Finnish mid-rise timber apartment buildings: Architectural, structural, and constructional features

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Abstract

Timber apartment buildings are becoming more common in Finland in the form of mid-rise buildings. This study examined data from 55 Finnish mid-rise timber apartment buildings built between 2018 and 2022 under the Finnish Land Use and Building Act, which came into force on 1 January 2018. The study aims to increase the understanding of contemporary practices, potential, benefits, challenges, and future prospects of mid-rise timber apartment buildings in Finland. The data was collected through literature surveys and case studies to examine the architectural, structural, and constructional features. The main findings of this study indicated that (1) shear wall structural system was the only structural system, (2) the most preferred construction method was 3D volumetric construction, followed by 2D panel construction, (3) among the 55 case buildings, solid timber studs (i.e., lightweight timber frame walls) were the most used material for shear walls, followed by cross-laminated timber (CLT), (4) the prevalence of specific structural materials varied depending on the construction method and the number of stories. CLT and laminated veneer lumber (LVL) were

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utilized in 7- and 8-story buildings, and there was no shear wall at these heights, consisting only of solid timber studs, (5) all case-study buildings had a prismatic (i.e., extruded) form, (6) the most dominant core typology was peripheral core (>50%) with 28 cases, followed by a central core with 24 cases, (7) case studies built using the 2D panel construction method had significantly longer maximum lease span and the average of the maximum lease span, (8) case studies built with 2D panel construction method had higher average floor-to-ceiling and floor-to-floor heights, (9) the average total thickness of intermediate floors and party walls between apartments was similar for both 2D panel and 3D volumetric construction methods. Regarding the thickness of party wall structural material, the thickness of CLT had the most repetitions, followed by solid timber studs, (10) while certain buildings had walls with identical structural thicknesses, there were variations in the total thickness of the walls among them. The research also delves into the interrelations between the selected parameters and the construction methods employed.

Keywords: timber, timber apartment buildings, mid-rise, architectural features, structural system, construction method, Finland

Introduction

Timber apartment buildings are becoming more common in Finland in the form of mid-rise buildings. Especially over the past few years, the number of timber apartment buildings has seen an increase (Tulonen, L., 2020; The Finnish Timber Council, 2023), but still leaving behind the estimated growth of the industry. Timber is increasingly being used in multi-story timber buildings in the world and Finland due to technical and environmental features. According to the European Union's environmental program, timber construction is recognized as one of the key strategies for reducing carbon dioxide emissions in the construction industry.

The need for new construction due to population growth and migration caused by urbanization will consume up to 30-65% of the available carbon budget by 2050 (Rockström et al., 2017). In addition, Finland intends to promote the construction of wooden apartment buildings to achieve carbon neutrality goals by 2035 (Ministry of the Environment, 2022).

On the way to low-carbon construction, different procedures include incentives as well as tightening the requirements of legislation (Ilgın et al., 2022, European Union's environmental program). The National Building Code of Finland in 2011 incorporated a fire code that permits the construction of mid-rise timber apartment buildings (ranging from 3 to 8 stories).

It's crucial to note that the year 2018 marked the start of case study selection due to a new fire regulation. This rule allows up to 20% exposure of wooden surfaces in structural timber walls, fire department walls, and ceilings with R60 fire resistance. If raised to R90, 80% exposure is permitted. This has reduced the need for protective cladding, like gypsum board, on these surfaces since 2018. These provisions allow for the standard practice of applying for a building permit (The National Building Code of Finland, 2017). Despite the relief, Finland has strict fire and building regulations compared to Sweden or Norway (Maniak-Huesser et al., 2021).

Engineered wood products (EWPs) are a category of wood-based materials that are specifically engineered and manufactured to possess enhanced properties and performance characteristics. These products are created by bonding or assembling wood fibers, strands, veneers, or particles together using adhesives, resins, or other bonding agents. The manufacturing process of EWPs allows for improved dimensional stability, strength, and uniformity compared to traditional wood products. These products can be tailored to meet specific design and performance requirements, making them highly versatile for various applications in construction.

CLT is an EWP composed of multiple layers of solid lumber boards that are stacked in alternating directions and bonded together with adhesives. This manufacturing process creates a panel with enhanced strength, dimensional stability, and structural integrity. The panels are commonly fabricated in large sizes and can be used as load-bearing elements in walls, floors, and roofs, offering a sustainable and efficient alternative to traditional construction materials. CLT is known for its good strength-to-weight ratio, which has allowed large-scale and taller buildings to be constructed (Tulonen et al., 2021). It has excellent physico-mechanical properties due to its laminated structure, and it is most often used in wall or floor panels due to its high stiffness and in-plane and out-of-plane bearing capacity (Jeleč et al., 2017).

LVL is a type of EWP that is constructed by bonding thin layers of wood veneers together with adhesive. The veneers are typically oriented parallel to each other to create a strong and durable material. LVL is known for its consistent and uniform properties, including high strength and dimensional stability. It is commonly used as a versatile structural component in building construction, such as beams, headers, and columns, where its superior load-bearing capacity and resistance to warping or twisting are advantageous. LVL is an EWP that can withstand more technically demanding and legislative conditions (Hurmekoski et al., 2015). LVL is a relatively new material for the apartment sector. However, significant investments were made in the production of LVL for timber apartments in 2016 (Lazarevic et al., 2020). Compared to concrete, LVL has similar compressive strength parallel to the grain (Evison et al., 2018).

Finnish timber apartment buildings are mainly built as mid-rise (3-8 story) buildings (The Finnish Timber Council, 2023). Most of these mid-rise timber apartment buildings are built with solid timber stud walls (i.e., lightweight timber frame walls), followed by EWPs (The Finnish Timber Council, 2022a). The prevalence of solid timber stud walls may be due to their familiarity based on traditional wood construction practices. EWPs are increasingly being used as structural materials to increase sustainable construction (Karjalainen and Ilgın, 2021). The recent development of EWP technology in terms of strength and fire safety makes these products competitive against concrete and steel construction in mid-rise timber apartment buildings.

Timber, as a renewable resource, demands a very low amount of energy for extraction and manufacturing compared to conventional construction materials, and prefabricated CLT buildings can be assembled with low noise, low dust, and minimal on-site waste, offering environmentally friendly construction solutions (Harte, 2017). Timber materials are highly suitable for factory-based prefabrication, enabling the production of 2D panel elements and 3D volumetric units that can be transported to the construction site and lifted with relative ease, primarily owing to their lightweight nature. According to the study conducted by Ilgın et al. (2021b), the key advantages of wood over concrete, as perceived by respondents, include its lightweight nature, ecological properties, local availability, and low environmental impact. These favorable environmental characteristics were highlighted as the primary reasons for choosing wood in residential projects. The environmental advantages arising from the post-utilization handling of end-of-life materials are substantial, especially in terms of energy recovery from CLT and wood-based materials (Al-Najjar & Dodoo, 2023).

This study examined data from 55 of 62 Finnish mid-rise timber apartment buildings built between 2018 and 2022 under the Finnish Land Use and Building

Act. The sample group in this study included nearly 90% of the buildings constructed within the designated timeframe. During that time, 43% of all existing Finnish timber apartment buildings were built since 1996 (Karjalainen & Ilgın, 2021). During the specified timeframe, there were no noteworthy modifications made to the building code regarding timber construction.

The scope of the study was limited by the available data. In Appendix A, general information about the case studies was provided: building name, city, completion year, building height, and number of stories. Additionally, Appendix A supplies details regarding the structural material, thicknesses of structural components, and the overall thickness of shear walls for each case study. In this paper, the following structural design considerations were examined (1) structural system and (2) structural material. Architectural design considerations included: (1) form; (2) core typology; (3) floor-to-floor height and floor-to-ceiling height; and (4) lease span. Construction methods were also examined: (1) 2D panel construction and (2) 3D volumetric construction.

During the initial phases of a project, the principal designer, often the architect, should possess the essential expertise required to design the preliminary plans that align with the appropriate space requirements, enabling precise calculations of space efficiency (The Finnish Timber Council, 2022). The space requirements include horizontal and vertical structures, and thus, this study also considers the total thicknesses of typical wall and floor structures.

The current body of literature lacks an in-depth analysis of the architectural, constructional, and structural design aspects specific to mid-rise timber apartment buildings. Furthermore, there is insufficient research on the main vertical structural material and combinations of material types (such as solid timber stud + EWPs) used in shear walls within mid-rise timber apartment buildings with different heights and construction methods (Svatoš-Ražnjević et al., 2022). Moreover, there is also a lack of comparison of lease span, as well as the total thickness of the shear walls and intermediate floors in mid-rise timber apartment buildings constructed with the 2D panel construction method and 3D volumetric construction method. In addition, there was a lack of a precise classification related to structural systems and construction methods.

This study addresses these research gaps in the existing literature by examining the interrelations between the construction method and the selected parameters shown in figure 8, focusing on Finnish mid-rise timber apartment buildings, which represent the prevalent type of multi-story timber apartment buildings in the country. Through extensive case studies, the research enriches design guidelines for developers, architects, and structural engineers. It provides valuable contemporary data on design considerations and highlights crucial structural, architectural, and constructional features of mid-rise timber apartment buildings.

The remainder of this work is structured as follows: First, a literature review is presented. This is followed by a description of the research methods used. After this section, the findings based on 55 case studies are provided. Finally, the conclusions and discussion are given.

2. Literature review

Many studies carried out on the technical, environmental, societal, and financial features of EWPs in numerous building systems (Ilgın & Karjalainen, 2021). In addition, the current scientific literature on multi-story wooden buildings mainly is about technical, acoustic (Caniato et al., 2021), structural (Voulpiotis et al., 2021), or energy (Karjalainen et al., 2021a), and sustainability issues (Karjalainen et al., 2021b; Rinne et al., 2022). However, limited studies are focusing on the planning and structural aspects of multi-story wooden structures (Ilgın et al., 2022). The following literature review analyzes case study-based studies including planning and structural features of multi-story and tall timber buildings.

González-Retamal et al. (2022) reviewed over 250 academic papers indexed in the Web of Science between 2017 and mid-2022, examining the main developments and boundaries in the planning and implications of multi-story wooden buildings and classifying them from features such as sustainability, design, and engineering sciences. The results proved that most of the papers (>70%) showed innovations and constraints corresponding to the engineering disciplines, about 25% to sustainability, and nearly 5% to collaborative design. The major developments in multi-story wooden structures relate to earthquake studies, connection design, and fire safety issues.

Santana-Sosa & Kovacic (2022) evaluated the current state of the planning and implementation procedures of wooden structures in Austria through 15 expert interviews. The interview highlighted barriers and potentials, and formulated suggestions to increase the adoption of wood in multi-story buildings. Findings were structured in the classifications of planning and manufacture, construction, and further classified as obstacles and prospects to serve as a manual for more research and activities to popularize timber adoption.

