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Article

Space Efficiency in Finnish Mid-Rise Timber Apartment Buildings

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Abstract: As in many other building types, space efficiency in mid-rise timber apartment buildings is one of the critical design parameters to make a project feasible. Space efficiency depends on varying selection criteria related to construction materials, construction methods, and proper planning. To date, no study provides a comprehensive understanding of space efficiency in mid-rise timber apartment buildings. This paper examined data from 55 Finnish mid-rise timber apartment buildings built between 2018 and 2022 under the Finnish Land Use and Building Act to increase the understanding of which factors and design parameters influence the space efficiency of mid-rise timber apartment buildings. The main findings of this study indicated that: (1) among the case studies, the space efficiency ranged from 77.8% to 87.9%, and the average was 83%; (2) the mean values of the ratios of structural wall area to gross floor area, vertical circulation area to gross floor area, and technical spaces (including shafts) to gross floor area were found to be 12.9%, 2.6%, and 1.5%, respectively; (3) construction methods or shear wall materials make no significant difference in terms of space efficiency, and there is no scientific correlation between the number of stories and space efficiency; (4) the best average space efficiency was achieved with central core type, followed by peripheral core arrangement. This research will contribute to design guidelines for clients, developers, architects, and other construction professionals of mid-rise timber apartment building projects.

Keywords: space efficiency; timber; mid-rise; apartment building; Finland

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1. Introduction

As in many countries of the world [1–3], Finland has been substantially affected by the increase in global urbanization and the consequent urbanization trend [4,5]. In Finland, where more than 80% of the population lives in cities, this rate is estimated to reach 90% by 2050 [6]. This will lead to a significant increase in the employed population and hence the number of people living in major Finnish cities, e.g., Helsinki [7].

Increasing multi-story wooden construction can offer concrete and fast solutions to meet the housing need brought about by urbanization [8]. In accordance with the bioeconomic strategy implemented by Finnish authorities, which is focused on achieving a carbon-neutral environment by 2035 through the adoption of innovative, environmentally friendly, and sustainable technologies, the widespread utilization of bio-based materials such as wood in construction will facilitate a shift towards sustainability [9]. Multi-story wooden construction also plays a critical role in a bio-based circular economy [10] and in mitigating construction-based carbon emissions and embodied energy consumption [11,12]. As in many other locations that have adopted a forest-based bioeconomy, multi-story wooden construction in Finland has the potential to create a sustainable business model, which is assessed as a crucial element of the bioeconomic transition [13,14].

Wooden construction provides important benefits in tackling climate change by replacing the constructions made with traditional construction materials, e.g., steel and reinforced concrete, to reduce greenhouse gas emissions [15–17]. It can also store significant amounts of carbon [18]. Other than the usage of timber as a construction material, it can also be a raw material for other structures after completing its service life [19,20]. The usage of timber in indoor areas contributes to visually pleasant environments by maintaining one's physical well-being, emotional state, and living condition [21,22].

With a long and traditional history of wooden construction, Finland started a piloting effort in the early 1990s to re-explore the potential of wooden construction [23]. This endeavor achieved considerable success through the development of numerous innovative designs, which bolstered the legitimacy of timber as the future primary building material. The second wave of wooden building booms began in 2011 when a revision to the Finnish fire regulation allowed timber frames and façades to be included in projects [24]. This revision enabled the design of eight-story timber apartment buildings based on traditional fire classes and numerical table values. In addition, the maximum allowable building height for a wooden building has been increased to eight-stories [25]. Despite these developments, the use of timber as the primary construction material in medium and large-scale projects is challenging and has not yet reached the desired level, but wooden multi-story apartments in the form of mid-rise constructions have become widespread in Finland lately [26].

One of the most important parameters in terms of making the project viable in building design is space efficiency [27]. This particular parameter assumes even greater significance within residential buildings that strive to enhance the economic appeal of their design scheme by maximizing the available usable space [28]. There is limited research in the literature scrutinizing buildings' space efficiency [29]. Additionally, extensive research has been conducted on the technical, ecological, social, and economic aspects of timber constructions (e.g., [30–34]), while no study has explored the concept of space efficiency in timber buildings. Among the various types of timber apartment buildings constructed in Finland, mid-rise timber apartment buildings are the most frequently encountered [35].

