Assessing the Carbon Impacts of Five Apartment Buildings with Different Timber Frames: A Finnish Study

Ninni Westerholm
Tampere University
ninni.westerholm@tuni.fi

Abstract
The market share of wooden multi-story residential buildings has experienced rapid growth in Finland over the past decade, and this trend is expected to persist due to the nation's ambitious climate goals. 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. This paper compares the LCA results of five recently constructed residential multi-story timber buildings with a conventional concrete building and current climate goals.
The selected timber buildings encompass various construction methods and timber usage. The LCA adheres to the methodology established by the Ministry of the Environment Finland and utilizes the national co2data database developed for the permit application process. The chosen timber-framed buildings exhibit 15-26% lower total greenhouse gas (GHG) emissions and 26-34% lower embodied GHG emissions compared to the concrete building. Still, these results highlight that current timber-based construction methods are insufficient to achieve current climate goals and that further development of multi-story timber buildings is still necessary.
The embodied emissions account for the majority, 54-58% of the total whole-life emissions of the timber buildings. In the timber buildings, most emissions originate from materials other than timber. The intermediate floors and walls present the most significant decarbonization potential, as they contribute to 43-59% of the embodied emissions. The paper shows the distribution of emissions across various life cycle stages, material categories, structures, and building components. Consequently, it sheds light on carbon-intensive structures and material layers that need further refinement to meet the carbon targets driven by climate change mitigation.

Keywords: Multi-story timber buildings, life cycle assessment, decarbonization potential, climate change mitigation, industrial timber construction, sustainable construction

Introduction
In Finland, buildings account for nearly 40% of the energy consumption and contribute to over 30% of the country's emissions (Laine et al., 2020). Amidst the climate crisis, these statistics underscore the urgent need for change in the buildings and construction sector.

Finland has a strategic program to promote a circular economy, aiming to transition to a carbon-neutral circular economy in 2035 (Finnish Government n.d.). Embodied emissions originating from construction should be reduced by 50%

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and buildings' operational emissions by 90% by the year 2035 (FIGBC 2022). To achieve this goal, Finland intends to start regulating construction via Life Cycle Assessment (LCA) requirements in the construction permit processes by the year 2026. The nation is also in the process of establishing carbon budgets for certain building typologies and will require LCA to demonstrate that construction aligns with the designated budget before permits are granted (Ministry of the Environment Finland, 2019). Sweden made LCA obligatory in 2022 and plans to introduce limit values, meaning maximum allowable global warming potential (GWP) values, by 2027. Denmark made LCA obligatory in 2023 and set limit values for buildings exceeding 1 000 m^2. The European Union is set to make building emissions accounting mandatory for some buildings by 2028 and for all buildings by 2030 (EU Directive 2024/1275).

Finland intends to start regulating construction via Life Cycle Assessment (LCA) requirements in the construction permit processes by the year 2026.

The significance of low-carbon construction materials is growing for several reasons. Firstly, it's imperative to reduce emissions promptly, and material-related emissions cause the building's whole-life emissions to spike during construction, while the operational emissions accumulate over the years of usage. Secondly, the focus has for a long time been on energy efficiency, which has led to reduced operational emissions and increased the relative importance of embodied emissions. Paradoxically, the pursuit of energy efficiency has sometimes led to greater embodied emissions due to thicker insulation and increased reliance on technical systems. One potential solution to reduce embodied emissions is the substitution of carbon-intensive materials with bio-based alternatives like timber.

Recognizing the positive environmental impacts of timber, Finland has actively promoted the use of wood through initiatives such as The Wood Building Program (2016-2023), a joint government undertaking coordinated by the Ministry of the Environment, aimed at boosting wood usage in construction. The Government Program (Finnish Government, 2019) also includes a target of doubling wood usage in construction from 2019 to 2023.

Numerous researchers have highlighted the carbon advantages of using timber in multi-story construction (Skullestad *et al.* 2016, Dodoo 2019, Bionova 2021, Duan *et al.* 2022). However, less is known about the impact of structural timber systems on the entire life cycle of a building. This study assesses and compares the life cycle emissions of various contemporary timber-based construction systems used in residential multi-story construction in Finland. The emphasis is on embodied emissions and showing the dispersion of emissions among different structural elements, building components, material categories, and material layers. Additionally, the study compares selected wall and floor structures across projects, pinpointing carbon-intensive materials in main structures. LCA results from the timber buildings are compared with those of a more conventional concrete building to highlight the emission reduction potential compared to conventional construction and to enhance the understanding of emission dispersion in timber buildings. This insight into the sources of emissions in timber buildings facilitates the construction sector's efforts to decarbonize and prepare for forthcoming emission restrictions.

The article consists of five sections. The first section introduces multi-story timber buildings and explains why they were chosen as subjects of the study. The following section presents the selected case study projects, the selection criteria, as well as the LCA method and databases used. The third section presents the results of the LCA and the distribution of emissions into different material categories and structural components. In addition, the section discusses the observed differences and similarities between the studied buildings. The fourth section provides the conclusions and their potential applications for different actors involved in construction. In the fifth section, future research directions are proposed.

Multi-story timber buildings
In Finland, the market share of residential multi-story timber buildings has exhibited a rapid increase in the last decade, rising from a mere 1% in 2010 to approximately 5-7% by 2022. As of 2022, Finland has a total of over 130 multi-story timber buildings, comprising more than 4 160 apartments (Karjalainen and Ilgın 2022).

While residential multi-story concrete buildings in Finland are typically constructed with prefabricated sandwich and hollow-core concrete elements (Häkkinen and Vares 2018), residential multi-story timber buildings exhibit greater structural diversity. Residential multi-story timber buildings built in Finland between 1995-2022 have predominantly a structural frame consisting mainly of lightweight timber frame (LWT) panel elements (47%), followed by volumetric cross-laminated timber (CLT) or LWT elements (40%), post and beam frames (6%) or CLT or laminated vaneer lumber (LVL) panel elements (6%) (Karjalainen and Ilgın 2022).

For the purposes of this study, five recently constructed residential multi-story timber buildings have been chosen as case studies, collectively representing all main structural frame categories identified in the study by Karjalainen and Ilgın (2022), except for post and beam frame structures. The exclusion of post and beam designs is due to the absence of such residential multi-story buildings constructed in Finland after 2018, coinciding with the implementation of updated fire regulations that permitted the use of timber in multi-story construction while ensuring fire safety.

In addition to the timber buildings, one concrete building has been included in the study to facilitate comparisons with more conventional construction methods.

Decarbonization potential
Mandatory LCA requirements and carbon budgets are anticipated to promote wood construction, as timber offers a substantial reduction in the GWP of buildings compared to conventional reinforced concrete (RC) structures (Skullestad *et al.* 2016, Dodoo 2019, Bionova 2021, Duan *et al.* 2022). Skullestad et al. (2016) report that a timber structure exhibits 34-84% lower emissions than an RC structure in mid- and high-rise buildings. Bionova (2021) suggests a 14% reduction in emissions when opting for a timber frame instead of an RC frame in residential multi-story buildings. The reduction potential is significantly higher in research done by Dodoo (2019) and Duan et al. (2022). Dodoo's study reveals that multi-story buildings with different timber-based frames exhibit approximately 33-43% lower total emissions and 39-51% lower embodied emissions compared to conventional RC scenarios. In the research done by Duan et al., average RC buildings are found to have 30% higher emissions than CLT buildings.

Timber buildings in relation to national climate goals
This study assesses the negative climate impacts (carbon footprints) and potential positive environmental impacts (carbon handprints) of the selected case buildings. By comparing these results, this research explores the alignment of these projects with Finland's climate goals and examines ways to further promote the nation's transition to a carbon-neutral circular economy.

Furthermore, the carbon footprints are compared to the carbon limit for residential multi-story buildings proposed by Bionova (2021) in a report commissioned by the Ministry of the Environment Finland and to the carbon limits set by the city of Helsinki. This analysis aims to determine whether the case buildings would be granted building permits if the suggested limit values were to regulate future construction activities.

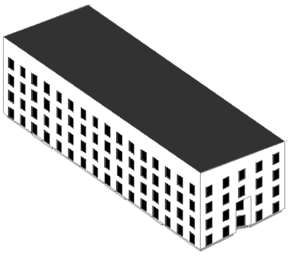

Figure 1. Kide and Kirsikka

Materials and methods

The materials and methods section is divided into two parts. The first part introduces the case study buildings, while the second part presents the scope of the study and outlines the LCA method used to evaluate embodied and operational emissions of these case buildings. Furthermore, this section includes data sources and elucidates the author's underlying assumptions.

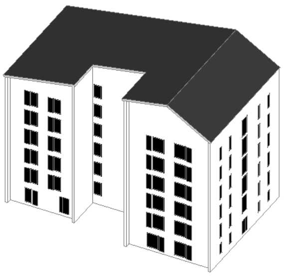

Figure 2. Lumipuu

The selected case study buildings encompass Kide, Kirsikka, Lumipuu, Kuusikko, Kuusikulma, and Wood City. Kide serves as a benchmark building constructed with RC, as it is the twin building of Kirsikka, the sole distinction lies in the choice of building materials. All buildings except Kide feature timber as their primary load-bearing construction material. They were selected because they represent residential multi-story timber buildings that incorporate engineered wood products extensively but in different ways. Table 1 details the diverse structural frameworks of each case study, while Table 2 offers a concise overview of material consumption in each case.

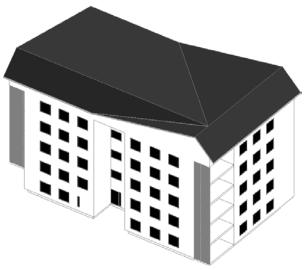

Figure 3. Kuusikko

The selection of timber case studies was influenced by the following criteria:

- The projects are 4-8 story residential apartment buildings located in Finland with a structural frame mainly out of timber.
- The case buildings were completed after the enactment of the Construction Act in 2018.
- Comprehensive project data was accessible, facilitating the assessment.
- Each project has a different structural frame. One project was chosen from each category identified in the statistical study on multi-story timber residential buildings (1995-2022) in Finland (Karjalainen and Ilgın 2022). These categories encompass LWT panel element, volumetric CLT or LWT element, post-and-beam frame, and CLT or LVL panel element. Notably, the post-and-beam frame category lacks representation as no projects with this framework have been completed since 2018. The Wood City project exhibits slight deviations from the others as it includes business premises. However, it was included in the study due to its status as the sole mid-rise timber apartment building completed after 2018 where LVL has been used as the main frame material.