Ilgın et al. (2022) examined 13 international tall timber residential buildings, considering architectural, structural, and constructional aspects. The results showed that: (1) a centrally located core was the favored core arrangement; (2) prismatic forms were extensively employed; (3) the average floor-to-floor height was 3 m; (4) the use of pure wood was higher than for hybrid construction; (5) shear wall system was the most frequently employed structural system; and (6) in general, the fire resistance of primary structural members exceeded the minimum duration detailed in the related standards.

Svatoš-Ražnjević et al. (2022) presented a review of architectural diversity and spatial opportunities in multi-story timber construction using data from 350 contemporary case studies. The study resulted mainly in the categorization of design schemes into four load-bearing system clusters and four material classes.

Žegarac Leskovar & Miroslav (2021) examined the architectural and structural design approaches of European multi-story wooden buildings by examining 32 cases built between 2007 and 2021. The results indicated that the change in architectural design, especially in the building exterior, and the transition from a solid panel to a composite load-bearing system are evident. There are also distinct variations in structural and energy efficiency design, strengthened by position and seismic and climatical attributes.

A comparison of the architectural, energy, and structural design characteristics of the selected structures reveals the major design modifications according to the regional geographic framework. Salvadori (2021a; 2021b) conducted a comparative study of over 190 multi-story timber buildings, identifying geographic variations in the properties of multi-story wooden buildings. Salvadori's study (2021a) was an excerpt from the thesis (Salvadori, 2021b) presented entirely on structural classification, whereas Salvadori (2021b) presented a more comprehensive overview of multi-story timber buildings with the inclusion of assessment of specific building elements, such as exterior cladding.

Tupenaite et al. (2019) examined the tallest modern wooden buildings in terms of financial and ecological efficiency. This indicated that taller wooden buildings are both financially and ecologically more efficient owing to the use of lightweight contemporary EWPs. In addition, the prefabricated building components reduce the project time and cost.

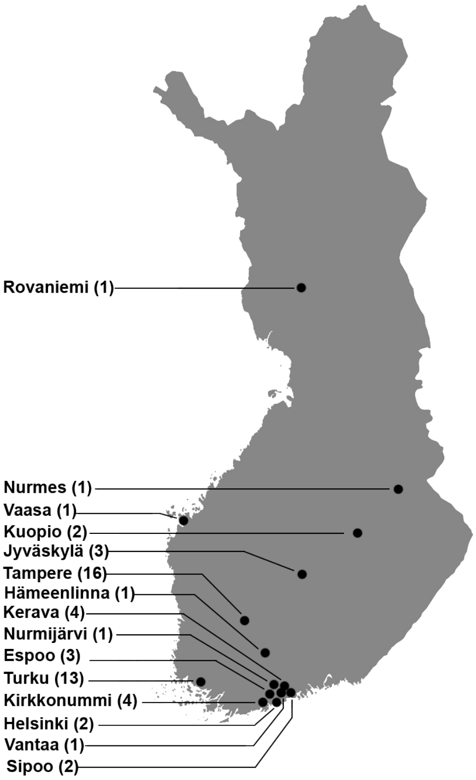


Figure 1. Case studies in the map of Finland.

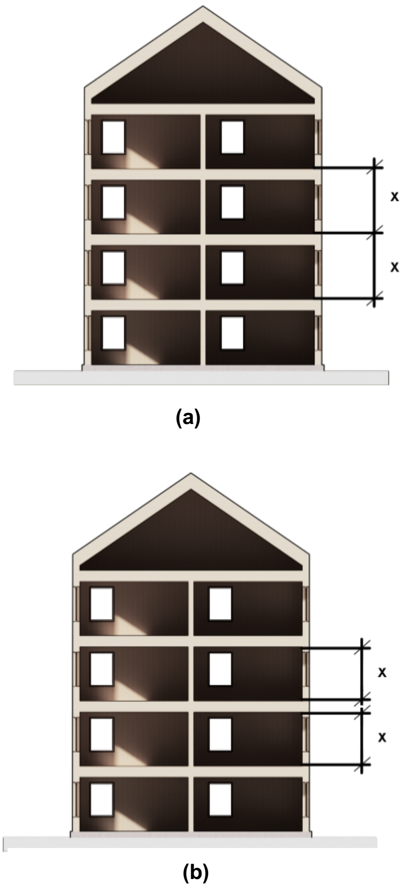


Figure 2. (a) floor-to-floor height; (b) floor-to-ceiling height.

Kuzmanovska et al. (2018) researched emerging trends for high-rise wood applications regarding structure, façade, and architectural mass by examining 46 (non-) residential multi-story buildings, particularly regarding their design and artistic features. These primarily include load-bearing systems, façade systems, and manufacturing methods. Some of the highlights were (a) boosted use of CLT floor slabs and post and beam structures, (b) reduced use of structural exterior walls, and (c) the predominance of linear plans and regular extrusions. Salvadori (2017) scrutinized 40 case study buildings (7-story and above) with their load-bearing system and structural material, building envelope system, and some fire issues to compare other solid wood structures with a similar reinforced concrete structure.

Public recognition of wood was emphasized as a barrier rather than a technological barrier to realizing taller wooden buildings. According to the findings of Smith et al. (2015), the primary advantages of information and off-site massive timber manufacture include improved pace of construction, climatic variability, access to suitable raw materials, and carbon reduction. Conversely, the main disadvantages identified in the study encompass logistical challenges, design considerations, sound quality issues, and vibration concerns.

Perkins & Will (2014) surveyed 10 case studies of wood with five or more floors. In combination with the survey cited above, Holt and Wardle's research (2014) outlined the market perspective and justification for the utilization of tall wooden construction. The results emphasized that employing timber in constructing taller buildings is a viable method, which has the potential to significantly mitigate the negative effects of the constructed environment.

Based on the comprehensive review of existing literature, previous studies have primarily concentrated on investigating the architectural aspects of multi-story or tall timber buildings. Our analysis of the existing literature unveiled a lack of precise terminology and comprehensive categorizations regarding structural systems, construction methods, and structural materials (Duncheva et al., 2019; Tulonen et al., 2021; Hurmekoski et al., 2015; Leskovar & Miroslav, 2021; Svatoš-Ražnjević et al., 2022). To bridge this research gap, the study undertook an analysis of structural and constructional characteristics within the case studies, employing the classification introduced by Ilgın et al. (2022). This classification was selected due to its clarity in contrast to the current categorization of structural systems found in the existing literature.

3. Research methods

The case study method was administrated to collect data about mid-rise timber apartment buildings to explore the structural, architectural, and constructional aspects. This method is extensively utilized in built environment evaluations (Ilgın, 2021a; Ilgın, 2022a). The cases were 55 mid-rise wooden residential buildings built between 2018 and 2022 under the Finnish Land Use and Building Act which came into force on 1 January 2018, in 15 Finnish municipalities (16 cases from Tampere, 13 from Turku, two from Kuopio, four from Kirkkonummi, three from Espoo, three from Jyväskylä, four from Kerava, two from Helsinki, two from Sipoo, one from Vaasa, one from Hämeenlinna, one from Nurmes, one from Nurmijärvi, one from Rovaniemi, and one from Vantaa, as shown in Figure 1).

It should be noted that there are 62 buildings built between 2018 and 2022 in total. The information of only seven buildings (two from Kuopio, one from Kajaani, one from Hanko, one from Jyväskylä, one from Espoo, and one from Lahti) could not be accessed.

To gather the necessary data of the buildings for the article, the authors employed The Finnish Timber Council's database, which provided information on constructed timber apartment buildings in Finland (The Finnish Timber Council, 2023). By utilizing this database, the relevant timber apartment buildings built between 2018 and 2022 were identified. Subsequently, the authors contacted the construction supervisors responsible for the communication of these projects to inform them about the research being conducted. The authors specifically requested access to publicly available design documents, including construction permission drawings, which were stored in the digital archives of building control. The authors made it explicitly clear that their analysis encompassed all residential timber apartment buildings that had been applied for and constructed in Finland during the designated time period. After receiving the design documents, a 3D modeling program was used to open the PDF drawings in vector format, which made it possible to take accurate measurements of the buildings and their structures.

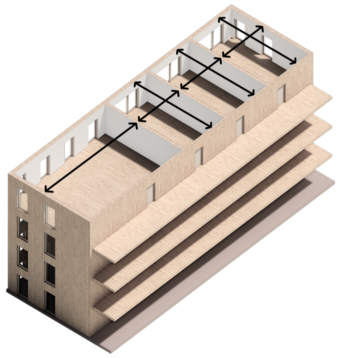


Figure 3. Lease span.

The research encompassed an extensive literature review, incorporating peer-reviewed papers, master theses, and PhD dissertations, as well as drawings from diverse Finnish municipalities, conference proceedings, architectural and structural design journals, and Finnish building codes. This approach ensured a thorough examination of the subject matter from multiple sources and perspectives.

In this study, the following architectural design considerations, which have an essential role in the design of timber structures, were discussed: (1) form; (2) core typology; (3) floor-to-floor height and floor-to-ceiling height; and (4) lease span. In terms of building form and core (i.e., vertical lift and staircase location and organization) type, the following classifications were employed in this paper (Ilgın et al., 2021b): as building forms; (1) prismatic (i.e., extruded), (2) setback, (3) tapered, (4) twisted, (5) leaning/tilted and (6) free forms; and as core types; (1) central core, (2) atrium core, (3) external core and (4) peripheral core.

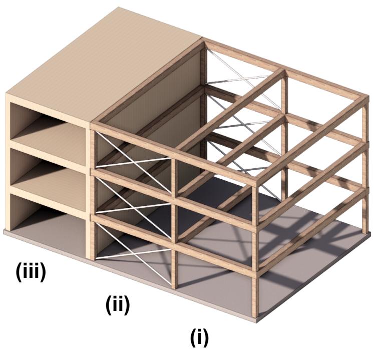


Figure 4. Components of structural systems: (i) rigid frame; (ii) shear truss; (iii) shear wall.

Floor-to-floor height is defined as the sum of the necessary ceiling height, the depth of the floor system, and the depth of the space needed for accommodating the horizontal mechanical and electrical services (Ilgın, 2018) (Figure 2a). The floor-to-ceiling height is the distance between the room's finished floor and finished ceiling (Figure 2b).

Lease span can be defined as the distance between a fixed internal element (such as a service core wall) and outer envelope (such as a window) (Ilgın, 2022c). This study expands the lease span definition to encompass the space between fixed internal elements and the outer envelope, or between fixed internal elements themselves (Figure 3).

Structural systems and structural materials were examined as structural design considerations (Tulonen et al., 2021; Karjalainen et al., 2021c). Many structural system classifications for multi-story (timber) buildings are studied in the literature (e.g., Kuzmanovska et al., 2018). As it is more complete than the current load-bearing system categorization in the literature, the authors used the following classification based on structural behavior for mid-rise timber apartments (Ilgın et al., 2022) (Figure 4): (i) rigid frame system; (ii) shear-frame system (shear trussed frame and shear walled frame systems); (iii) shear wall system. Shear walls are usually designed in solid timber stud walls, where the authors use the term 'solid' as non-engineered wood products (Figure 5).

