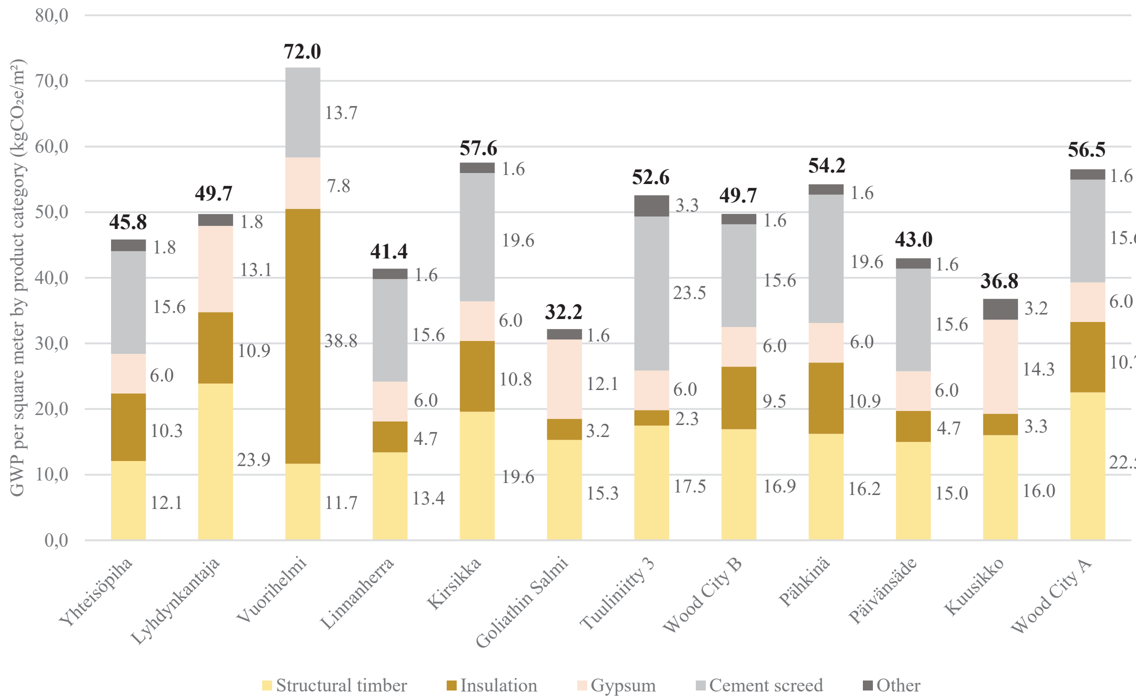

Figure 6. GWP per square meter by product category.

Although the material volumes in Fig. 5 appear to be quite evenly distributed across the case studies, the GWP values show significant variations between the projects. Fig. 6 shows the GWP per square meter by product category in the intermediate floors. Total emissions per square meter of the intermediate floors varied from 32.2 – 72.0 ($kgCO_2e/m^2$).

Of the 12 different floor systems, 9 included a cement screed, which accounted for an average of 33.4% of the floor's GWP per square meter in those cases. In Tuuliniitty 3, where a thicker layer of cement screed was used, the cement screed contributed to nearly half of the total GWP of the floor.

The analysis of intermediate floor emissions highlights the critical role of insulation. Across the examined projects, insulation densities varied significantly, ranging from 16 to 174 kg/m³. In Vuorihelmi, where there is a lot of insulation in relation to floor area, the GWP of the insulation is 54% of total GWP. In the other case studies, the share of the insulation is 4-22% of total GWP.

Table 4: Interrelation of the longest structural spans and the GWP per square meter of the intermediate floor.

Structural Span Range (m)	GWP Range ($kgCO_2e/m^2$)
5–6 (3 cases)	41.4 – 72.0
6–7 (3 cases)	32.2 – 57.6
7–8 or more (6 cases)	36.8 – 56.5

Table 4 shows that no clear correlation was found between increasing structural spans and the GWP in the intermediate floors of the analysed case studies. This is likely influenced by material choices, particularly in the selection of materials used to achieve the required vibration and acoustical performance. Additionally, the type of structural timber played a role, as glulam structure exhibited the lowest emissions among the timber products used in the intermediate floors.

6 – CONCLUSION

This study investigated the interrelations of intermediate floor beam structures, longest structural spans, material efficiency, and GWP in Finnish mid-rise timber apartment buildings. The material efficiency and GWP were calculated per one square meter of the apartment space, thus allowing for the comparison of various case studies.

This research supports the design of more sustainable multi-story timber buildings by informing decision-making, identifying floor structures that require improvement, and emphasising the importance of using low-carbon products to reduce embodied emissions.

The key findings of this study are as follows:

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- Among the 21 case studies, there were 12 different floor systems.

- Across the floor systems, material volume per square meter varied from 0.22 – 0.50 (m^3).

- GWP per square meter varied from 32.2 – 72.0 ($kgCO_2e/m^2$).

- No clear correlation was found between increasing structural spans and the GWP. For spans of 5–6 m, 6–7 m, and 7–8 m, the GWP ranged from 41.4 – 72.0, 32.2 – 57.6, and 36.8 – 56.5 ($kgCO_2e/m^2$), respectively.

- No clear correlation was found between increasing structural spans and the material volume. For spans of 5–6 m, 6–7 m, and 7–8 m, the material volume ranged from 0.24 – 0.50, 0.22 – 0.31, and 0.24 – 0.30 (m^3), respectively.

- Structural timber accounted for 22-39% of the total material volume, with an average contribution of 31%.

- Structural timber contributes 16-48% of total GWP, with an average of 35%.

- The glulam structure exhibited the lowest GWP among the structural timber used in the intermediate floors across all case studies.

- 9 different intermediate floors included a cement screed, which accounted for an average of 33.4% of the floor's GWP per square meter.

Timber building design requires careful material selection and structural dimensioning to balance emissions and structural performance. Timber-based structures, especially intermediate floors, involve greater complexity than conventional concrete constructions due to the inclusion of multiple material layers and a broader range of materials. Consequently, to reduce emissions, it is recommended to prioritize environmentally sustainable materials, particularly for layers and products that add mass to the floor or provide insulation, as these are essential for vibration and acoustical performance.

Future research could examine similar relationships to those explored in this study, but with a larger sample size and across different countries to identify the best practices currently employed in construction. Additionally, future studies could investigate the potential reduction in GWP by replacing high-impact materials with low-carbon alternatives, such as bio-based products. However, conducting such an assessment would require collaboration with acousticians, fire safety engineers, and structural engineers to ensure the floor meets all essential technical requirements.

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