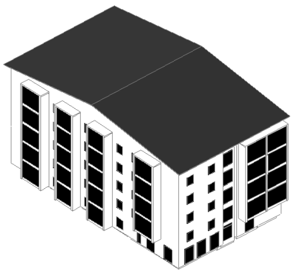

Figure 4. Kuusikulma

Cases 1 & 2: Kide and Kirsikka

Kide and Kirsikka are two similar four-story residential buildings situated in Turku. Kide is constructed out of RC whereas Kirsikka is out of timber. Kide was included in the study to act as a reference building, whereas Kirsikka was included to represent construction using CLT panel elements. The net heated floor area (NHFA) of Kide is 2 974 m^2 and of Kirsikka 3 014 m^2, both hold an energy class B classification and were completed in 2022.

Case 3: Lumipuu

Lumipuu is a project located in Tampere, comprising two similar six-story residential timber buildings. For this study, only Building A was considered. It has a NHFA of 2 746 m^2 and it is constructed mainly using CLT volumetric elements. The building is categorized under energy class A and it was completed in 2022. Lumipuu is the only case study with energy class A rating.

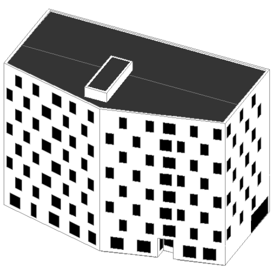

Figure 5: Wood City

Case 4: Kuusikko

Kuusikko in Tampere is among the biggest residential multi-story timber projects in Finland and it consists of six buildings with four to six stories. These buildings consist mainly of LWT panel elements. Building B, one of the five-story buildings, was selected for this study. The building has a NHFA of 2 301 m^2 and it was completed in 2022, holding an energy class B classification.

Case 5: Kuusikulma

Kuusikulma is a project situated in Kerava featuring one five-story and one three-story residential building. Both projects are constructed mainly out of volumetric LWT elements. Only the five-story building was included in this study. It has a NHFA of 3 097 m^2, energy class B classification and was completed in 2021.

Case 6: Wood City

Wood City is a city block situated in Helsinki, featuring two residential eight-story timber buildings and one eight-story office timber building. Only building A was included in this study. Building A has commercial spaces and apartments on the first floor, while the floors above only include apartments. The first floor is out of RC but the floors above are out of timber. The structural timber is mainly LVL. LVL has been used as massive panels in vertical and horizontal structures and some of the intermediate floors have ribbed LVL slabs. The building has a NHFA of 4 370 m2, energy class B classification and it was completed in 2020.

Table 1. Selected case studies and the materials used in main structures

Kide	
Base floor	in situ RC
Exterior walls	concrete sandwich elements
Walls between apartments	prefabricated massive concrete elements
Intermediate floors	prefabricated massive concrete elements
Roof:	hollow-core concrete + timber trusses
+ an air raid shelter	in situ RC
Kirsikka	
Walls between apartments	CLT
Intermediate floors	ribbed LVL
Roof:	timber trusses
+ an air raid shelter	in situ RC
Lumipuu	
Base floor	LWT
Exterior walls	CLT
Walls between apartments	CLT
Intermediate floors	CLT + LWT
Roof	CLT + timber trusses
Kuusikko	
Base floor	in situ RC
Exterior walls	LWT
Walls between apartments	LWT
Intermediate floors	ribbed LVL
Roof	timber trusses
Kuusikulma	
Base floor	LWT
Exterior walls	LWT
Walls between apartments	LWT
Intermediate walls	ribbed LVL
Roof	timber trusses
	+ walls surrounding and slab above common spaces of pre-cast concrete elements (sandwich and solid wall elements + hollow-core slabs)
Wood City	
1st floor	
Base floor	in situ RC
Exterior walls	concrete sandwich elements
Interior walls	prefabricated RC elements
Intermediate floor above floor 1	prefabricated RC elements
2nd-8th floor	
Exterior walls	LVL or LWT
Walls between apartments	LVL
Intermediate floors	ribbed LVL
Roof	LVL

Table 2. Part 1: Amount (volume or surface area) of materials used in different structures and components during a 50-year assessment period for Kide, Kirsikka and Lumipuu. Concrete structures of the air raid shelters are listed as concrete ARS.

Kide

Structure/ component	Material	m²	m³
Base floors	Surface materials		13,7
	Floor screed		49,6
	Concrete		139,2
	Insulation		91,1
	Other		219,9
	Total		**513,5**
Intermediate floors	Surface materials		30,5
	Floor screed		86,7
	Concrete		541,7
	Concrete ARS		31,5
	Insulation		82,7
	Other		0,2
	Total		**773,2**
Roof	Surface materials		64,9
	Timber structures		26,3
	Concrete		288,5
	Insulation		388,2
	Gypsum		28,6
	Other		0,2
	Total		**796,6**
Exterior walls	Surface materials		0,2
	Concrete		519,6
	Concrete ARS		6,3
	Insulation		49,4
	Total		**575,4**
Interior walls	Surface materials		46,3
	Concrete		451,8
	Concrete ARS		30,9
	Insulation		4,2
	Other		0,4
	Steel		0,3
	Total		**432,5**
Glazing		**619**	
Doors		**456**	

Kirsikka

Structure/ component	Material	m²	m³
Base floors	Surface materials		12,2
	Floor screed		49,6
	Concrete		139,2
	Insulation		91,1
	Other		219,9
	Total		**512,0**
Intermediate floors	Surface materials		34,1
	Floor screed		100,5
	Timber structures		190,9
	Timber		*1,6*
	Glulam		*6,6*
	LVL		*143,9*
	CLT		*38,8*
	Concrete		10,8
	Concrete ARS		31,5
	Gypsum		53,6
	Insulation		246,4
	Steel		0,3
	Other		0,4
	Total		**668,6**
Roof	Surface materials		61,5
	Timber structures		134,9
	Timber		*26,8*
	CLT		*108,1*
	Insulation		448,4
	Steel		0,2
	Gypsum		28,7
	Other		0,05
	Total		**673,6**
Exterior walls	Surface materials		59,4
	Timber structures		228,7
	Timber		*33,1*
	CLT		*195,6*
	Concrete		3,4
	Concrete ARS		14,1
	Gypsum		3,9
	Insulation		229,5
	Total		**539,0**
Interior walls	Surface materials		24,5
	Timber structures		230,1
	Timber		*21,8*
	Timber-b. boards		*4,1*
	CLT		*204,3*
	Concrete		3,8
	Concrete ARS		30,9
	Gypsum		120,9
	Insulation		211,9
	Other		0,0
	Total		**622,1**
Glazing		**619**	
Doors		**456**	

Lumipuu

Structure/ component	Material	m²	m³
Base floors	Surface materials		6,9
	Floor screed		16,5
	Timber structures		38,7
	Timber		*30,8*
	Timber-b. boards		*7,9*
	Gypsum		4,5
	Insulation		80,4
	Other		0,1
	Total		**147,1**
Intermediate floors	Surface materials		35,8
	Floor screed		83,3
	Timber structures		315,3
	Timber		*105,5*
	Timber-b. boards		*33,1*
	CLT		*176,6*
	Gypsum		21,5
	Insulation		327,9
	Steel		0,2
	Total		**783,9**
Roof	Surface materials		14,9
	Timber structures		78,5
	Timber		*34,0*
	Timber-b. boards		*8,2*
	CLT		*36,3*
	Insulation		204,3
	Total		**297,7**
Exterior walls	Surface materials		66,0
	Timber structures		153,4
	Timber		*3,3*
	CLT		*150,0*
	Insulation		290,0
	Steel		0,1
	Total		**509,4**
Interior walls	Surface materials		24,4
	Timber structures		296,3
	Timber		*1,3*
	CLT		*295,0*
	Gypsum		108,9
	Insulation		84,0
	Steel		1,1
	Total		**514,7**
Glazing		**355**	
Doors		**471**	

Table 2. Part 2: Amount (volume or surface area) of materials used in different structures and components during a 50-year assessment period for Kuusikko, Kuusikulma and Wood City

Kuusikko

Structure/ component	Material	m²	m³
Base floors	Surface materials		7,3
	Concrete		43,8
	Insulation		87,6
	Other		131,4
	Total		**270,1**
Intermediate floors	Surface materials		27,1
	Floor screed		7,2
	Timber structures		120,0
	Timber		*4,7*
	LVL		*115,3*
	Gypsum		119,0
	Insulation		180,8
	Steel		0,3
	Total		**454,3**
Roof	Surface materials		95,7
	Timber structures		183,9
	Timber		*27,1*
	LVL		*84,3*
	CLT		*72,5*
	Insulation		203,6
	Steel		0,1
	Gypsum		18,1
	Other		0,5
	Total		**501,7**
Exterior walls	Surface materials		48,0
	Timber structures		55,4
	Timber		25,8
	CLT		*29,5*
	Insulation		290,7
	Gypsum		31,8
	Total		**425,8**
Interior walls	Surface materials		7,1
	Timber structures		64,5
	Timber		*29,1*
	CLT		*35,4*
	Insulation		266,1
	Gypsum		104,1
	Other		0,7
	Total		**442,5**
Glazing		**376**	
Doors		**321**	