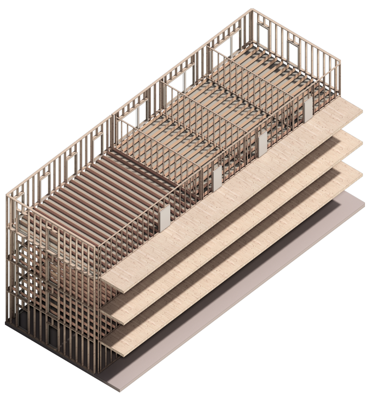


Figure 5. Solid timber stud wall.

Structural materials can be divided into two main types: (1) timber (2) composite/hybrid such as timber + (reinforced) concrete, timber + steel or timber + (reinforced concrete) + steel (e.g., Gunel and Ilgın, 2014a; Ilgın et al., 2022). The authors used the term "hybrid construction" to refer to cases where some shear walls are made of reinforced concrete and other shear walls are made of timber. In this sense, this paper took into consideration the primary load-bearing components: columns, beams, shear trusses and shear walls, excluding floor slabs (Gunel and Ilgın, 2014b; Ilgın et al., 2021a). Moreover, the authors use the term "party wall" for the fire compartment wall between two apartments.

It was considered that the main vertical structural materials are typically in and around apartments, and the structural materials of the ground-level walls and elevator shaft walls were also excluded from the table (Appendix A) and structural material analysis. Moreover, regardless of the material of the load-bearing structures on the first floor, it does not affect the classification of the structural system, or the construction method mentioned below.

Additionally, in the literature, there is no consensus on the construction method categorization of massive timber buildings (Svatoš-Ražnjević et al., 2022) and the proposed classifications are gathered under the heading of structural systems (e.g., Wiegand & Ramage, 2022). In this study, construction methods are divided into three classes: (1) 1D frame (Figure 6a); (2) 2D panel (Figure 6b); and (3) 3D volumetric (Figure 6c). The first category addresses the method with frame elements such as post and beams, also called post-and-beam, and post-and-slab-band. The second one contains a prevalent panel or wall system, with smaller areas with other elements, also called cross-wall and party wall, honeycomb, panel + external frame (balconies). The last category points out the method with 3-dimensional units, also called space modules.

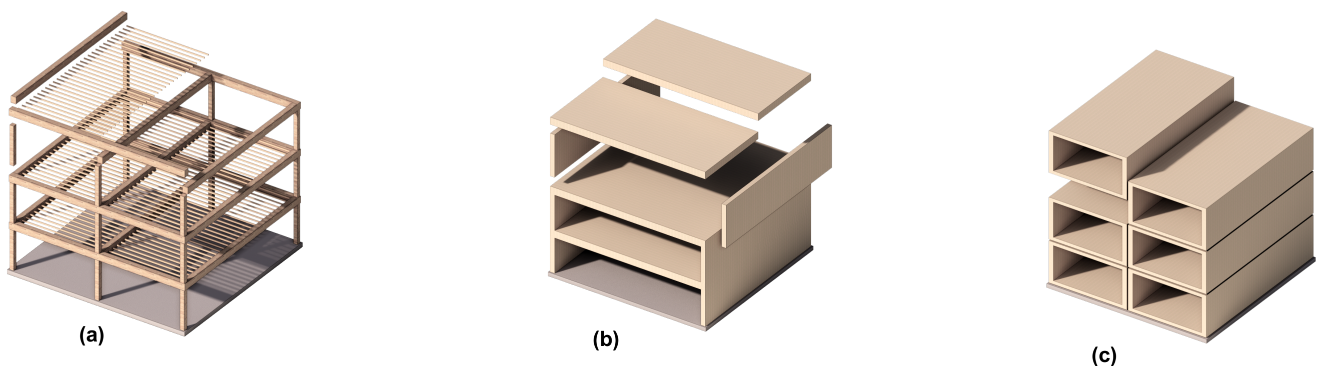


Figure 6. Construction methods: (a) 1D frame construction; (b) 2D panel construction; and (c) 3D volumetric construction.

Regarding the definitions of "low-rise building", "multi-story building", "mid-rise building" and "tall building", there is no universal consensus on their height or number of stories. In this article, "low-rise building", "multi-story building", "mid-rise building" and "tall building" are defined as a building with one- to two-story, over two-story, three- to eight-story, and over eight-story, respectively (Ilgın et al., 2021b). Here, the definition of the mid-rise building by the number of stories is based on the definition in the Finnish fire code (The National Building Code of Finland, 2017) (Figure 7). This study covers only mid-rise timber apartment buildings (three- to eight-story) where the main structural elements are mostly wood or wood-based products.

Figure 8 depicts the theoretical framework of the research methodology employed for the identification and selection of the case studies, along with the selected design considerations and classifications. Regarding the classifications, the grey shading indicates the absence of these features within the case study sample.

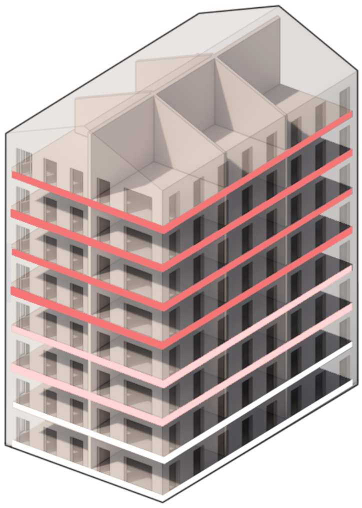


Figure 7. Mid-rise timber apartment building according to Finnish fire code: 3-8 story, Fire class P2 (maximum 8-story and 28 m tall building).

Protective cladding class K2 30 for the bearing frame of 5-8 story buildings (30-min protection time).

Protective cladding class K2 10 for the bearing frame of 3-4 story buildings (10-min protection time).

Providing the theoretical framework of the methodology was essential for several reasons. Firstly, it clarified the terminology and classifications related to the selected parameters. This clarity was crucial for establishing a common ground in the research community, preventing confusion, and enabling accurate communication of findings. Secondly. By outlining these parameters, the framework provided a structured approach, enhancing the study's organization. It also facilitated comparisons between different buildings and enabled researchers to draw meaningful conclusions about the architectural, structural, and constructional aspects of mid-rise timber apartment buildings.

When multiple studies adhere to the same theoretical framework, it becomes significantly easier to compare results, identify patterns, and draw conclusions. This comparability enhances the quality of research in the field, fostering a more comprehensive understanding of timber construction.

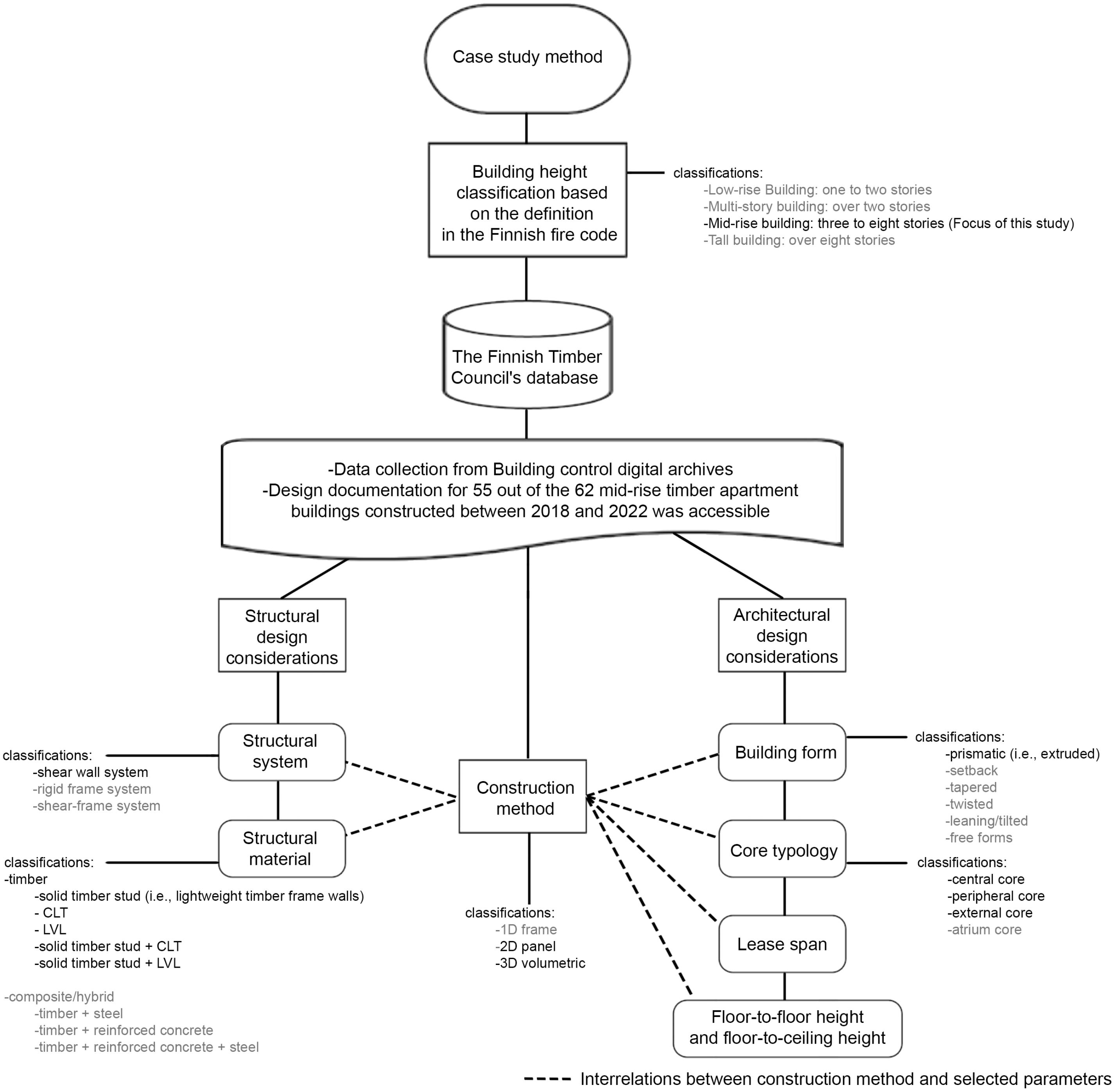


Figure 8. Theoretical framework of the research methodology.

3. Findings

This chapter presents the structural, architectural, and constructional design features of the 55 case buildings. As mentioned in the previous section, structural design considerations include (1) a structural system and (2) structural material. Architectural design considerations include (1) form; (2) core typology; (3) floor-to-floor height and floor-to-ceiling height; and (4) lease span. Construction methods include (1) 2D panel construction and (2) 3D volumetric construction.