This article aims to map out, gather, and consolidate the data on space efficiency in mid-rise timber apartments in Finland in terms of key architectural and structural features. To accomplish this goal, data were collected from 55 buildings constructed between 2018 and 2022 under the Finnish Land Use and Building Act, which came into force on 1 January 2018. It is important to highlight that the year 2018 marked a significant starting point for the selection of case studies due to the implementation of a new fire regulation. This regulation introduced the allowance for up to 20% of wooden surfaces in structural timber walls, fire department walls, and ceilings to be exposed when the fire resistance of the walls are rated as R60. Moreover, if the fire resistance of the walls is further elevated from R60 to R90, up to 80% of the wooden surface in structural timber walls or ceilings, such as CLT or LVL, is permitted to be exposed. Consequently, since 2018, there has been a reduced necessity for installing protective cladding, such as gypsum board, on the surface of these structural timber walls or ceilings. In the context of this study, no essential changes have been made to the building code concerning timber apartment building construction during 2018–2022.

In the scope of this paper, four key points were addressed to examine the important features and their interrelations to space efficiency in Finnish mid-rise timber apartment construction: (1) general information (building name, location, height, number of stories, and completion date), (2) key features having an effect on space efficiency (load-bearing system, construction method, structural materials, building form, and core design), (3) space efficiency, and (4) the interrelationship of space efficiency and key planning parameters. To understand the space efficiency along with the relevant parameters for the planning and construction of mid-rise wooden apartment projects in the Finnish context, the research questions were determined as follows:

(1) What are the space efficiencies of the case study samples, and within what range do these ratios vary?
(2) What are the effects of architectural and structural design parameters on the space efficiency of mid-rise timber apartment building projects?
(3) What could be the recommendations to increase space efficiency?

The scientific contribution of this research is the comprehensive examination of space efficiency in mid-rise timber apartment buildings. This study analyzes data from 55 Finnish mid-rise timber apartment buildings constructed within a specific time frame under the Finnish Land Use and Building Act. By investigating various factors and design parameters that influence space efficiency, this research provides valuable insights into optimizing design approaches for such buildings.

The primary hypotheses addressed in this research are:

1. Variation in Space Efficiency: This study hypothesizes that there will be a range of space efficiency values across the examined mid-rise timber apartment buildings due to differences in design choices, construction methods, and other factors.
2. Impact of Design Parameters: This research aims to explore how specific design parameters, such as the ratios of structural wall area to gross floor area, vertical circulation area to gross floor area, and technical spaces (including shafts) to gross floor area, influence overall space efficiency.
3. Construction Methods and Shear Wall Materials: This study seeks to investigate whether different construction methods and shear wall materials have a significant impact on space efficiency.
4. Correlation with Number of Stories: This research aims to determine whether there is a scientific correlation between the number of stories in mid-rise timber apartment buildings and their space efficiency.
5. Impact of Core Arrangement: This study explores whether different core arrangements (central core type vs. peripheral core arrangement) affect the space efficiency of mid-rise timber apartment buildings.

By examining these hypotheses and providing evidence-based findings, the research contributes to the development of design guidelines that can benefit clients, developers, architects, and other professionals involved in mid-rise timber apartment building projects.

This paper can assist designers, owners, and developers during the design phase to enhance and refine space efficiency by providing insights to make more appropriate design decisions for wooden residential developments. In this article, buildings are categorized based on their number of stories into low-rise (one to two stories), multi-story (over two stories), mid-rise (three to eight stories), and tall buildings (over eight stories) [36]. The definition of a mid-rise building by the number of floors is based on the definition in the Finnish fire code. Overall, this article only covers mid-rise wooden apartments (three to eight stories) where the main structural elements are mostly wood or wood-based products.

The remainder of the article is outlined as follows: First, a literature review on space efficiency is provided. Then, the research materials and methods employed are given. After this part, findings based on 55 detailed case study buildings are presented, followed by the discussion section. Finally, conclusions with recommendations and limitations of the research are presented.