Kuusikulma

Structure/ component	Material	m²	m³
Base floors	Surface materials		10,6
	Floor screed		2,7
	Concrete		55,7
	Timber structures		17,1
	Timber		10,2
	Timber-b. boards		6,9
	Gypsum		13,8
	Insulation		123,0
	Steel		0,003
	Other		73,2
	Total		**296,1**
Intermediate floors	Surface materials		52,1
	Floor screed		12,7
	Timber structures		202,8
	Timber		*108,5*
	Timber-b. boards		*94,3*
	Concrete		15,2
	Gypsum		107,8
	Insulation		827,8
	Steel		0,02
	Other		0,6
	Total		**1219,0**
Roof	Surface materials		55,0
	Timber structures		75,2
	Timber		*58,8*
	Timber-b. boards		*16,4*
	Insulation		257,6
	Gypsum		29,0
	Steel		0,01
	Other		0,6
	Total		**417,5**
Exterior walls	Surface materials		114,8
	Timber structures		44,1
	Timber		*27,4*
	Timber-b. boards		*16,7*
	Insulation		338,0
	Gypsum		57,0
	Other		0,3
	Total		**554,1**
Interior walls	Surface materials		21,3
	Timber structures		103,8
	Timber		*73,6*
	CLT		*30,2*
	Concrete		80,5
	Insulation		644,6
	Gypsum		208,4
	Other		6,3
	Total		**1064,7**
Glazing		**796**	
Doors		**562**	

Wood City

Structure/ component	Material	m²	m³
Base floors	Surface materials		13,5
	Concrete		101,50
	Insulation		86,7
	Other		173,4
	Total		**375,1**
Intermediate floors	Surface materials		86,4
	Floor screed		166,0
	Timber structures		267,2
	Timber		*7,0*
	LVL		*260,2*
	Concrete		114,7
	Gypsum		87,2
	Insulation		347,4
	Steel		0,8
	Other		0,4
	Total		**1070,1**
Roof	Surface materials		24,8
	Timber structures		63,5
	Timber		*7,5*
	LVL		*56,0*
	Insulation		238,6
	Gypsum		18,8
	Total		**345,7**
Exterior walls	Surface materials		90,4
	Timber structures		63,5
	Timber		*7,5*
	LVL		*56,0*
	Insulation		238,6
	Gypsum		18,8
	Total		**411,4**
Interior walls	Surface materials		45,6
	Timber structures		325,6
	Timber		*21,4*
	CLT		*304,2*
	Concrete		87,0
	Insulation		297,7
	Gypsum		144,3
	Steel		18,5
	Other		10,0
	Total		**928,7**
Glazing		**979**	
Doors		**530**	

LCA method and databases

LCA for the selected buildings was conducted in accordance with the calculation method outlined by the Ministry of the Environment Finland (2021). The method has been developed based on EN standards (15804, 15978, and 15643) and the European Commission's Level(s) method. However, since the Ministry's method is intended to serve as a basis for legislation, some aspects have been refined and specified.

The assessment utilizes the national open-source co2data emissions database (CO2D). The method and the database have been developed for the forthcoming mandatory permit application process, slated for implementation by 2026. In cases where specific material data were absent from the aforementioned database, values were taken from the Ministry's LCA tool used for piloting the assessment method in 2019 (Ministry of the Environment Finland, 2019) or from the Swedish open emissions database (Boverket 2023). The assessment period extended over 50 years.

To closely resemble the future permit application process, the LCA was conducted based on publicly available permit documents for each project. The carbon footprint of each project was compared to the carbon limit value suggested by Bionova (2021) to determine whether the selected cases would be granted a building permit if that were to regulate future construction activities. Furthermore, the projects' carbon handprints (the potential positive environmental impacts), were compared. The Finnish regulations will require the reporting of the handprints during building permit applications, albeit without specified limit values.

The values retrieved from CO2D and the Swedish database are based on average values in product-specific Environmental Product Declarations (EPDs). However, an uncertainty factor of +20% for CO2D and +25% for the Swedish database have been incorporated into the average GWP values. Consequently, the LCA results obtained using these values are anticipated to be higher than those derived from EPDs or non-conservative GWP values.

In this study, the LCA, aligned with the Ministry of the Environment Finland's methodology, includes Modules A1-5, B4, B6, C1-4 and D1-5 from the following stages; product stage, construction process stage, use stage, end-of-life stage and benefits beyond the system boundary. The scope and assessment methods are presented in greater detail in Table 3.

Table 3. Scope and assessment methods

A1-3	• Emissions for the *production phase* are calculated using project-specific quantity data and material specifications • LCA considers construction materials, fixed kitchen and bathroom cabinets and housing services • The quantity data is obtained by 3D-modeling the case buildings in ArchiCAD and utilizing the area information obtained from there. The areas of each structure type are then multiplied by the emissions per 1 m^2 of each structure type • Emissions for each construction type are calculated using the material and layer thickness specifications used in the license documents. • Cutoffs and waste created during the construction are included according to estimates in CO2D • The housing services included in the product phase are calculated using NHFA obtained from the project-specific Energy Performance Certificates (EPC) and conservative average emission values from CO2D • Fasteners, nails, screws, glues and seals are not included in the assessment
A4-5	• Emissions for the *construction process* are calculated using the NHFAs obtained from the EPCs and emission values from CO2D
B4	• Emissions for *replacements* consider the emissions caused by the production of all the products that need replacing during the assessment period of 50 years and the assessment is done using CO2D values.

B6	• The emissions of the *operational energy use* are calculated using the NHFA, calculated energy use for district heating and electricity per year per NHFA, and conservative emission values for these. The values for the former two are obtained from the project-specific EPCs and the latter from CO2D. • To facilitate comparison, the emissions of B6 have been calculated as if all case buildings were completed in 2022
C1-2	• The emissions of *demolition/deconstruction* and *transport* in the end-of-life stage are calculated using the NHFAs obtained from the EPCs and conservative average emission values from CO2D
C3-4	• Emissions related to *waste processing* and *disposal* are calculated using average waste processing and disposal values (divided into categories of glass, metals, wood, concrete, gypsum, plastics, and materials for disposal) obtained from CO2D and multiplying these with the weight of the replaced materials in each material category
D1-5	• Potential benefits outside of the system boundary are mainly calculated using values from CO2D but carbonation of concrete uses average values by the Finnish Environment Institute (Häkkinen, 2022).

Limit values

No absolute limit values for building's carbon footprints have been set by the Ministry of the Environment Finland yet. Nevertheless, the Ministry commissioned a report (Bionova, 2021) that offers suggested limit values for various building typologies. Bionova Ltd, today (2023) known as One Click LCA Ltd, which is the developer of the world's leading buildings and construction products LCA software, was commissioned to propose limit values for different building types. These proposed limit values generally reflect a reduction of approximately 20% compared to the carbon footprints of benchmark buildings. To establish a baseline of building carbon footprints, the construction materials' carbon footprints from 482 actual Finnish construction projects and operational emissions from 3 748 project-specific EPCs were collected and analyzed. The benchmark residential multi-story building is a conventional concrete building with district heating and energy class B classification.

It should be noted that the Bionova report adopts generic GWP values from One Click LCA rather than the conservative values found in the subsequently published national CO2D database. Consequently, there is a disparity between the values presented in the Bionova report and the LCA outcomes of this study, which represents a limitation of this research. The author assumes that incorporating the +20% uncertainty factor utilized in CO2D into Bionova's values makes them moderately comparable to the LCA results obtained in this study. The inclusion of these limit values in this work is justified by the expectation that the Ministry will introduce some limit values and the values by Bionova are the only values, though only suggestions, published to date.

For residential multi-story buildings, the recommended limit value stands at 11,5 $kgCO_2e/m^2/yr$. When applying the +20% uncertainty factor, the adjusted limit value becomes 13,8 $kgCO_2e/m^2/yr$.

Even though no national limit values have been published yet, the Urban Environment Committee of Helsinki, the capital of Finland, decided in June 2023 to adopt the carbon footprint as a tool for promoting low-carbon construction before national limit values come into effect (City of Helsinki, 2023). In Helsinki, the carbon footprint limit of residential apartment buildings is 16,0 $kg/m^2/yr$. The total carbon footprint is calculated and reported using the Ministry of the Environment's assessment method when applying for a building permit. The overall carbon footprint requirement is introduced in new zoning plans that include residential apartment building construction, and thus, the carbon footprint requirement expands as construction commences in the planned areas.

It is imperative to emphasize that this study refrains from offering commentary on the limit values themselves. Instead, the study exclusively juxtaposes the carbon footprints of the chosen projects against these limit values to assess how the projects would align with regulatory requirements if the maximum allowable carbon footprints for residential multi-story buildings were set at 11,5 $kgCO_2e/m^2/yr$, 13,8 $kgCO_2e/m^2/yr$ or 16,0 $kgCO_2e/m^2/yr$.

Assumptions
Given that this study's LCA relies on publicly accessible documents, the level of specification for the different structures varies across the projects. In cases where documentation lacked specificity, the author made the following assumptions based on typical specifications:

- All vertical timber/steel structures that have non-specified spacings have spacing S=600mm.
- All horizontal timber structures that have non-specified spacings, a spacing of S=600mm was assumed for non-load-bearing elements, while a spacing of S=400mm was assumed for load-bearing elements.
- All projects were assumed to have cement-based floor screed.
- For in situ concrete structures lacking specific details, ready-mixed C30/37 non-porous concrete was assumed.
- All concrete structures (including screed) with a thickness exceeding 70mm were assumed to have the following steel reinforcing:
  - Slab/wall thickness of 160-180mm: 2x6-150
  - Slab/wall thickness of 200-240mm: 2x8-200
  - Floor screed thickness of 70-100mm: 6-150
  - Air raid shelter wall thickness of 300mm: 2x10-150 + 2x10-150
  - Slab above air raid shelter with a thickness of 300 mm: 10-150 + 10-150

The scope of the study
The scope of this study encompasses the carbon impacts associated with a wide range of components, including most construction materials, stairs, elevators, HVAC systems, fixed kitchen and bathroom cabinets, construction processes, transportation, replacements, operational energy consumption, waste processing and disposal, as well as potential benefits from carbon storage, carbonation, recycling and energy recovery. Any prospective carbon benefits are incorporated into the carbon handprint and are reported separately from the carbon footprint.