3.1 Structural design considerations

3.1.1 Structural system

Analysis indicated that the only structural system used in the case study sample was the shear wall system. This may be due to the speed of construction and prefabrication possibilities of shear walls (Ilgın et al., 2022). It is noteworthy that there was no post and beam (i.e., rigid frame system, 1-D) among the case studies. The absence of this system may be that the frame system is more suitable for office buildings than for residential buildings (Svatoš-Ražnjević et al., 2022). A rigid frame system supports the greater lease span and design flexibility required by office buildings (The Finnish Timber Council 2020b).

3.1.2 Structural material

Typical shear wall material types found are listed in Figure 9. Figures 10 & 11 were utilized to conduct a comparative evaluation of building materials, aiming to investigate the specific types of materials employed in the typical shear walls for both the 2D panel construction method and the 3D volumetric construction method. To examine differences in material usage across buildings of varying heights, a comparative analysis of material types was conducted among different projects, categorizing them based on the number of stories (Figure 10).

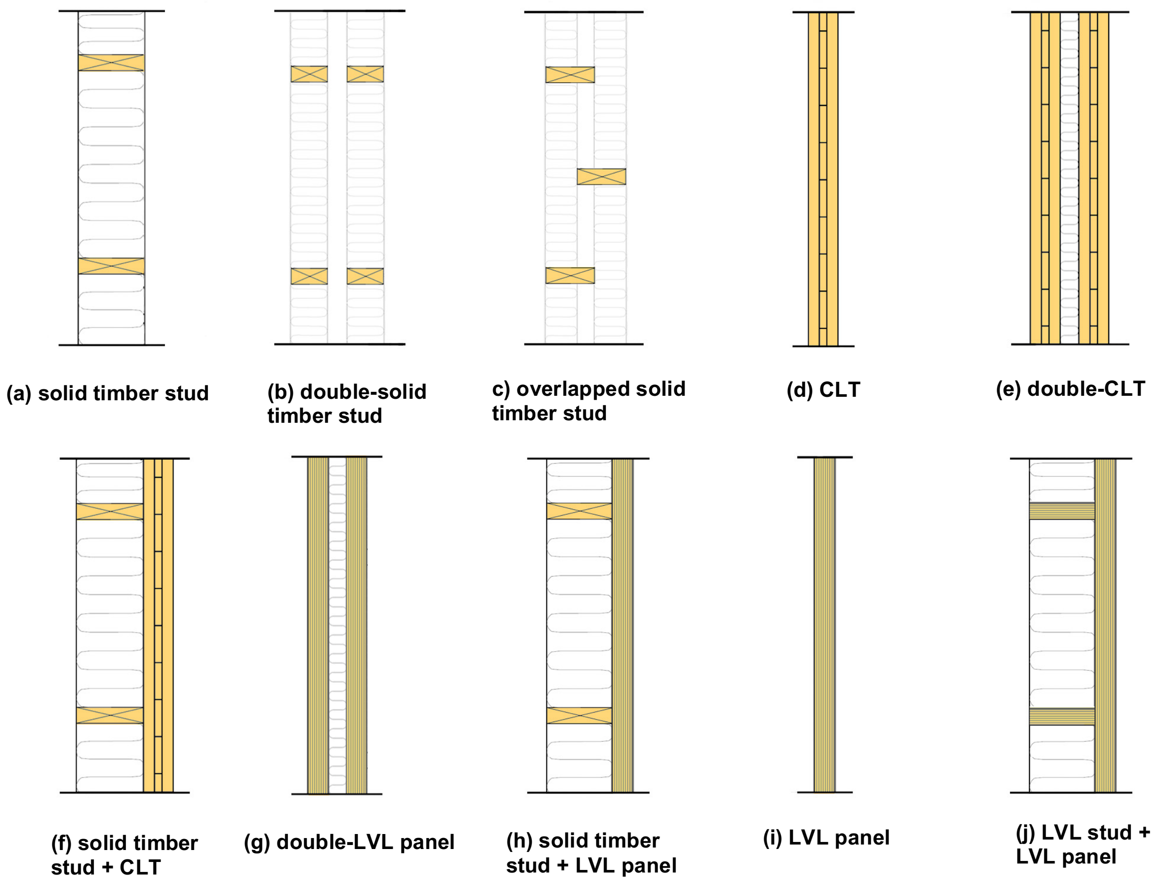


Figure 9. Typical sheal wall material types (a)…(j).

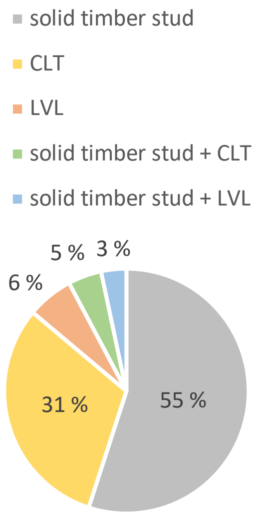
Based on the observations from Figures 10 and 11, the predominant material used in the shear walls of the 55 case studies was solid timber studs, followed by CLT. Shear walls with timber studs provide sufficient rigidity to resist loads effectively and economically in buildings up to 5–6 stories. The use of timber studs was dominant in 3-5-story buildings. A 5-story shear wall building built with solid timber studs starts to be challenging in terms of loads (Tuohimaa, L., 2018).

The case study data showed that mid-rise timber apartment buildings' fire compartment walls (i.e., party walls and corridor-apartment walls) built with solid timber studs use less wood material compared to CLT. However, it was revealed that solid timber stud walls had more gypsum board sheathing to achieve the required protective cladding class and fire protection time.

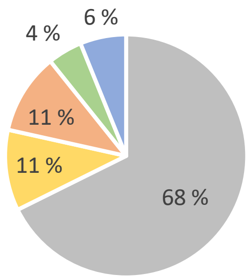
As seen in Figure 10c, the case studies constructed with the 3D volumetric construction method had a relatively high percentage of CLT shear walls. CLT and LVL were utilized in 7- and 8-story buildings, and there was no shear wall at these heights, consisting only of timber studs. (Figure 11).

Figure 10. Typical shear walls by material types.

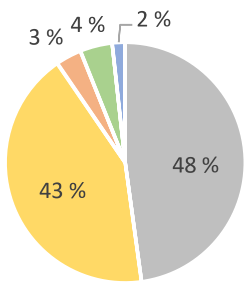
(a) all case studies;
(b) 2D panel construction method;
(c) 3D volumetric construction method.



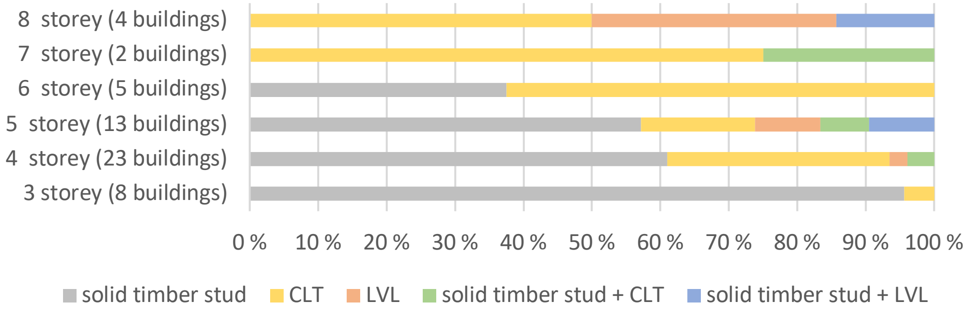
(a) all case studies.



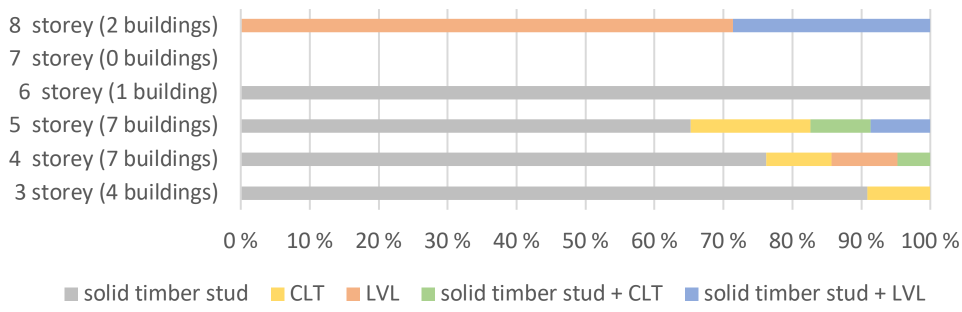
(b) 2D panel construction method.



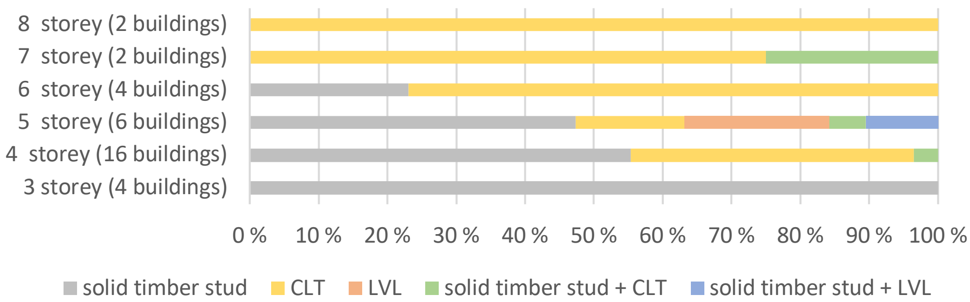
(c) 3D volumetric construction method.



(i) all case studies.



(ii) 2D panel construction.



(iii) 3D volumetric construction method.

Figure 11. Shear walls by material types and number of stories. (i) all case studies; (ii) 2D panel construction method, (iii) 3D volumetric construction method.

As indicated in Appendix A, the analysis revealed that among 36 case buildings (out of a total of 55), the typical shear walls were constructed using a single material type. Specifically, these shear walls were exclusively composed of either CLT in 8 cases or solid timber studs in 28 cases. The remaining 19 case studies consisted of a combination of material types (e.g., solid timber stud + CLT). Specifically, in *Hyljetie 3* and *Goliathin Salmi*, shear wall material consisted of LVL on the lower stories and timber studs on the upper stories. In some case buildings, e.g., *Vuores Kuusikko*, the internal shear walls stud spacing consisted of two timber studs on the lowest stories, while on upper stories, internal shear walls stud spacing consisted of the more commonly used single stud spacing. These variations may be due to material optimization, or on the other hand, a matter of improving the load-bearing and stiffening properties of the building.