2. Literature Review

Although there is a lack of literature that offers a comprehensive understanding of space efficiency in wooden residential buildings, very limited research exists on space efficiency in non-wooden buildings. Among them, Okbaz and Sev [37] generated a simulation for the space efficiency in non-prismatic tall office towers by analyzing the service core area, net floor area, lease span, and load-bearing elements of 11 selected cases. They found that: (i) the pyramidal form has the highest space efficiency ratio, while the free form has the lowest; (ii) while the building form affects space efficiency the most, the floor–floor height and floor–ceiling height criteria affect the least. Hamid et al. [38] analyzed the space efficiency in 60 hybrid villa apartment projects in Sudan by using main spatial parameters, including plot location, vertical circulation, and courtyard position, through interviews with architectural offices. Their findings showed that (a) corner location is most efficient for land use, (b) the center edge for vertical circulation is recommended, and (c) space efficiency is maximized for plot sizes where width is longer than depth. Suga [39] focused on the concept of space efficiency in hotel development. Some key findings of the work are as follows: (1) metrics used in the industry for measuring space efficiency are among important parameters; (2) space-efficient planning practices are perceived to have a positive impact on hotel projects; (3) large areas, such as guest rooms, are most in need of increasing space efficiency; and (4) space-efficient planning of common areas is more evident than marginal improvement of the footprint of a guest room. Ilgın [29] investigated space efficiency in super-tall office towers by using key architectural and structural planning features, including form, core arrangement, structural material, and structural system, whereas Ilgın [28] scrutinized space efficiency in super-tall residential towers by using the same planning criteria. In addition, Ilgın [40] focused on space efficiency in mixed-use buildings using 64 case studies from around the world. All three studies of Ilgın found that: (a) the central core is the most prevalent core typology; (b) the most used structural system is an outriggered frame system; (c) as the height of the tower increases, the space efficiency ratio decreases. Arslan Kılınç [41] determined the variables affecting the core and structural system in box-form tall buildings and the relationships between these variables using correlation and regression analysis. The results showed that: (i) as the height or number of floors in tall office buildings increase, it is observed that the core area and dimensions of the structural system also expand; (ii) there is no scientific correlation between structural material and space efficiency. Nam and Shim [42] investigated the impact of high-rise building corner shapes and lease span on space efficiency for interior usage. Some key findings of their work are as follows: (1) square-cut corner form exhibits the highest degree of structural obstruction, (2) the impact rate of corner cuts on space efficiency is about 4% compared to building without corner cuts, and (3) lease span has a significant effect on spatial efficiency, so it should be considered at the early stage of high-rise tower design. Sev and Özgen [43] examined the space efficiency of tall office towers by comparing 10 cases, considering lease span, floor-to-floor height, core arrangement, structural material, and structural system. The results indicated that: (a) a load-bearing system and service core design are the most critical parameters having an effect on the space efficiency of tall office towers, (b) core space can vary significantly based on user needs, (c) the central core is the most used typology, and (d) mega-column and outriggered frame systems are the most common among tall offices. Saari et al. [44] analyzed the changes in the total cost of the building by increasing the space efficiency in office buildings. Analysis of the total cost of a selected building demonstrated that when space usage increases radically, measures must be taken to guarantee an adequate indoor climate. Kim and Elnimeiri [45] introduced planning considerations, e.g., building function, floor-to-floor height, lease span for multi-function high-rise towers, and their interrelationships to space efficiency by examining 10 case study samples. Some key findings of their work are as follows: (i) besides space efficiency, other types of efficiencies, e.g., structural and energy efficiency must also be considered; (ii) functional distribution plays a critical role in space efficiency in multi-use tall buildings; (iii) space efficiency can be improved by considering ideal load-bearing systems and building forms together; and (iv) implementing strategies aimed at reducing the service core area by minimizing the quantity of lifts enhances space efficiency.

This research endeavors to bridge the aforementioned gap in the literature by examining crucial design parameters and space efficiency in wooden residential buildings within the specific context of Finland. By offering valuable insights, this paper aims to support designers, owners, and developers in making well-informed design choices during the development phase, thus optimizing space efficiency for wooden residential projects.

3. Materials and Methods

In our article, we employed a case study method to collect data on mid-rise timber apartment buildings in Finland, with the aim of analyzing space efficiency while considering key structural and architectural features.

The case study method is extensively used in built environment assessments [46,47]. The cases were 55 mid-rise timber apartment buildings from a variety of Finnish municipalities (sixteen in Tampere, thirteen in Turku, two in Kuopio, four in Kirkkonummi, three in Espoo, three in Jyväskylä, four in Kerava, two in Helsinki, two in Sipoo, one in Vaasa, one in Hämeenlinna, one in Nurmes, one in Nurmijärvi, one in Rovaniemi, and one in Vantaa), as shown in Figure 1. It should be noted that there are a total of sixty buildings built between 2018 and 2022 under the Finnish Land Use and Building Act, and only five buildings (two in Kuopio, one in Kajaani, one in Hanko, and one in Lahti) are not available, so only five projects were missing from the case study sample.