Notably, the national carbon footprint limit values will probably not encompass emissions related to foundations, air raid shelters, parking structures, and other external areas. Consequently, these elements are also excluded from the scope of this study, mirroring the exclusions made in the Bionova report, which serves as a reference for suggested limit values.

Of the case studies examined, Kide and Kirsikka are the only ones featuring air raid shelters. Since the assessment method does not specify how to exclude these shelters from the assessment, the emissions of them have been included in the total carbon footprint but the carbon-intensive walls and roof of the air raid shelters are reported separately from the other materials.

Results and discussions

GHG emissions
The total GHG emissions for the timber cases, namely Kirsikka, Lumipuu, Kuusikko, Kuusikulma, and Wood City are 15,83 $kgCO_2e/m^2/yr$, 14,92 $kgCO_2e/m^2/yr$, 14,16 $kgCO_2e/m^2/yr$, 13,80 $kgCO_2e/m^2/yr$ and 15,15 $kgCO_2e/m^2/yr$, respectively. In contrast, the total GHG emissions for Kide are 18,54 $kgCO_2e/m^2/yr$ (Fig. 6). Should the limit value for residential multi-story buildings be set at 13,8 $kgCO_2e/m^2/yr$, only Kuusikulma would be granted a building permit. When comparing the emissions to the lower limit value, none of

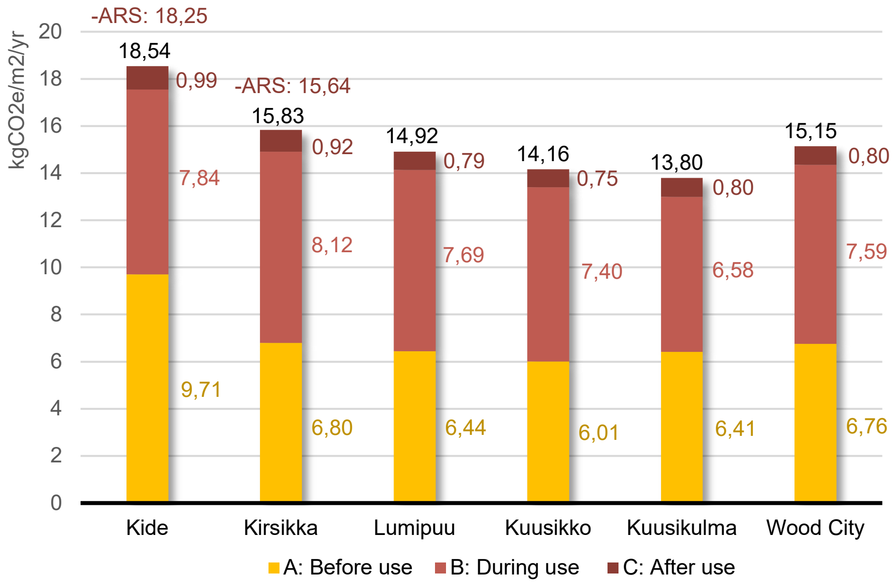

Figure 6. Total GHG emissions of selected cases. Modules A1-5, B4, B6, and C1-3 have been considered.

the cases would be granted a building permit. The city of Helsinki's limit, on the other hand, would grant permit to all examined timber apartment buildings, but the examined RC building would exceed the allowed carbon budget. While definitive information on national limit values for residential apartment buildings is unavailable, values in Fig. 6 indicate that a limit significantly lower than that of conventional construction would be advantageous for timber construction.

Given that this study primarily seeks to elucidate the impact of different ways of building out of timber on the timber buildings GWP, it is more relevant to study the embodied GHG emissions rather than total GHG emissions, which include building operation. The differences in emissions caused by operation are very small, while bigger differences are found when studying the embodied emissions, particularly when comparing the timber buildings to the RC building. The embodied emissions account for the majority, 54-58% of the total whole-life emissions of the timber buildings. If considering only embodied emissions to practical completion (Modules A1-A5), they are 6,80 $kgCO_2e/m^2/yr$ of Kirsikka, 6,44 $kgCO_2e/m^2/yr$ of Lumipuu, 6,01 $kgCO_2e/m^2/yr$ of Kuusikko, 6,41 $kgCO_2e/m^2/yr$ of Kuusikulma, and 6,76 $kgCO_2e/m^2/yr$ of Wood City. In comparison, the embodied emissions until practical completion for the RC building stand at 9,71 $kgCO_2e/m^2/yr$ (Fig. 6).

The residential multi-story concrete building has 35-51% higher embodied emissions than the residential multi-story timber buildings

During the 50-year assessment period, the embodied emissions of the timber buildings are 26-34% lower than those of the RC building. In other words, the embodied emissions of the RC reference building are 35-51% higher than the emissions of the selected timber buildings, and 35-42% higher if considering only the CLT alternatives. These findings align with the results of Duan et al. (2022), who report that the embodied emissions of RC buildings were, on average, 43% higher than those of CLT buildings. However, if the benefits in Module D are considered, the advantages of timber structures become even bigger (Fig. 14).

When examining the embodied emissions solely related to construction materials until practical completion, the conventional RC building exhibits 40-109% higher embodied emissions compared to the selected timber case studies. These results are similar to those of Dodoo (2019), who conducted a comparison between four different timber-based structural systems and conventional RC in a four-story building, reporting that the emissions of the latter were 63-103% higher than those of the timber-based alternatives. It is worth noting that all cases in Dodoo's assessment had concrete base slabs and included foundations, which is likely to explain the slight disparities in the findings.

Embodied emissions by material category

In the RC building, concrete is the predominant contributor to material-related emissions, while in the timber building, emissions are more evenly distributed across a variety of materials. The sandwich elements have been classified as concrete since the CO2D includes GWP values for these elements without reporting how they are divided into different materials. The higher embodied emissions of Kide, the RC building, are primarily due to its concrete frame (Fig. 7).

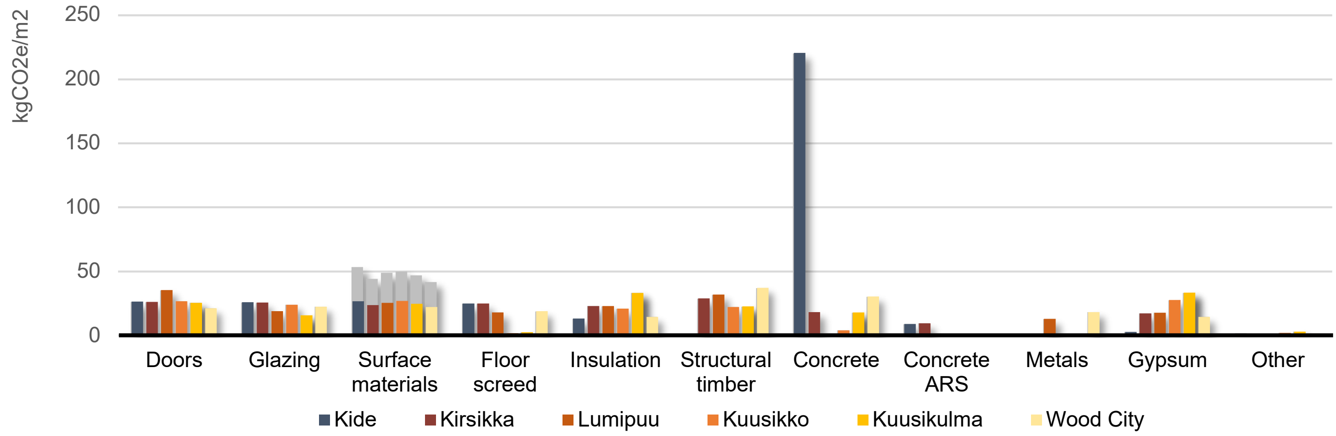

Figure 7. Embodied emissions by main material categories during a 50-year assessment period. Emissions caused by material **r**eplacements are shown in grey. ARS stands for air raid shelter. Elevators, stairs, building services, transportation and construction processes are excluded from the figure.

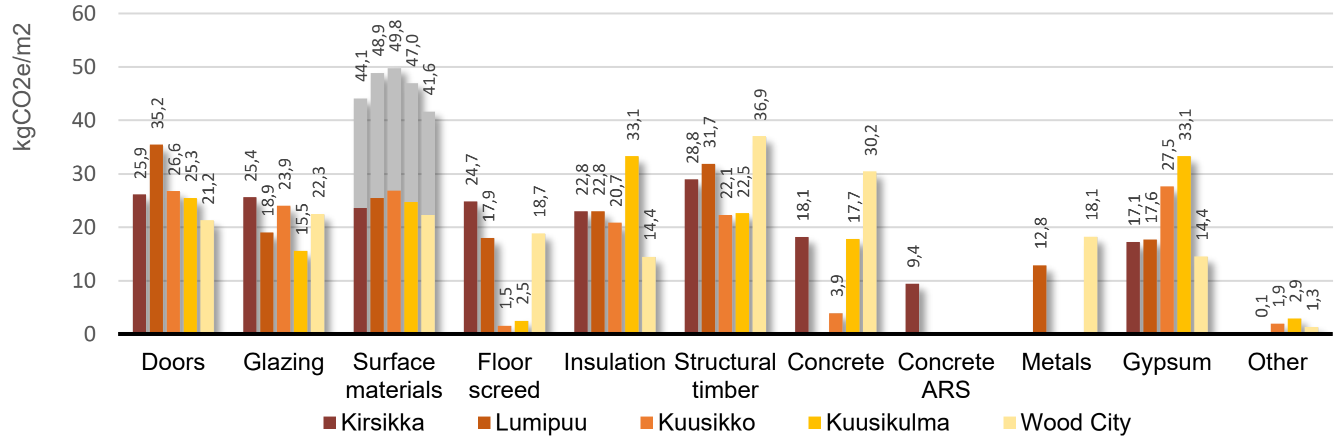

Figure 8. Embodied emissions by main material categories of the timber buildings during a 50-year assessment period. Emissions caused by material **r**eplacements are shown in grey. ARS stands for air raid shelter. Elevators, stairs, building services, transportation and construction processes are excluded from the figure. Kide has been excluded to make the comparison of the timber buildings easier.