Regarding repetition in the typical shear walls between different projects, it was noteworthy that twelve case studies built with the 3D volumetric construction method had 160 mm CLT in party walls between apartments (80 mm CLT + 80 mm CLT), creating a total wall thickness of 240 mm or 246 mm including every wall layers. In addition, eleven case studies built with the 2D panel construction method had party walls made of 123 mm overlapped solid timber studs, creating a total wall thickness of 254 mm. The typical shear wall structures were made purely of CLT material in the following case studies: *DAS Kelo*, *Toimela*, *Konsulintorni*, *Puumanni building A and B*, *TOAS Kauppi*, and *Lumipuu building A and B* (Appendix A). In many case buildings, the wall separating the corridor and the apartment was significantly thicker between the bedroom and the corridor in comparison to the hallway and the corridor. This variation in thickness is due to different sound insulation requirements.

In addition, none of the case studies had shear walls built only from LVL material, and this may be because LVL is a material that can cope with more technically demanding and legislative conditions (Hurmekoski et al., 2015). Compared to concrete, LVL has similar compressive strength parallel to the grain (Evison et al., 2018). The fact that LVL, where significant investments were made in the production of wooden apartments in 2016, is a relatively new material for the apartment sector may explain its low preference in the case study (Lazarevic et al., 2020).

In ten case studies, the ground-level shear walls were made entirely of reinforced concrete. Other case studies' first floor structures were made of pure timber or hybrid construction. In the cases which had a concrete-structured civil defense shelter located at the ground level, the apartments' typical shear walls were still made of timber. *Tampereen Härmälänsydän* and *Vaasan Viherlehto* case buildings had bathrooms walls made of concrete from ground level to the top floor, located next to the building core, and concrete-timber composite elements were used in the bathroom walls inside the apartments. The elevator shaft was made of reinforced concrete in four case buildings. The potential reason for using concrete in the elevator shaft or at the first floor level might be to enhance the overall stiffening properties of the building.

3.2. Construction methods

Among the 55 case buildings, the most preferred construction method was 3D volumetric construction with 34 cases (62%), followed by 2D panel construction with 21 cases (38%) (Figure 12). The reason for the dominance of the 3D volumetric construction method might be due to improved working conditions and speed of construction (Hough, et al., 2019), especially when having few unique volumetric units (Bhandari et al., 2023). However, constructing the building with few unique volumetric units may affect the overall architecture of the building. Figure 13 demonstrates that buildings with a height of four stories, constructed using 3D volumetric elements, were the most prevalent in the study.

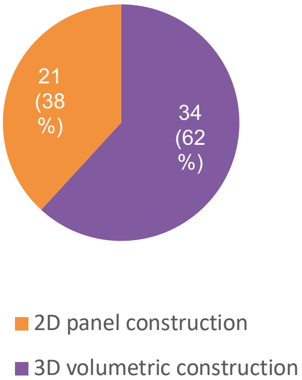


Figure 12. Case studies by construction method.

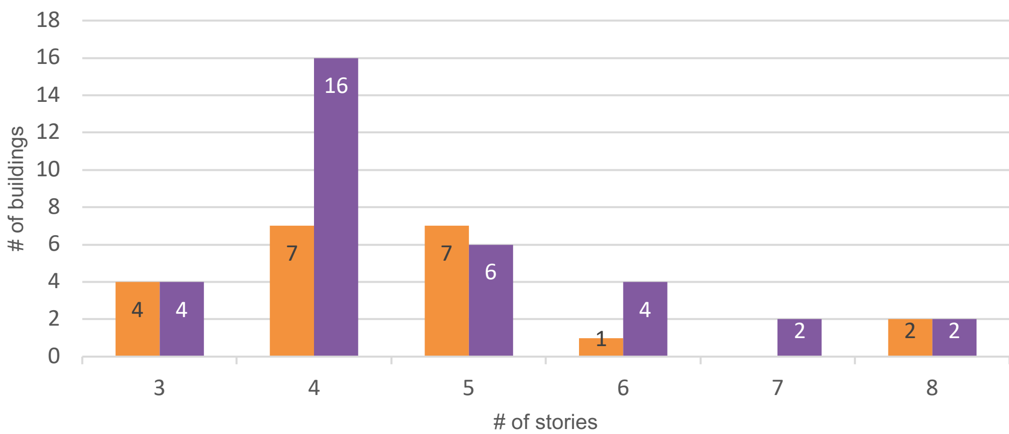


Figure 13. Construction method by number of stories.

Figure 14. Goliathin Salmi timber apartment building constructed with 2D panel construction method, located in Turku, Finland. Photo courtesy of Vesa Loikas.

Figure 15. DAS Kelo timber apartment building constructed with 3D volumetric construction method, located in Rovaniemi, Finland. Photo courtesy of Aaro Artto.

Figure 16 depicts markers representing the case buildings, arranged in ascending order based on the number of stories present in each case building. As seen in Figures 16 and 17, the structural thicknesses do not follow any linear formula as the number of stories changes. The data shows that there is no scientific correlation between the number of stories and the thicknesses of shear walls and intermediate floors, since in Finland, the P2 fire class enables 8-story timber apartment buildings with a maximum height of 28 meters. Over 8-story buildings belong to the P1 (or P0) fire class, in which the requirements for load-bearing structures are greater as they must withstand the fire and cooling phase without collapsing, thus affecting the structural thickness of shear walls.

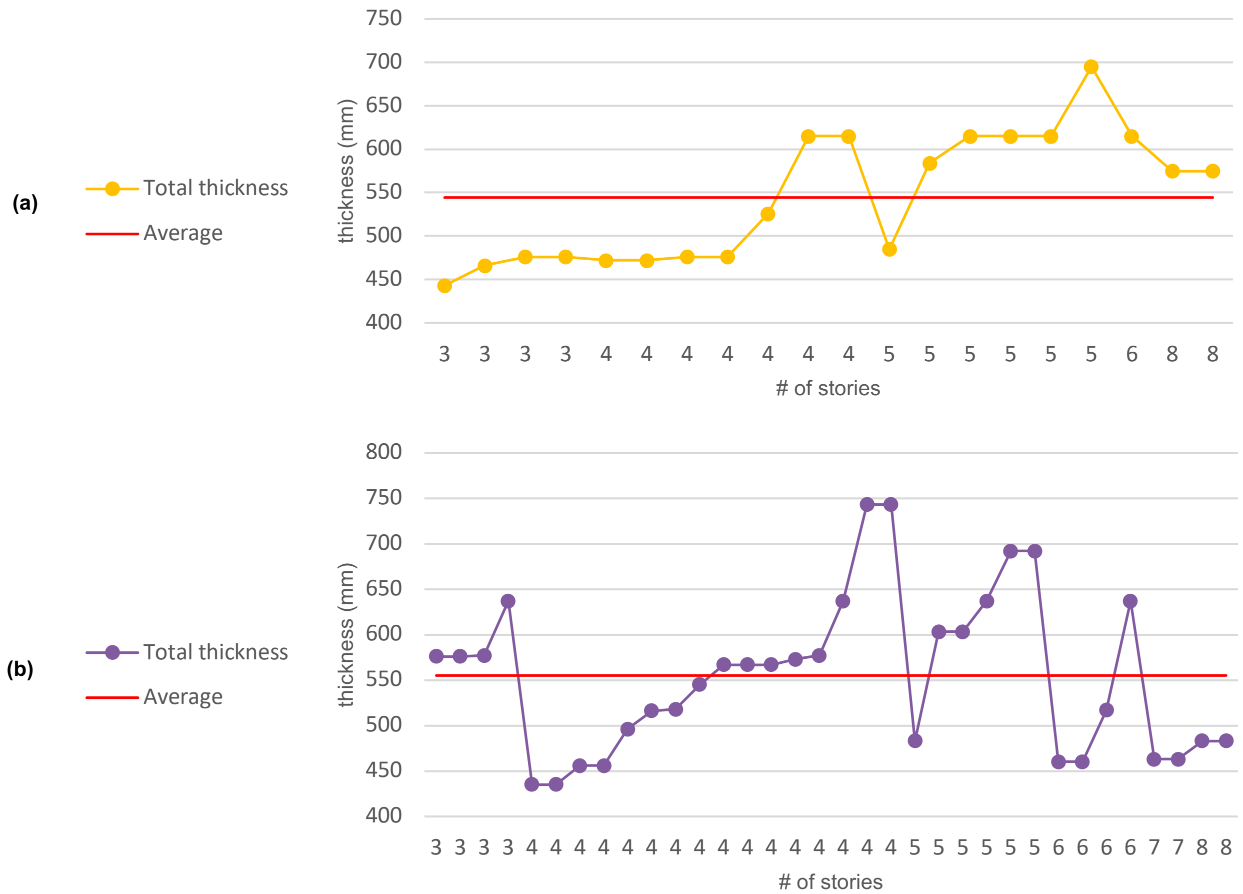


Figure 16. The total thickness of intermediate floors based on the number of stories in (a) 2D panel construction method; (b) 3D volumetric construction method.

	Construction method	Min	Max	Average
Total thickness	2D panel construction	443	695	544
	3D volumetric construction	435	743	555
All dimensions in mm				

Table 1. The total thickness of intermediate floors and the chosen construction method.

Due to the 3D volumetric construction method, the buildings' party walls between apartments and intermediate floors have double structures since every 3D volumetric unit has wall, floor, and roof elements. However, the data indicates that the average total thickness of intermediate floors and party walls in the 2D panel and 3D volumetric construction methods were relatively similar. Specifically, there is merely an 11 mm difference in the average total thickness of intermediate floors and a 13 mm difference in the average total thickness of party walls between these two construction methods (Table 1-2). In Figure 16a, it is evident that the 8-story Wood City buildings, constructed using the 2D volumetric construction method, exhibited the most significant variations in terms of the structural and total thickness of party walls. This distinction arises from the fact that these buildings were the only ones in the study sample where the party walls were composed of LVL panels with fire and sound insulation layers on both sides of the panel.

Figure 17. The structural thickness and total thickness of party walls based on the number of stories in (a) 2D panel construction method; (b) 3D volumetric construction method.

	Construction method	Min	Max	Average
Total thickness	2D panel construction	240	348	267
	3D volumetric construction	240	346	280
Structural thickness	2D panel construction	141	200	189
	3D volumetric construction	126	246	186
All dimensions in mm				

Table 2. Interrelations of the total thickness and structural thickness of party walls, and the chosen construction method.

3.3 Architectural design considerations

3.3.1 Form

The only building form used in the sample group was the prismatic (i.e., extruded) form. The most important reason for this may be that the prismatic form can be constructed more economically, easily, and quickly than other building forms (Ilgın et al., 2022). In addition, prismatic forms and especially rectangular masses might come together efficiently in urban planning, minimizing the residual space.

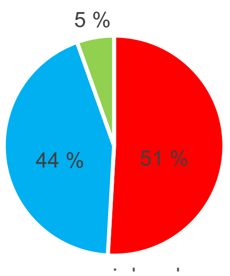


Figure 18. Case studies by core type.

3.3.2 Core typology

The most dominant core typology was the peripheral core (>50%) with 28 cases, followed by the central core with 24 cases (Figure 18). Additionally, in the case buildings, the central core was mostly used in squarish floor plans. The sample group generally consisted of buildings with rectangular floor plans. In buildings with a narrow depth, i.e., rectangular form, positioning the core often adjacent to the building envelope to provide an effective floor plan can justify the dominance of the peripheral core.

The ratio of peripheral core typology was the same for buildings constructed with 2D and 3D construction methods (Figure 19). However, in buildings with a central core typology, there were major differences between the construction methods.

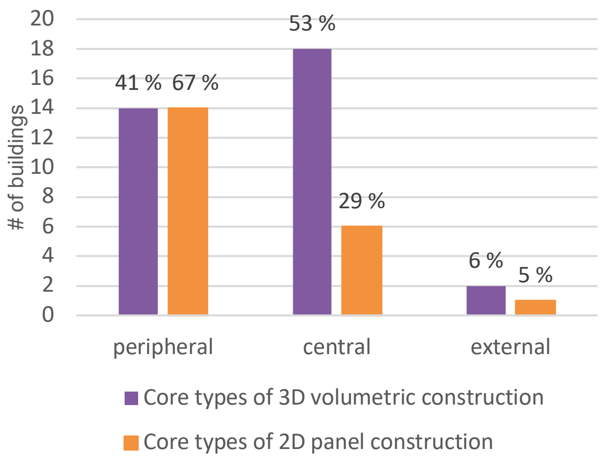


Figure 19. Core type by construction method.

3.3.3 Floor-to-floor height and floor-to-ceiling height

According to the Finnish Building Code, an apartment building must have a floor-to-floor height and floor-to-ceiling height of at least three meters and 2.5 meters, respectively (The National Building Code of Finland, 2017).

Between the 2D panel and 3D volumetric construction methods, there is a difference of 58 mm in the average floor-to-floor height and 69 mm in the average floor-to-ceiling height, as observed in Table 3. Floor-to-floor height differences might be due to the manufacturers' maximum heights for the 3D volumetric unit.

Table 3. Interrelations of floor-to-floor heights and floor-to-ceiling heights and construction method.

	Construction method	Min	Max	Average	Typical
Floor-to-floor heights	2D panel construction	3080	3414	3194	3200
	3D volumetric construction	3000	3300	3136	3200
Floor-to-ceiling heights	2D panel construction	2525	2830	2649	2585
	3D volumetric construction	2504	2723	2580	2583
All dimensions in mm					

3.3.4 Lease span

	Construction method	Min	Max	Average
Maximum lease span	2D panel construction	7203	15100	11826
	3D volumetric construction	6299	12265	8911
All dimensions in mm				

Table 4. Interrelation of maximum lease span and construction method.

There is a difference of approximately 3 meters in the average maximum lease spans between 2D panel- and 3D volumetric construction methods (Table 4). Figure 20. shows the maximum lease span of the case buildings from the smallest to the largest dimension. In 3D volumetric construction, the shear walls are placed more densely on average than in 2D panel construction. This can be explained by the structural features of the 3D volumetric unit, in which all the walls are generally load-bearing (Tulonen et al., 2021, 6). In addition, there are width restrictions in volumetric units due to factory conditions and road transport legislation (Duncheva et al., 2019). The maximum size of the volumetric unit is typically 12 × 4,2 × 3.2 meters, where 4,2 m is the width (The Finnish Timber Council, 2020a), which affects the maximum lease spans.

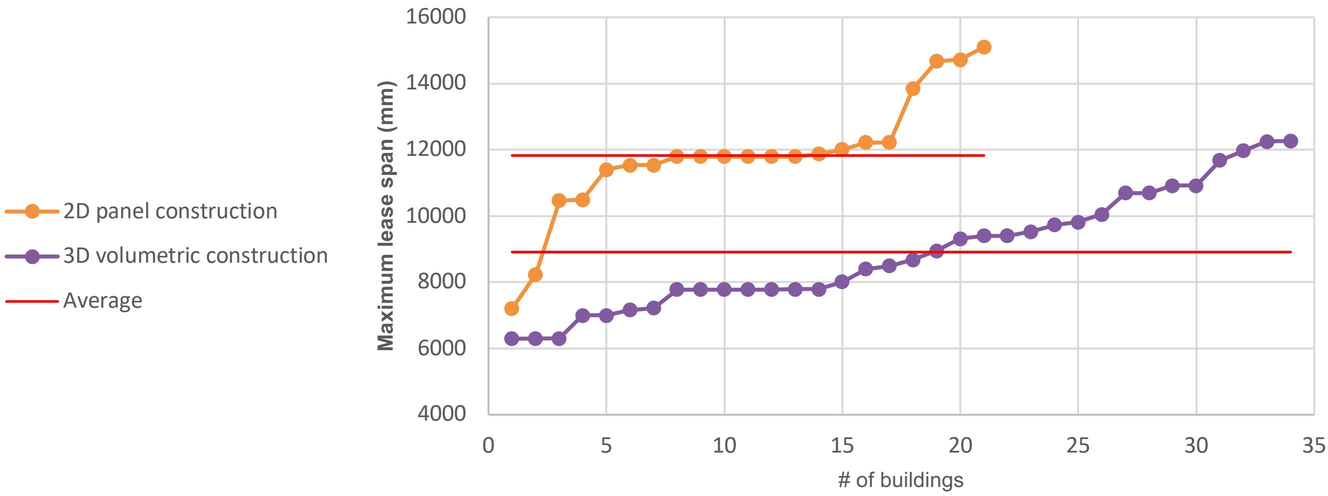


Figure 20. Interrelation of maximum lease span and construction method.

4. Discussion

The analysis revealed that the shear wall system was the sole structural system utilized among the case studies. However, Ilgın et al. (2022) found that among the 13 studied tall timber buildings the shear wall system was the most dominant structural system, followed by the shear walled frame system.

This study demonstrated that shear walls in mid-rise timber apartment buildings are typically composed of a diverse range of wood materials. Moreover, there is no single wood material that is suitable for all circumstances. The selection of shear wall materials may depend on varying selection criteria related to the construction method, building height, lease span, site conditions (e.g., wind conditions and geometry of the plot) and material availability.

Interestingly, out of the 55 case buildings, 36 had shear walls constructed using a single material type (e.g., CLT or solid timber studs). Specifically, typical shear wall structures were made purely of solid timber stud material among 28 case studies. Similarly, Ilgın et al. (2022) reported that in terms of structural material, the use of pure/solid timber was predominant compared to composite/hybrid materials. In 19 case studies, there were material type combinations in shear wall materials used, either in different types of walls (e.g., outer walls and inner walls) or between different stories of the building. These material combinations and variations may be due to material optimization or, on the other hand, a matter of improving the load-bearing and stiffening properties of the building. Utilizing a combination of different wood materials (e.g., solid timber stud + CLT or solid timber stud + LVL) in mid-rise timber apartment buildings' shear walls can at best create an optimal result from the perspective of material use, space efficiency and cost efficiency. Further studies are needed to understand the benefits of wood material combinations in shear walls. Due to the lack of literature, it was not possible to conduct a discussion to provide information on wood material type combinations and Lease span.

CLT has been proven to be a very efficient material in multi-story timber buildings up to 10 stories (Kuilen et al., 2019). In this study, CLT shear walls were used in all case studies. However, solid timber stud shear walls cannot easily cope with buildings with more than six stories (Hurmekoski et al., 2015). Rarely, however, some 8-story wooden apartments in Sweden have been known to be implemented with solid timber studs. (Tulonen, L., 2020).

In our study, the most dominant core typology was the peripheral core (>50%). However, the central core type was used the most in square floor plans. (Ilgın et al., 2022) study defined "tall timber building" as a timber building with more than 8 stories, and their study found that the central core type was used the most in 13 cases. This may be due to the efficiency of the location of the stairs and elevator in the core of the building in square floor plans. In addition, (Oldfield et al., 2019) found that the central core type had an 85% prevalence among 500 tall non-timber buildings.

Regarding our case study sample group, the floor-to-floor average was 3,17 m. In the case studies constructed with the 2D panel construction method and 3D volumetric construction method, the maximum floor-to-floor height was 3,41 and 3,30 m, respectively. Similarly, in the study by Ilgın et al. (2022), the floor-to-floor height maximum was 3.30 m with an average of 3 m. According to the study by Duncheva et al. (2019), the floor-to-floor height of UK factory products and EU factory products of 3D volumetric units varied from 3-4 m and 3-3,8 m, respectively.

In this paper, the most preferred construction method was 3D volumetric construction with 34 cases (62%), followed by 2D panel construction with 21 cases (38%). In contrast, the study of Svatoš-Ražnjević et al. (2022) showed that 3-8-story residential and non-residential timber buildings were mostly constructed with 1D frame (>45 %) and 2D panel (>40 %), and only 10% of 3D volumetric construction methods.

It has been identified that projects could benefit by including the wood product supplier in the early design stage, since there are manufacturers' limitations and instructions for different materials. In addition, there are road legislations for the size of 3D volumetric units. Engaging the wood product supplier during the early stages is often challenging since tendering processes are typically conducted at a later stage. Alternatively, enhancing the standardization of building components and their thicknesses can streamline the design process. Particularly, prioritizing the standardization of party wall thicknesses between adjacent apartments is crucial, considering their frequent repetition throughout the building.

In this study, one remarkable finding for practitioners in terms of structural design considerations is the prevalence of solid timber studs and CLT as effective materials for shear walls in mid-rise timber construction. This highlights their suitability for structural purposes, emphasizing the importance of considering these materials when designing timber apartment buildings utilizing the shear wall system.

Regarding construction methods, the study reveals that 3D volumetric construction is preferred over 2D panel construction. This finding suggests that practitioners should explore the adoption of 3D volumetric construction methods to enhance efficiency and speed in construction projects, potentially leading to shorter project timelines and improved productivity. The results of this study also provide valuable insight for designers during the initial design phase of mid-rise timber apartment buildings, enabling them to assess the suitable total thickness of timber elements based on the 2D panel and the 3D volumetric construction methods. However, it is important to note that this study does not provide insights regarding the applicability of the construction methods for varying apartment layouts, average apartment sizes, or varying quantity of apartments. The choice of construction method can be substantially influenced by the specific size requirements of the apartments.

In terms of architectural design considerations, the dominance of the peripheral core typology is a noteworthy finding. In buildings characterized by a narrow depth and rectangular shape, the placement of the core adjacent to the building envelope yields an efficient floor plan.

Mid-rise timber apartment buildings in Finland, like in many other countries, face several challenges, despite their increasing popularity. Overcoming traditional biases and educating the public about the safety, sustainability, and aesthetic appeal of timber constructions is essential for wider adoption. Although timber is a renewable resource with a positive carbon handprint, it is crucial to thoughtfully evaluate the environmental impact of timber construction, considering all the materials involved. This assessment should encompass the entire building lifecycle, including stages like material acquisition, production, building assembly, occupancy, and eventual disposal or recycling. Incorporating timber apartment buildings that utilize 3D volumetric elements into existing urban infrastructure demands careful planning. For example, when constructed using 3D volumetric elements, lifting equipment may face challenges in narrow urban areas.