The load-bearing timber structures account for only 11-17% of the material-related emissions

When considering embodied carbon emissions in the timber buildings caused by production and replacements (elevators, stairs, building services, transportation and construction processes excluded) over a 50-year assessment period, the load-bearing timber structures account for only 11-17% of the emissions. The massive timber-structures have higher emissions than the LWT structures, with values ranging from 28,8-36,9 kgCO_2e/m^2, in contrast to 22,1-22,5 kgCO_2e/m^2 for the LWT structures.

In the case of timber buildings, the highest share of embodied emissions is due to surface materials, which account for 19-27% of the emissions (Fig. 8-9). The high share is due to the generally short service life of surface materials (Fig. 8). Therefore, when aiming to reduce emissions, particularly for surface materials, factors like service life and GWP should play a significant role in material selection.

Additionally, apart from structural timber and surface materials, other contributors to embodied emissions in timber buildings include insulation (6-16%), gypsum (7-16%), windows and balcony glazing (8-13%), doors (10-17%), and floor screed (1-11%) when considering only construction materials and building components. Notably, the share of emissions due to gypsum is higher in the LWT cases (15-16%) than in the other three timber buildings (7-9%). This discrepancy is primarily due to mass being added to intermediate floors with gypsum rather than cement-based floor screeds in Kuusikko and Kuusikulma and the load-bearing light-weight timber frame needing more fire protection than the massive timber structures.

In the case of Lumipuu and Wood City, where bathroom modules have a steel structure, metals contribute 6-8% of embodied emissions. In Kirsikka, Kuusikulma, Kuusikko, and Wood City, where concrete has been used in base

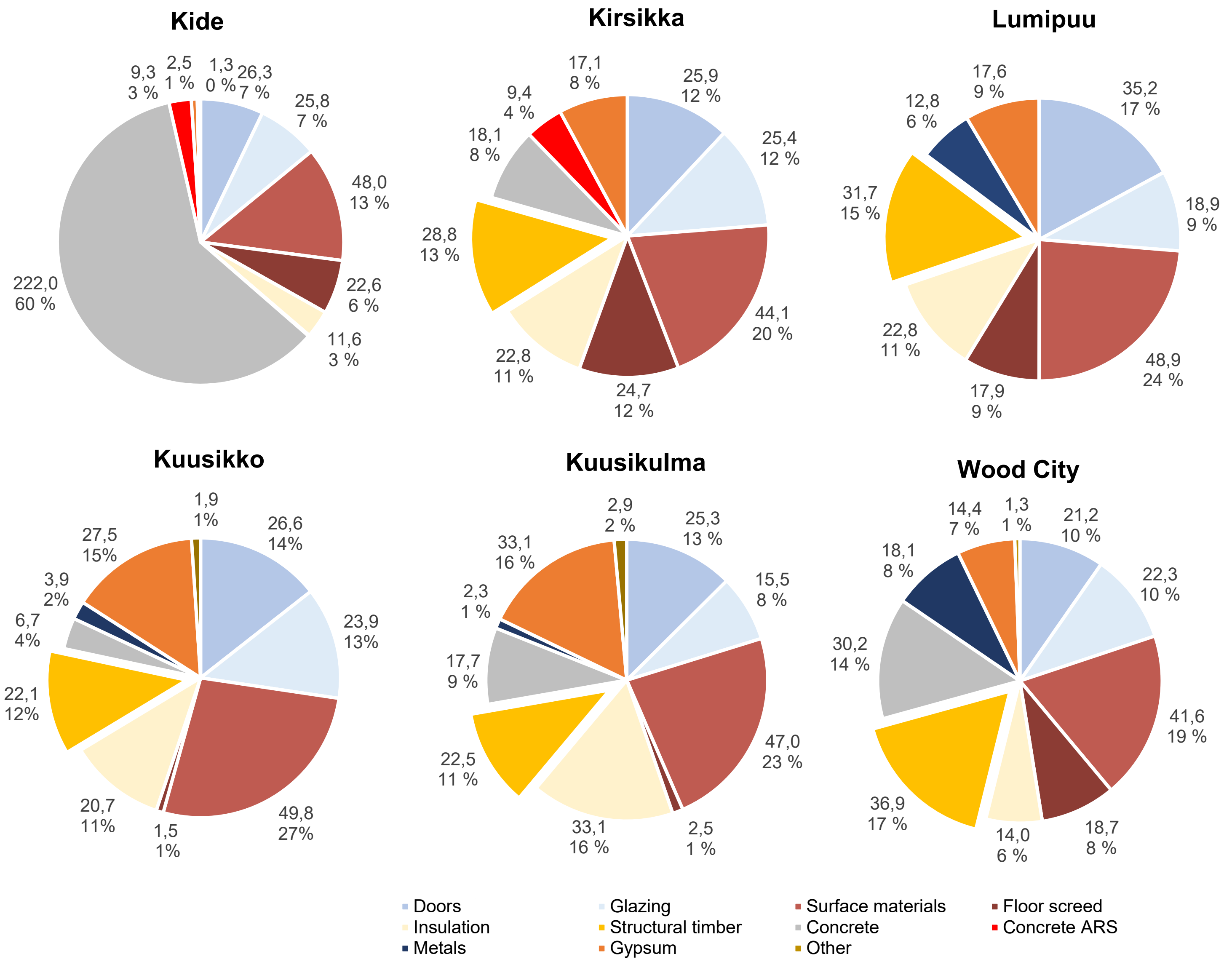

Figure 9. The share of emboded emissions by material category during a 50-year assessment period. ARS stands for air raid shelter. Elevators, stairs, building services, transportation and construction processes are excluded from the figure.

floors, walls, and intermediate floors, concrete accounts for 4-14% of embodied emissions. It is worth noting that the carbon-intensive air raid shelter in Kirsikka has been separated from the other concrete structures and contributes 4% to embodied emissions. The share of concrete used in Wood City and Kirsikka is significantly higher compared to Kuusikulma and Kuusikko, explaining why the emissions of concrete are higher for the former (30,2 $kgCO_2e/m^2$ for Wood City, and 18,1 $kgCO_2e/m^2$ for Kirsikka, plus an additional 9,4 $kgCO_2e/m^2$ for the air raid shelter) than the latter (while they are only 17,7 $kgCO_2e/m^2$ for Kuusikulma and 6,7 $kgCO_2e/m^2$ for Kuusikko).

Kuusikko and Kuusikulma, the buildings with LWT structures, demonstrate the lowest embodied emissions. This is mainly due to lightweight frame-structures having lower emissions than massive timber ones, and the choice of adding mass by using gypsum instead of floor screed in the intermediate floors.

The intermediate floors and walls stand for the biggest share of embodied emissions in timber buildings

Embodied emissions by structural category and building components

Embodied emissions distributed across structural categories and building components reveal that the intermediate floors and walls stand for the biggest share of emissions (Fig. 10-11). In the RC building, exterior walls also contribute significantly to embodied emissions, in addition to the intermediate floors and walls. In the timber buildings, if replacements are considered, intermediate floors account for 25-35%, intermediate walls for 16-25%, the roof for 6-15%, base floors for 5-14%, exterior walls for 6-11%, doors for 10-17% and windows and balcony glazing for 9-13% of the embodied emissions.

In the timber buildings, the intermediate floors and walls account together for 43-59% of the embodied emissions related to structures and building components. Consequently, decarbonizing these structures has the biggest effect on the overall carbon footprint. Given the high emissions associated with these structures and the fact that their emissions result from a broader range of materials compared to the RC building, these structures are assessed in greater detail.

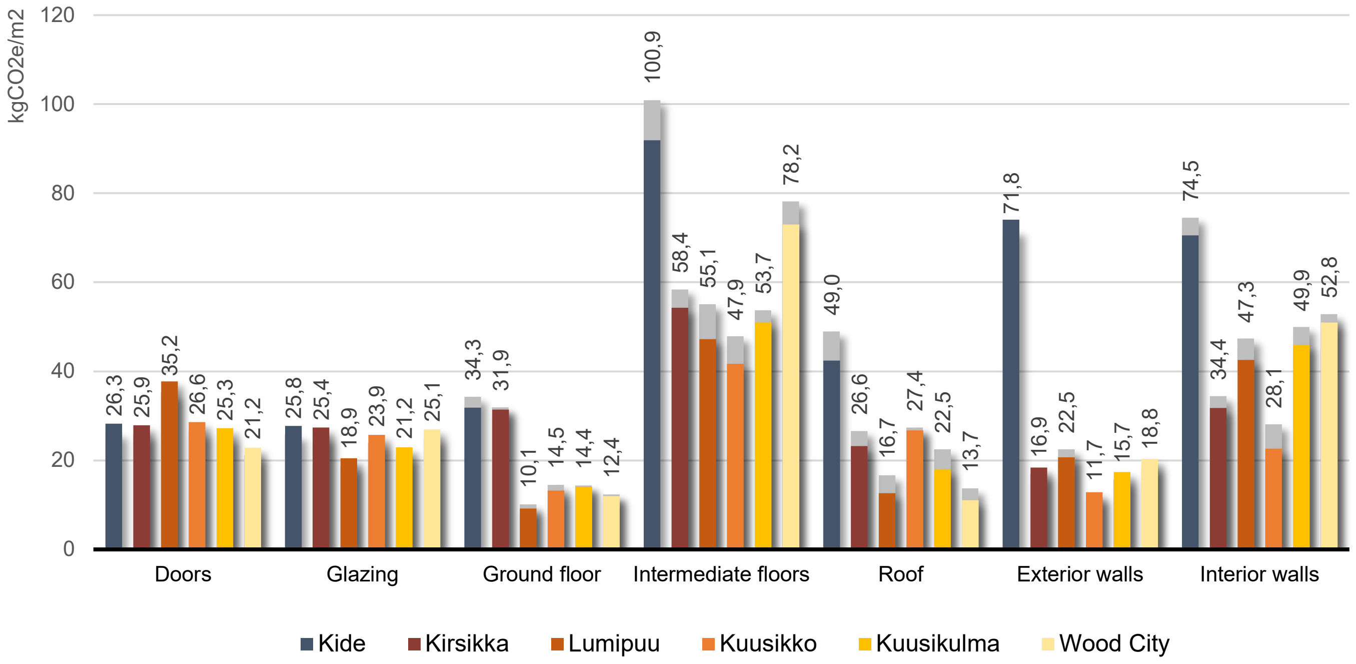

Figure 10. Embodied emissions by structural category and building components during a 50-year assessment period. Emissions caused by material replacements are shown in grey. Elevators, stairs, building services, transportation and construction processes are excluded from the figure.