In the interview research conducted by Valkola (2022), the answers of the interviewees revealed problems with the varying availability of elements in terms of geographic location, thus the general availability of wood elements and prevailing market conditions might influence the choice of shear wall material. In addition, the interpretation of the building regulations may vary between municipalities (Määttä et al., 2016), which may have an impact on the use of building materials. According to their survey, building control authorities often had suspicions about tall timber buildings, which could lead to different procedures in different municipalities; in some cases, special inspections were conducted for tall timber buildings. The survey also underlined that when building processes are regulated by authorities, it is imperative to employ solutions that are instantly effective, previously validated, and easily accessible in the market. Furthermore, Määttä et al. (2016) noted that the structural material was specified in the local building construction guidelines for various development projects. To overcome the regulatory challenges associated with wooden construction, it could be favorable to unify the practices of building control services regarding the interpretation of construction solutions for wooden apartment buildings. The study by Ilgın et al. (2021b) highlighted that the lack of demand from the client or building contractor was the biggest barrier to the use of timber products. This barrier may be because concrete construction has longer traditions in Finland compared to timber, making it a more familiar material to many.

Regarding the design of timber buildings, as in many other building projects, communication between different parties at an early stage is important (Gosselin et al., 2021), this may be because engineered wood products are relatively new and there is a general perception that the industry needs more skilled designers and standardization. Architects and structural designers should be given instructions (e.g., in the form of training and seminars) related to structural systems, construction methods, wood materials and combinations of different types of wood materials (e.g., solid timber stud + CLT). Additionally, for enhancing business prospects within the wood construction sector, effective solutions should be shared among construction professionals. This collaborative approach can significantly contribute to well-executed mid-rise timber apartment construction.

5. Conclusions

The study mapped the current state of the art regarding architectural and structural considerations of built mid-rise (3-8 story) timber apartment buildings in the Finnish context. Typical shear wall material types were also demonstrated to understand what structural materials have been used in buildings that were built with different construction methods and with a different number of stories.

The findings are summarized as follows:

- The shear wall structural system was the only structural system.
- The most preferred construction method was 3D volumetric construction, followed by 2D panel construction.
- Among the 55 case buildings, solid timber studs (i.e., lightweight timber frame walls) were the most used material for shear walls, followed by cross-laminated timber (CLT).
- The prevalence of specific structural materials varied depending on the construction method and the number of stories. CLT and LVL were utilized in 7- and 8-story buildings, and there was no shear wall at these heights, consisting only of solid timber studs.
- All case-study buildings had a prismatic (i.e., extruded) form.
- The most dominant core typology was peripheral core (>50%) with 28 cases, followed by a central core with 24 cases.
- Case studies built using the 2D panel construction method had significantly longer maximum lease span and the average of the maximum lease span.
- Case studies built with 2D panel construction method had higher average floor-to-ceiling and floor-to-floor heights.
- The average total thickness of intermediate floors and party walls between apartments was similar for both 2D panel and 3D volumetric construction methods. Regarding the thickness of party wall structural

material, the thickness of CLT had the most repetitions, followed by solid timber studs.

- While certain buildings had walls with identical structural thicknesses, there were variations in the total thickness of the walls among them.

The data was limited to the Finnish context, considering the valid Land use and building Act (2018-2022), so other studies could examine buildings from different Building Acts over a longer period. Further studies could focus on buildings with different structural systems and different building types, e.g., office buildings in other countries (e.g., Nordic countries, Central Europe). Other studies could focus on whether the building's geometry, core type, or placement of hybrid materials influence the lower use of building materials throughout the building, improving the project's economics and reducing climate impacts.

In most cases, the shear wall thickness was different in the architectural drawings compared to the structural drawings. It is identified as a risk because it can lead to architectural revision planning, which may lead to additional design- or construction costs.

This study addresses a gap in the existing literature by comparing different construction methods and the selected parameters. The study concentrates on Finnish mid-rise timber apartment buildings, which represent the prevalent type of multi-story timber apartment buildings in the country. Through extensive case studies, the research enriches design guidelines for developers, architects, and structural engineers. It provides valuable contemporary data on design considerations and highlights crucial structural, architectural, and constructional features of mid-rise timber apartment buildings.

The future prospect of the research lies in examining alternative structural systems beyond shear wall structures, which could yield valuable insights. In future research endeavors, the focus could be on evaluating specific parameters outlined in the theoretical framework within buildings utilizing various structural systems, including the rigid frame system. This system is recognized for its ability to adjust spatial layouts and achieve extended spans due to its constructional elements, which entail the on-site utilization of vertical posts and horizontal beams. Also, conducting in-depth lifecycle assessments of mid-rise timber buildings can provide a holistic understanding of their environmental impact. Comparing these assessments with other construction materials can help in making informed decisions regarding the ecological sustainability of timber buildings. It is important to highlight that, in Finland, a regulation concerning the climate assessment of construction projects will be implemented in 2025. Adherence to this regulation will be obligatory for securing a building permit.

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Appendix A. General information of the case studies.

Building name City completion year	Building height (mm) & # of storys	Construction method	Structural material	Structural material thickness	Total thickness (mm)	Maximum lease span	Core type	Typical floor-to-floor height (mm) Typical floor-to-ceiling height (mm)
DAS Kelo Rovaniemi 2019	26632 8	3D Volumetric construction	OW: CLT PW: CLT CAW: CLT	80 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT	335 240 186	8400	peripheral	3042 2559
Goliathin Salmi Building A Turku 2019	14420 4	2D Panel construction	OW: STS PW: STS CAW1: LVL* CAW2: STS ** *1-2 stories **3-4 stories	42x198 STS C24 42x123 mm STS + 42x123 mm STS C24 (s.s 300)* 84 mm LVL panel + 84 mm LVL panel 42x123 mm STS + 42x123 mm STS C24 (s.s 300)* *overlapped frame (overlapping 75 mm)	347 254 254 254	12220	peripheral	3200 2728
Goliathin Salmi Building B Turku 2019	14000 4	Same as Goliathin Salmi building A						
Visa 1 Hämeenlinna 2019	12730 4	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x220 mm STS 45x95 mm STS + 45x95 mm STS 95x145 mm STS	372 270 205	7225	external	3031 2515
Tuohi Tampere 2019	15295 4	3D Volumetric construction	OW: STS PW: STS CAW: STS ISW: STS	48x123 mm STS C24 (s.s 600) 48x123 mm STS + 48x123 mm STS C24 (s.s 600) 48x123 mm STS (s.s 600) C24 48x123 mm STS + 48x123 mm STS C24 (s.s 600)	340 326 208 326	6300	peripheral	3150 2583
Toimela Nurmijärvi 2019	14155 4	3D Volumetric construction	OW: CLT PW: CLT CAW: CLT	80 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT	328 240 110	8015	central	3000 2504
Linnanfältin Lyhdynkantaja Turku 2019	17496 5	2D Panel construction	OW1: STS + CLT OW2: STS + CLT PW: CLT CAW: STS + CLT	48x98 mm STS (s.s 600) + 100 mm CLT 48x98 mm STS + 120 mm CLT 80 mm CLT + 80 mm CLT 48x98 STS + 80 mm CLT	263 283 240 238	10498	central	3080 2595
Marinum, Building B Turku 2019	12557 3	3D Volumetric construction	OW: STS PW: STS CAW: STS	98 mm STS + 123 mm STS 123 mm STS + 123 mm STS 123 mm STS	345 326 182	6299	peripheral	3150 2574
Marinum, Building C Turku 2019	12527 3	Same as Turun Marinum building B						

Wood City, Building A Helsinki 2019	26012 8	2D Panel construction	OW: STS + LVL PW: LVL CAW1: LVL CAW2: LVL IW: LVL	48x98 mm STS + 141 mm LVL panel 141 mm LVL panel 141 mm LVL panel 195 mm LVL panel 141 mm LVL panel	462 348 348 408 348	13845	peripheral	3100 2525
Wood City, Building B Helsinki 2019	25876 8	Same as Wood City Building A				14675	Same as Wood City Building A	
Kirkkonummen Konsulintorni Kirkkonummi 2020	14814 4	3D Volumetric construction	OW: CLT PW: CLT CAW: CLT IW: CLT	120 mm CLT (40-40-40) 120 mm CLT + 120 mm CLT (40-40-40) 120 mm CLT (40-40-40) 120 mm CLT + 120 mm CLT (40-40-40)	360 346 211 346	11972	peripheral	3200 2655
Tinankartano Building A Kirkkonummi 2020	13933 4	3D Volumetric construction	OW: STS PW: STS CAW: STS	48x98 mm STS + 48x123 mm STS C24 (s.s 600) 48x123 mm STS + 45x123 mm STS C24 (s.s 600) 48x123 mm STS C24 (s.s 600)	345 326 208	7000	peripheral	3150 2583
Tinankartano Building B Kirkkonummi 2020	Same as Kirkkonummen Tinankartano building A							
Puumanni Building A Jyväskylä 2020	16274 4	3D Volumetric construction	OW: CLT PW: CLT CAW: CLT IW: CLT	200 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT 140 mm CLT	215 240 125 170	10700	central	3000 2565
Puumanni Building B Jyväskylä 2020	15206 4	Same as Puumanni building A						
Yhteisöpihan puukerrostalo Nurmes 2020	10364 3	2D Panel construction	OW: CLT PW: STS CAW: -	100 mm CLT 48x98 mm STS + 48x98 mm STS -	355 270 -	10465	peripheral	3100 2657
Puubyygeli Building A Turku 2020	14517 4	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x195 mm STS 45x95 mm STS + 45x95 mm STS 45x70 mm STS + 45x70 mm STS	335 265 215	7163	central	3300 2723
Puubyygeli Building B Turku 2020	11264 3	Same as Puubyygeli building A				8949	Same as Puubyygeli building A	
Päivänsäde 3 Building C Turku 2020	13925 4	2D Panel construction	OW: STS PW: STS CAW: STS	45x195 mm STS 98 mm STS + 98 mm STS 98 mm STS + 98 mm STS	343 271 271	11540	central	3200 2724
Päivänsäde 3 Building D Turku 2020	10426 3	Same as Päivänsäde 3 building C				14720	Same as Päivänsäde 3 building C	