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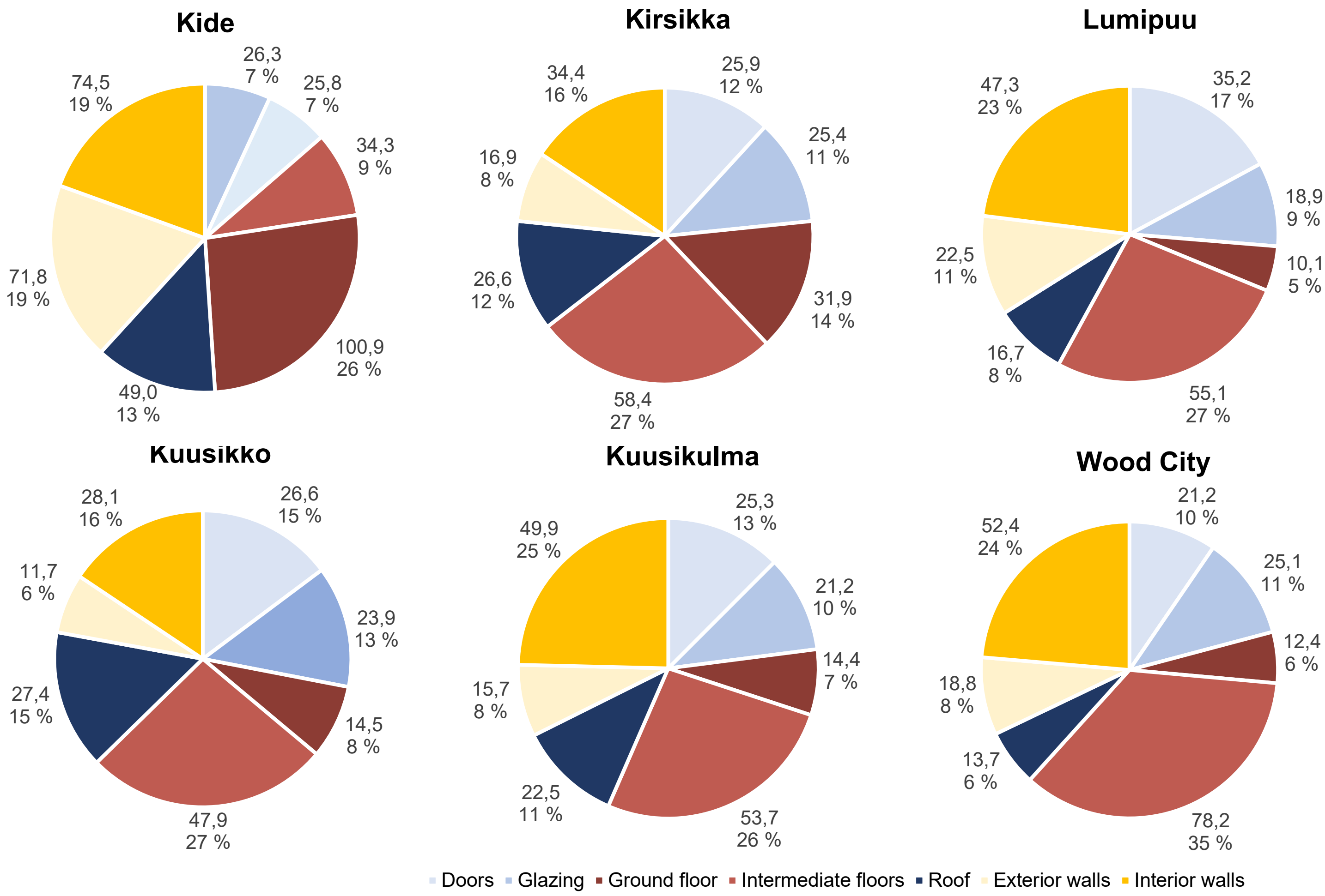


Figure 11. Share of embodied emissions by structural category and building components during a 50-year assessment period. Elevators, stairs, building services, transportation and construction processes are excluded from the figure.

Comparative assessment of structural solutions

This section compares the embodied emissions of the characterizing structural solutions for the five timber buildings. The base floors under apartments, intermediate floors between apartments, intermediate walls between apartments and between apartments and corridors, and exterior walls of apartments from the selected cases were assessed to demonstrate how timber has been used in the structures and how the different structural solutions influence the embodied emissions.

In Wood City, where various types of exterior walls were used, the one selected for the comparison is the load-bearing exterior wall. Figure 12 illustrates the emission per 1 m2 of each structure until practical completion (Module A), while Table 4 provides cross-sections of each structure, emissions for individual material layers, the overall carbon footprint, and the carbon handprint for each structure.

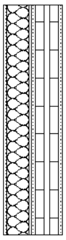
Horizontal structures exhibit, in general, higher emissions than vertical structures. When comparing base floors, concrete slab-on-grade structures can have over double the emissions (ranging from 62,3-112,8 $kgCO_2e/m^2$) of suspended timber structures (46,5-52,4 $kgCO_2e/m^2$). It is important to note that these calculations exclude foundations and groundworks. Therefore, it is worth acknowledging that unfavorable site conditions for suspended timber base floors can

Table 4. Selected structural solutions and their total carbon footprint and carbon footprint per material layer ($kgCO_2e$) per 1 m^2 of the structure until practical completion (Module A) and carbon handprint per 1 m^2 of the structure. Material replacements have not been included in the table but layers that would need to be replaced once during a 50-year assessment period are marked with an asterisk (*).

Intermediate wall between apartment and corridor

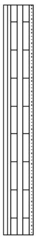
Kirsikka

Gypsum	4,6
CLT	9,9
Gypsum	4,6
Timber	0,3
Mineral wool	4,1
Gypsum	3,9
Footprint	**27,5**
Handprint	**-83,8**



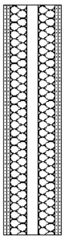
Lumipuu

Gypsum	7,7
CLT	7,9
Gypsum	4,6
Footprint	**20,2**
Handprint	**-62,4**



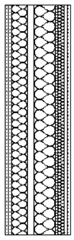
Kuusikko

Gypsum	6,1
Timber	1,0
Mineral wool	8,0
Gypsum	6,1
Footprint	**21,1**
Handprint	**-15,5**



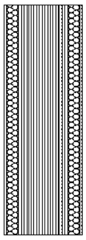
Kuusikulma

Gypsum	6,6
Timber	0,2
Mineral wool	3,0
Timber	0,3
Mineral wool	4,0
OSB board	2,4
Timber	0,1
Mineral wool	1,3
Gypsum	6,6
Footprint	**24,5**
Handprint	**-19,7**



Wood City

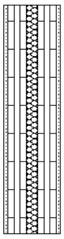
Gypsum	2,8
Timber	0,2
Mineral wool	2,1
Gypsum	3,9
LVL	27,2
Gypsum	3,9
Timber	0,2
Mineral wool	2,1
Gypsum	2,8
Footprint	**45,2**
Handprint	**-127,7**



Intermediate wall between apartments

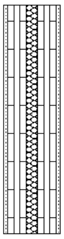
Kirsikka

Gypsum	4,6
CLT	7,9
Mineral wool	2,3
CLT	7,9
Gypsum	4,6
Footprint	**27,3**
Handprint	**-120,3**



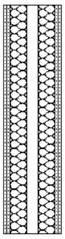
Lumipuu

Gypsum	4,6
CLT	7,9
Mineral wool	2,3
CLT	7,9
Gypsum	4,6
Footprint	**27,3**
Handprint	**-120,3**



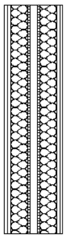
Kuusikko

Gypsum	6,1
Timber	1,0
Mineral wool	8,0
Gypsum	6,1
Footprint	**21,1**
Handprint	**-15,5**



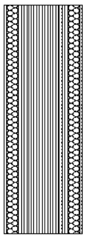
Kuusikulma

Gypsum	5,9
Timber	0,3
Mineral wool	4,0
OSB board	4,8
Mineral wool	4,0
Gypsum	5,9
Footprint	**22,2**
Handprint	**-27,7**



Wood City

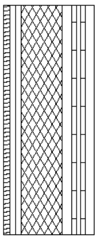
Gypsum	2,8
Timber	0,2
Mineral wool	2,1
Gypsum	3,9
LVL	27,2
Gypsum	3,9
Timber	0,2
Mineral wool	2,1
Gypsum	2,8
Footprint	**45,2**
Handprint	**-127,7**



Exterior wall of apartments

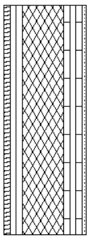
Kirsikka

Timber	1,7
Mineral wool	17,0
CLT	13,8
Footprint	**32,4**
Handprint	**-137,8**



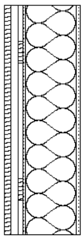
Lumipuu

Timber	1,7
Mineral wool	17,0
CLT	7,9
Gypsum	4,6
Footprint	**31,2**
Handprint	**-91,0**