Tohtori Tampere 2020	18692 5	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x170 mm STS 45x95 mm STS + 45x95 mm STS 45x95 mm STS + 45x95 mm STS	339 290 290	8500	peripheral	3200 2597
Tuuliniitty 3 Espoo 2020	19003 5	2D Panel construction	OW: STS PW: STS CAW: STS IW: STS	42x198 C24 (s.s 600) 42x123 mm STS + 42x123 mm STS C24 (s.s 300)* 42x123 mm STS + 42x123 mm STS C24 (s.s 300)* 42x148 mm STS C24 (s.s 600) *overlapped frame (overlapping 75 mm)	347 254 254 204	15100	peripheral	3200 (varies)
Vantaan Voltti Vantaa 2020	16905 5	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x170 mm STS (s.s 600) 45x95 mm STS + 45x95 mm STS 45x95 mm STS + 45x95 mm STS	334 290 290	7780	central	3200 2597
Vuorihelmi Jyväskylä 2021	16503 5	2D Panel construction	OW: STS PW: CLT CAW: CLT IW: CLT	48x198 mm STS 100 mm CLT 100 mm CLT 100 mm CLT	396 282 282 162	11400	central	3266 2571
Kuusikulma Building A Kerava 2021	17581 5	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x145 mm STS + 45x95 mm STS C24 (s.s. 600) 45x95 mm STS + 45x95 mm STS 45x95 mm STS (s.s 600) + 45x70 mm STS (s.s 600)	339 290 289	7780	central	3251 2614
Kuusikulma Building B Kerava 2021	10900 3	Same as Keravan Kuusikulma building A					external	Same as Keravan Kuusikulma building A
Kaarna Kuopio 2021	22994 7	3D Volumetric construction	OW: CLT PW: CLT CAW: STS + CLT IW: CLT	80 CLT 80 mm CLT + 80 mm CLT 42x68 STS + 80 mm CLT 140 mm CLT	356 246 198 176	10922	central	3000 2537
Niemenrannan Rantapuisto Tampere 2021	15194 4	3D Volumetric construction	OW1: STS OW2: LVL PW: STS CAW: STS IW1: STS IW2: LVL	42x223 mm STS C24 (s.s 600) 45x180 mm LVL-S stud (s.s 600) + 43 mm LVL-Q panel 42x98 mm STS + 42x98 mm STS* 45x66 mm STS + 42x98 mm STS* 42x98 mm STS + 42x98 mm STS* 45x70 mm LVL-S stud (s.s 600) + 43 mm LVL-Q panel *C24 k200...600	332 319 290 240 290 139	9820	peripheral	3200 2627
Päivänsäde 4 Building A Turku 2021	10563 3	2D Panel construction	OW: STS PW: STS CAW: STS	45x195 mm STS 98 mm STS + 98 mm STS 98 mm STS + 98 mm STS	343 271 271	11875	central	3200 2724
Päivänsäde 4 Building B Turku 2021	13400 4	Same as Päivänsäde 4 building A				11540	Same as Päivänsäde 4 building A	
Söderkullan puukerrostalot Building 1 Sipoo 2021	13227 4	3D Volumetric construction	OW: STS PW: STS CAW: STS IW: STS	48x197 mm STS 48x97 mm STS + 48x97 mm STS 48x97 mm STS 48x97 mm STS + 48x97 mm STS	341 334 170 334	12265	central	3252 2509

Söderkullan puukerrostalot Building 2 Sipoo 2021	13229 4	Same as Söderkullan puukerrostalot building 1				12250	Same as Söderkullan puukerrostalot building 1	
Härmälänsydän Tampere 2021	14700 4	3D Volumetric construction	OW1: CLT OW2: RC OW 2: CLT PW1: CLT PW2: CLT PW3: RC CAW1: CLT CAW2: RC IW: CLT	100 mm CLT 120 mm RC 80 mm CLT 100 mm CLT + 100 mm CLT 80 mm CLT + 80 mm CLT 120 mm RC + 120 mm RC 100 mm CLT 120 mm RC 80 mm CLT + 80 mm CLT	353 408 333 280 240 300 261 160 210	9316	central	3100 2582
Kaupin puukerrostalo Tampere, 2021	27718 8	3D Volumetric construction	OW: CLT PW: CLT CAW1: CLT CAW2: CLT IW: CLT	80 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT + 80 mm CLT	336 246 128 246 246	8680	central	3000 2517
Viherlehto Vaasa 2021	19891 6	3D Volumetric construction	OW1: CLT OW2: RC PW1: CLT PW2: CLT PW3: RC CAW1: STS + CLT CAW2: RC IW: CLT	100 mm CLT 120 mm RC 100 mm CLT + 100 mm CLT 80 mm CLT + 80 mm CLT 120 mm RC + 120 mm RC 48x98 mm STS + 100 mm CLT 120 mm RC 80 mm CLT + 80 mm CLT	355 408 280 240 300 261 160 210	9530	central	3100 2583
Rautalepänkatu 2 Building A Tampere 2021	15585 4	3D Volumetric construction	OW: CLT PW: CLT CAW1: STS + CLT CAW2: CLT * IW: CLT * staircase	80 mm CLT 80 mm CLT + 80 mm CLT 66x42 STS + 80 mm CLT 80 mm CLT + 80 mm CLT 80 mm CLT + 80 mm CLT	336 246 210 246 216	9730	peripheral	3040 2584
Rautalepänkatu 2 Building B Tampere 2021	14630 4	Same as VTS Rautalepänkatu 2 building A				11685	Same as VTS Rautalepänkatu 2 building A	
Hyljetie 3 Building A Espoo 2022	18712 5	3D Volumetric construction	OW: STS + LVL* PW: LVL* CAW1: LVL* OW: STS** PW: STS** CAW 1: LVL** CAW 2: STS** CAW 3: LVL + STS** *1-3 stories **4-5 stories	48x173 mm STS C24 + 39mm LVL-Q panel 63 mm LVL-Q panel + 63 mm LVL-Q panel 63 mm LVL-Q panel + 63 mm LVL-Q panel 48x197 mm STS C24 48x97 STS + 48x97 STS 63 mm LVL-Q panel + 63 mm LVL-Q panel 48x97 mm STS + 48x97 mm STS 63 mm LVL-Q panel + 48x97 STS	339 280 280 339 334 280 334 331	9398	central	3200 2508

Hyljetie 3 Building B Espoo 2022	18582 5	Same as Hyljetie 3 building A						
Terhikintie 1 Building A Kerava 2022	15484 4	3D Volumetric construction	OW: STS PW: STS CAW: STS	45x145 mm STS + 45x95 mm STS C24 (s.s 600) 45x95 mm STS + 45x95 mm STS (s.s 600) 45x95 mm STS + 45x70 mm STS (s.s 600)	336 290 290	7780	central	3251 2614
Terhikintie 1 Building B Kerava 2022	22939 6	Same as Keravan Terhikintie 1 building A						
Nila Kuopio 2022	22878 7	3D Volumetric construction	OW: CLT PW: CLT CAW: STS + CLT IW: CLT	80 CLT 80 mm CLT + 80 mm CLT 42x68 STS + 80 mm CLT 140 mm CLT	356 246 198 176	10922	central	3000 2537
Lumipuu Building A Tampere 2022	20581 6	3D Volumetric construction	OW1: CLT OW2: CLT PW: CLT CAW: CLT	80 mm CLT 123 mm CLT 80 mm CLT + 80 mm CLT (30-20-30 layers) 80 mm CLT	336 376 246 128	7792	peripheral	3100 2640
Lumipuu Building B Tampere 2022	20597 6	Same as Lumipuu building A						
Pyssysepänkaari 3 Kirkkonummi 2022	16298 5	3D Volumetric construction	OW: CLT PW: CLT CAW: STS + CLT IW: CLT	80 mm CLT 80 mm CLT + 80 mm CLT 66x42 mm STS (s.s 600) + 80 mm CLT 140 mm CLT (40-20-20-20-40)	333 240 186 170	10053	peripheral	3000 2517
Tampereen Pähkinä Tampere 2022	19280 5	2D Panel construction	OW1: STS + LVL OW2: STS + LVL OW3: STS PW: STS CAW: STS + LVL	42x173 mm STS C24 (s.s 600) + 51 mm LVL panel 42x148 mm STS C24 (s.s 600) + 75 mm LVL panel 42x223 mm STS C24 (s.s 600) 42x123 mm STS + 42x123 mm STS C24 (s.s. 300)* 42x123 mm STS C24 (s.s. 300...600 + 63 mm LVL panel *overlapped frame (overlapping 75 mm)	322 322 322 254 254	7203	peripheral	3414 2830
Hirvensalon Kirsikka Turku 2022	14563 4	2D Panel construction	OW: CLT PW: CLT CAW: STS + CLT	140 mm CLT 80 mm CLT + 80 mm CLT 98 mm STS + 100 mm CLT	398 246 259	12006	peripheral	3216 2690
Linnanherra Turku 2022	12500 3	2D Panel construction	OW: STS PW: STS CAW: STS	42x223 mm STS C24 48x123 mm STS + 48x123 mm STS C24* 48x123 mm STS + 48x123 mm STS C24* *overlapped frame (overlapping 75 mm)	308 254 254	8238	External	3200 2734

Vuores Kuusikko (A-Kruunu Oy) Building D Tampere 2022	14369 4	2D Panel construction	OW: STS PW: STS CAW: STS	48x223 mm STS (s.s 600) 48x123 mm STS + 48x123 mm STS* 48x123 mm STS + 48x123 mm STS* *overlapped frame (overlapping 75 mm)	332 254 254	11800	peripheral	3200 2585
Vuores Kuusikko (A-Kruunu Oy) Building B Tampere 2022	17348 5	Same as Vuores Kuusikko (A-Kruunu Oy) building D						
Vuores Kuusikko (A-Kruunu Oy) Building C Tampere 2022	17484 5	Same as Vuores Kuusikko (A-Kruunu Oy) building D						
Vuores Kuusikko (TA-Asumisoikeus Oy) Building A Tampere 2022	20849 6	2D Panel construction	OW: STS PW: STS CAW: STS	48x223 mm STS (s.s 600) 48x123 mm STS + 48x123 mm STS* 48x123 mm STS + 48x123 mm STS* *overlapped frame (overlapping 75 mm)	332 254 254	11800	peripheral	3200 2585
Vuores Kuusikko (TA-Asumisoikeus Oy) Building E Tampere 2022	17578 5	Same as Vuores Kuusikko (TA-Asumisoikeus Oy) building A						
Vuores Kuusikko (TA-Asumisoikeus Oy) Building F Tampere 2022	14876 4	Same as Vuores Kuusikko (TA-Asumisoikeus Oy) building A						

*Note: Despite structural uniformity among buildings within a construction project, they were incorporated into the case study sample and diagrams.

*Note: Regarding structural material, the number (1) indicates the most typical material type.

*Note: Abbreviations: OW: Outer wall material; PW: party wall material; CAW: corridor-apartment wall material; IW: internal load bearing wall material.

STS: solid timber stud; CLT: cross-laminated timber; LVL: laminated veneer lumber; RC: reinforced concrete; s.s.: stud spacing; b.s.: beam spacing.

All dimensions in mm.

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