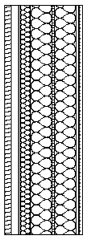
Kuusikko

Timber	1,5
Gypsum	2,5
Timber	0,8
Mineral wool	9,4
Gypsum	2,8
Footprint	**17,0**
Handprint	**-39,6**



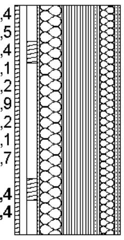
Kuusikulma

Timber	1,2
Gypsum	2,5
Timber	0,5
Mineral wool	6,1
OSB board	2,4
Timber	0,3
Mineral wool	4,0
Gypsum	2,7
Vapour barrier	0,5
Gypsum	3,9
Footprint	**24,2**
Handprint	**-63,3**



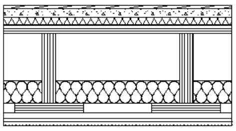
Wood City

Timber	1,4
Gypsum	2,5
Timber	0,4
Mineral wool	4,1
LVL	27,2
Gypsum	3,9
Timber	0,2
Mineral wool	2,1
Gypsum	5,7
Footprint	**47,4**
Handprint	**-154,4**



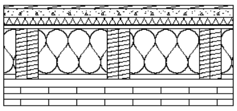
Intermediate floor between apartments

Kirsikka



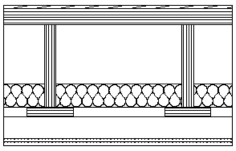
Laminate flooring*	12,8
Floor screed	19,7
Mineral wool	1,4
Ribbed LVL	18,2
Mineral wool	4,2
Acoustic studs	4,7
Gypsum	7,7
Footprint	**68,7**
Handprint	**-80,4**

Lumipuu



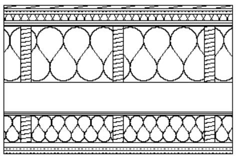
Laminate flooring*	12,8
Floor screed	19,7
EPS insulation	1,7
OSB board	4,8
Timber	2,4
Mineral wool	6,9
Timber	0,2
CLT	7,9
Footprint	**56,6**
Handprint	**-125,8**

Kuusikko



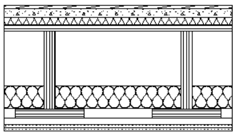
Laminate flooring*	12,8
Gypsum	9,4
Ribbed LVL	14,6
Mineral wool	2,8
Acoustic studs	4,7
Gypsum	7,7
Footprint	**58,1**
Handprint	**-64,1**

Kuusikulma



Laminate flooring*	12,8
Gypsum	5,5
Mineral wool	2,5
Chipboard	7,6
Timber	1,3
Mineral wool	9,9
Steel net	2,0
Chipboard	7,6
Timber	0,6
Mineral wool	4,9
Timber	0,1
Gypsum	6,6
Footprint	**61,8**
Handprint	**-86,3**

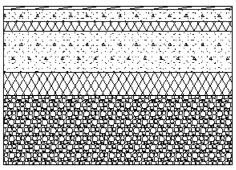
Wood City



Laminate flooring*	12,8
Floor screed	19,7
Mineral wool	1,4
Ribbed LVL	17,8
Mineral wool	4,2
Acoustic studs	4,7
Gypsum	7,7
Footprint	**68,3**
Handprint	**-78,3**

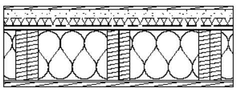
Base floor underneath apartment

Kirsikka



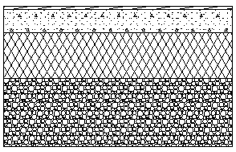
Laminate flooring*	12,8
Floor screed	25,4
EPS insulation	2,5
RC	63,5
EPS insulation	5,8
Gravel	3,2
Footprint	**112,8**
Handprint	**-11,7**

Lumipuu



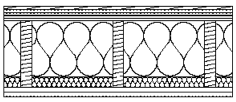
Laminate flooring*	12,8
Floor screed	19,7
EPS insulation	1,7
Vapour barrier	0,5
OSB board	4,8
Timber	2,4
Mineral wool	7,6
Gypsum	2,5
Timber	0,3
Footprint	**52,4**
Handprint	**-64,7**

Kuusikko



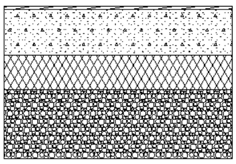
Laminate flooring*	12,8
RC	34,9
EPS insulation	11,5
Gravel	3,2
Footprint	**62,3**
Handprint	**-5,6**

Kuusikulma



Laminate flooring*	12,8
Gypsum	5,5
Vapour barrier	0,5
Chipboard	7,6
Timber	1,4
Mineral wool	11,7
Steel net	2,0
Timber	0,1
Gypsum	4,9
Footprint	**46,5**
Handprint	**-54,1**

Wood City



Laminate flooring*	12,8
RC	71,0
EPS insulation	8,7
Gravel	3,2
Footprint	**95,6**
Handprint	**-10,9**

make concrete solutions more favorable from the emissions point of view. Although emissions from the site are likely to be excluded from the Ministry of the Environment's future limit values, they should be considered in the design, since they can have a significant impact on the true carbon footprint (Bionova, 2021).

When comparing the three different wall structures, the LWT structures generally exhibit lower carbon footprints than the massive CLT or LVL structures when assessing 1 m^2 of wall surface area. The sole exception is the very simple CLT intermediate wall separating apartments and corridors in Lumipuu, which displays the lowest emissions in its category. The massive LVL structures, on the other hand, have significantly higher emissions compared to the CLT structures. When comparing the emissions of 1 m^2 of selected structural solutions across different projects, the floor or wall structure option with the lowest emission can result in up to a 64% reduction compared to the most carbon-intensive option.

When comparing structures, it is essential to include fire, sound, and energy-efficiency requirements, as materials required (such as gypsum, floor screed, acoustic studs, insulation, etc.) to meet these specifications lead to significantly higher emissions compared to structural components alone. This is particularly evident when studying the intermediate floors in Table 4, where the structural components in the intermediate floors stand for a minority of the emissions. The share of emissions produced by structural components is a minority in all selected timber-based wall and floor structures except for the massive LVL walls in Wood City.

Adding mass to intermediate floors with gypsum instead of cement-based floor screed lowers the emissions of the structure. The gypsum has in this case 52-72% lower emissions than the screed.

Timber-based structures, particularly intermediate floors, are more complex compared to conventional concrete structures. The timber structures have more material layers and a wider variety of materials. Therefore, when striving to minimize emissions, it is advisable to prioritize the layers and materials with the greatest decarbonization potential. These include surface materials, floor screed, gypsum, and insulation. Additionally, the choice of manufacturer can significantly impact emissions. A study conducted by Skaar et al. in 2017, focusing on timber-based intermediate floors, highlighted that emissions of a structure can vary considerably depending on the selected manufacturers. Opting for products from manufacturers that report high GWP for their products can lead to a structure with more than four times higher emissions than a structure where similar products are chosen from manufacturers that report the lowest GWP values.

Carbon balance

The carbon balance for the different buildings is as follows: Kide demonstrates 17,34 $kgCO_2e/m^2/yr$ Kirsikka 10,96 $kgCO_2e/m^2/yr$, Lumipuu 9,08 $kgCO_2e/m^2/yr$, Kuusikko 10,41 $kgCO_2e/m^2/yr$, Kuusikulma 10,40 $kgCO_2e/m^2/yr$ and Wood City 10,57 $kgCO_2e/m^2/yr$, as seen in Fig. 13. The carbon balance is significantly lower for the timber buildings compared to the RC building. The potential positive climate impacts (handprint) relative to negative climate impacts (footprint) are higher for the buildings with CLT or massive LVL structures. For example, in the case of Lumipuu, the size of the handprint constitutes 39,1% of the footprint, while it accounts for 30,8% in Kirsikka and 30,2% in Wood City. Regarding the LWT structures, the size of the handprint in relation to footprint for Kuusikko is 26,4% and for Kuusikulma 24,6%. If considering only embodied emissions and the potential climate benefits that are due to materials, we achieve a balance

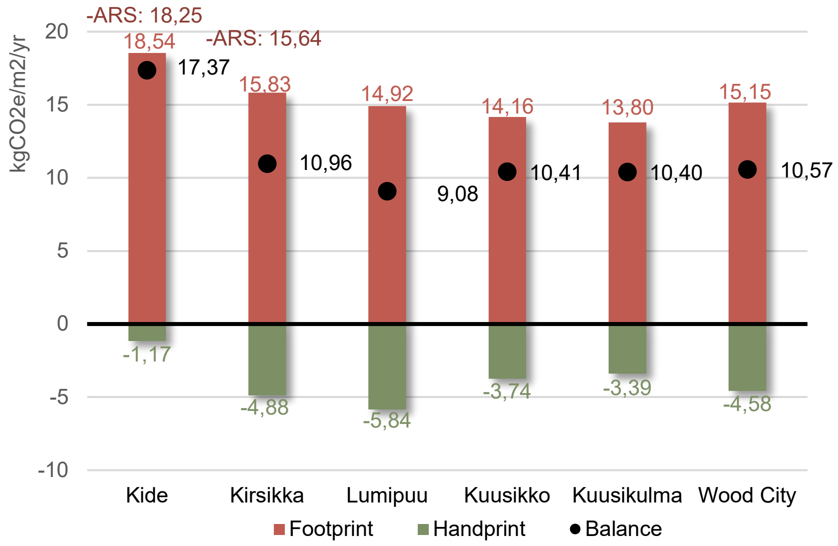


Figure 13. Carbon footprint, carbon handprint and balance of all selected case studies (A1-5, B4, B6, C1-5, D1-5). The carbon footprint without the air raid shelter is marked with -ARS.

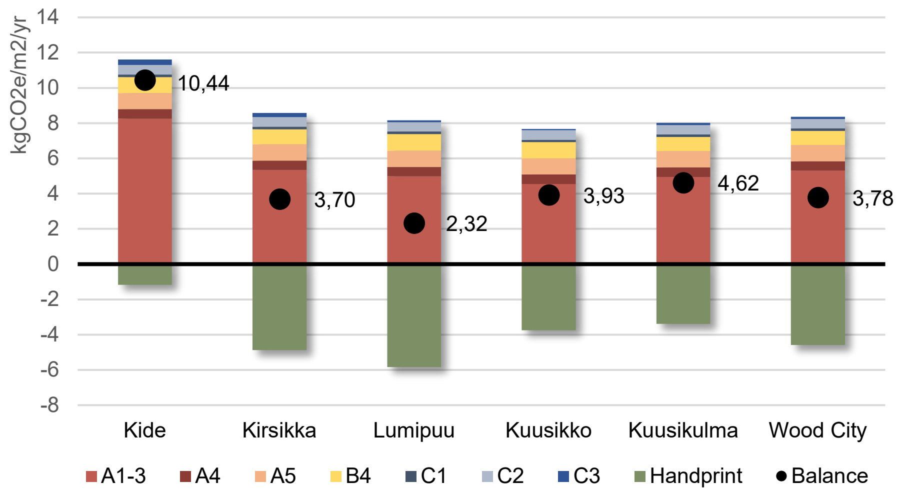


Figure 14. Embodied carbon by life cycle module, material-related carbon benefits and the carbon balance of all selected case studies (A1-5, B4, C1-5, D1-5).

closer to zero. In this case, the balance of Kide is 10,44 while it ranges between 2,32 and 4,62 kgCO_2e/m^2/yr for the timber buildings (Fig. 14).

However, it is important to note that the carbon balance of all the case studies is far from zero. Although the timber case studies exhibit smaller carbon footprints compared to conventional buildings and effectively store carbon through the use of timber, the substitution of concrete in load-bearing structures with timber alone is insufficient to meet national climate goals. There remains a need to develop structural solutions that enable the reduction of emissions stemming from carbon-intensive materials commonly used in multi-story timber buildings today, including conventional gypsum, mineral wool, EPS insulation, concrete, and steel.

This study shows that increasing the use of wood contributes positively to the carbon balance on a *building level*. However, it is important to understand that *on a national or global level, the impact on the carbon balance can be the opposite of that on a building level*. This can be the case, for example, if we increase timber construction by increasing logging. Increased logging negatively impacts the carbon sinks, and this negative impact is bigger than the avoided emissions from substituting conventional concrete with timber (Soimakallio *et al.*, 2021). This emphasizes the importance of resource efficiency and why carbon neutrality should always be primarily pursued by reducing the carbon footprint. However, in this study, the carbon handprint is assessed at the building level, as it is done in the method developed by the Ministry of the Environment Finland, and the carbon balance is reported at a building level because carbon-neutral and low-carbon buildings are widely discussed at the moment, and many aiming for ecological construction strive towards these goals. Nevertheless, the carbon balance reported on a building level, especially when it comes to biogenic carbon, should be approached with great caution as it may be misleading.

Identified barriers

Strict regulations, particularly those concerning acoustics and fire safety, have been identified as barriers to mainstreaming multi-story timber construction (Vihemäki *et al.* 2019, Maniak-Huesser *et al.* 2021, Wiegand and Ramage 2022). In Finland, to date, double safety measures mitigate the risk of fire in residential multi-story timber buildings. However, the fire regulations increase the embodied emissions of timber buildings since they increase the use of carbon-intensive gypsum and require the installation of sprinkler systems. The emissions associated with the sprinkler system, including maintenance during a 50-year assessment period, are estimated at 0,12 $kgCO_2e/m^2/yr$ (CO2data 2024).

The strict fire regulations in Finland also prohibit the use of bio-based low-carbon thermal insulation in multi-story timber buildings. Allowing the substitution of mineral wool with wood fiber insulation would enable emission reductions, especially in LWT-structured buildings, where more insulation is needed than in CLT or LVL buildings where massive timber provides some additional insulation. As an illustrative example, replacing the mineral wool with wood fiber in LWT-structured Kuusikulma, where the use of thermal insulation is the highest, would reduce the emissions of insulation by 56%. Simultaneously, the overall embodied emissions of the building would decrease by 4,8%, and the building's carbon handprint would increase by 20%. While acknowledging the importance of fire safety, these numbers prompt a discussion on whether very strict regulations should be reconsidered in the case of residential multi-story timber buildings, given the potential for significant emission reductions and reduced reliance on non-renewable raw materials.

Furthermore, research by Andersson et al. (2018) identified sound regulations as a prominent barrier to reducing embodied emissions in residential multi-story buildings in Sweden. The Finnish sound regulations for multi-story buildings are among the strictest in Europe, surpassing even those in Sweden (Rasmussen 2019). Compliance with sound regulations often requires the addition of mass, which typically involves concrete or gypsum. These sound regulations impact especially intermediate floors and walls, which together contribute to 43-59% of the embodied emissions from the construction materials in the five Finnish timber case buildings and 34% of the embodied emissions in the study by Andersson et al.

Conclusions

This study has assessed the carbon impacts of five residential multi-story timber buildings that use different timber-based structural frames. The results have been compared to those of a conventional concrete building and national climate goals. This study set out to present, evaluate, and discuss the LCA results from selected case buildings, and to identify materials and structures with the highest potential for emission reduction.

Given that the study only considers five timber apartment buildings and one concrete building, caution should be exercised when generalizing the results, especially due to the wide range of practices in timber construction, which are still evolving. As this examination is based on publicly available permit documents rather than the latest construction drawings, there is no guarantee that the buildings have been constructed exactly as assumed in this study. However, LCA will become obligatory when applying for a permit, which justifies the use of permit drawings in this study. Nevertheless, the study provides a good understanding of the emissions associated with multi-story timber apartment buildings. It is also worth noting that the assessment was done according to the method published by the Ministry of the Environment in 2021, and there is no guarantee that this will be the method implemented with the forthcoming legislative changes. The calculation method will likely be further updated. Nonetheless, the study is timely and relevant, as it emphasizes the structural elements and material layers of timber apartment buildings that should be further developed when aiming for carbon neutrality.

The key findings of this study are as follows:

- Current timber construction practices are insufficient to meet current climate goals.
- Further development of structures commonly used in residential multi-story timber buildings is necessary.
- Embodied emissions outweigh operational emissions and account for 54-58% of total emissions in the timber buildings over a 50-year assessment period.
- Structural timber contributes only 11-16% of total embodied emissions in selected timber buildings.
- Intermediate floors represent the biggest share, 26-35%, of emissions related to the production of construction materials in the timber buildings, followed by intermediate walls (16-25%), the roof (6-15%), base floors (5-14%), exterior walls (6-11%), doors (10-17%) and windows and balcony glazing (9-13%)
- Using concrete structures instead of timber structures in multi-story timber buildings significantly increases the embodied emissions.
- Suspended timber floors used in the cases built with volumetric elements have 16-59% lower emissions than concrete base floors.
- The LWT cases, both panel and volumetric, exhibit 2,5-11,7% lower embodied emissions compared to those cases that are based on the use of CLT or LVL.
- Adding mass to intermediate floors with gypsum boards instead of cement-based floor screed lowers the emissions. The gypsum has 52-72% lower emissions than the floor screed.
- Surface materials requiring replacement every 30 years contribute 19-27% of embodied emissions over a 50-year assessment period, emphasizing the preference for low-carbon surface materials with extended service lives.
- The share of embodied emissions from gypsum is higher in the LWT projects (15-16%) than in the CLT or LVL projects (7-9%), with gypsum contributing more emissions than structural timber in LWT projects.
- Steel-structured bathroom modules have much higher embodied emissions than timber-structured bathrooms.
- Comparative analysis of 1 m^2 of selected structural options in different projects, the floor or wall structure with the lowest emission can have up to 64% lower emissions than the most carbon-intensive option.
- Strict sound and fire regulations are prominent barriers to reducing embodied emissions in residential multi-story timber buildings.

The findings from this research offer valuable insights and practical implications for various stakeholders:

1. **Policymakers:** The research results highlight the inadequacy of current timber construction practices in meeting climate goals. Policymakers can use this information to reevaluate and strengthen regulations and incentives for sustainable construction practices. It underscores the importance of considering embodied emissions in building regulations and promoting the use of low-carbon materials.
2. **Architects and engineers:** Architects and engineers involved in the design of residential multi-story timber building projects can benefit from the research since it helps them make informed decisions. Additionally, it highlights structures that need further innovation.
3. **Construction industry:** The construction industry can use these findings to guide the development of new technologies and construction methods that reduce embodied emissions in multi-story timber construction. The findings emphasize the need for the industry to invest in research and development to create more sustainable building solutions.
4. **Clients and users**: Individuals and companies interested in building, purchasing, or living in residential multi-story timber buildings can use the information to make environmentally conscious choices.
5. **Manufacturers and suppliers**: Manufacturers of construction materials can innovate and produce low-carbon alternatives to meet the growing demand for sustainable building materials. Suppliers can promote these materials to builders and architects.

The research's innovative contribution to the existing literature lies in its comprehensive analysis of the carbon footprint of residential multi-story timber buildings. In summary, the research findings not only underscore the need for change in current construction practices but also provide actionable insights for achieving more sustainable and environmentally friendly multi-story timber buildings.

Suggested future research

As the results indicate, the majority of emissions from timber multi-story buildings are generated by components other than wood. Therefore, it is crucial to investigate novel solutions and material combinations that could reduce emissions from these buildings. It is particularly important to find solutions that reduce or eliminate the need to use carbon-intensive floor screeds and gypsum that now account for 24-32% of the embodied emissions. Additionally, the author suggests looking into the potential of bio-based low-carbon insulation materials, many of which are carbon-negative, to replace conventionally used insulation materials that produce 6-16% of the embodied emissions.

Moreover, questioning existing building regulations is relevant, but even more essential is developing structural solutions that can achieve fire safety, and pleasant acoustics while keeping emissions in check. Finding new and effective solutions for the intermediate floor structures in timber multi-story buildings is of particular importance.

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