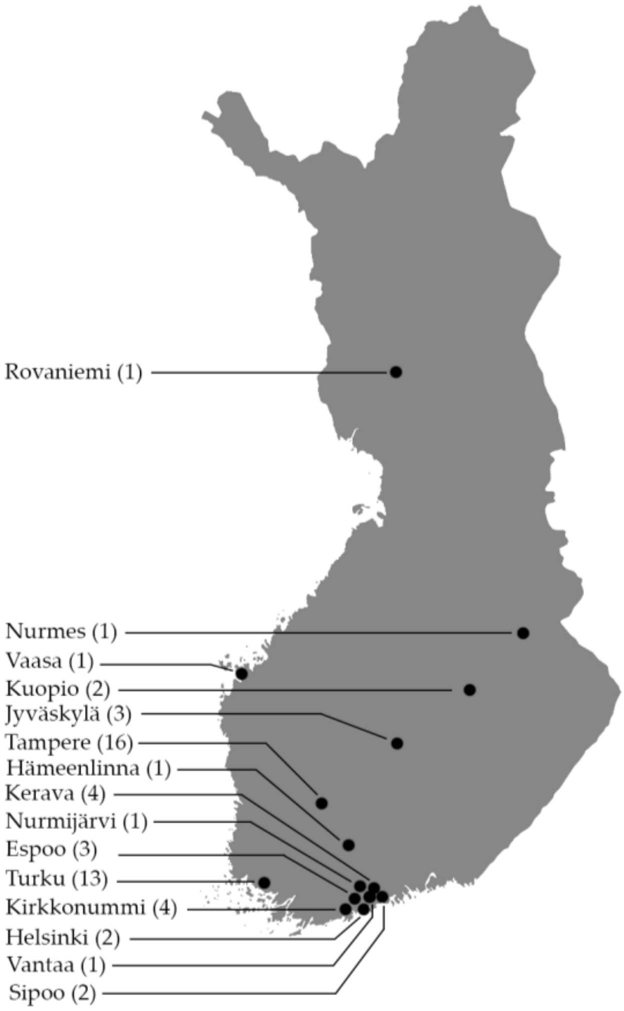


Figure 1. Case studies in map of Finland.

This study centers on mid-rise wooden apartments, as they represent the prevailing type among the diverse range of wooden apartments constructed in Finland [35]. In this article, buildings are categorized based on their number of stories into low-rise (one to two stories), multi-story (over two stories), mid-rise (three to eight stories), and tall buildings (over eight stories) [36].

In the context of timber residential buildings, decision-making is primarily guided by architectural and structural need-based requirements, as well as the main function of the building. Similar features also influence decision-making in various other building types. The main features are as follows [48]:

Among architectural features:

- Building form having an effect on floor slab size and shape.
- Core planning having an effect on the composition of vertical circulation and, in some cases, on the shaft distribution.

Among structural features:

- Structural system having an effect on the arrangement and size of the structural members.
- Structural material having an effect on the size of the structural elements.

Among constructional features:

- Construction method.

In terms of building form and core arrangement (namely, vertical circulation and its layout), the following classifications were used in this study: For building forms [49], (a) prismatic, (b) setback, (c) tapered, (d) twisted, (e) tilted, and (f) free forms. For core typologies, (a) central, (b) atrium, (c) external, and (d) peripheral cores.

Although many structural system classifications for multi-story (wooden) buildings have been studied in the literature [50], the authors employed the following classification based on structural behavior due to its more complete approach [36] (Figure 2): (1) rigid frame system; (2) shear frame system (shear trussed frame and shear walled frame systems); (3) shear wall system.

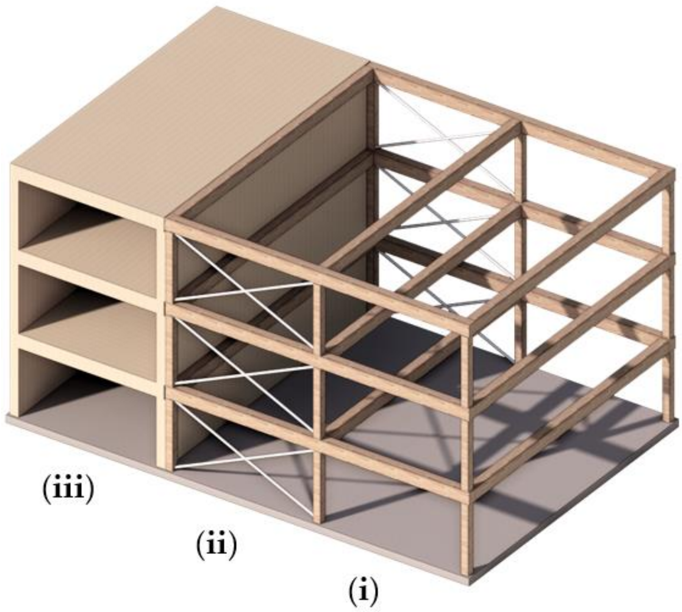


Figure 2. Components of structural systems: (i) rigid frame, (ii) shear truss, and (iii) shear wall.

Structural materials can be grouped as (1) timber and (2) composite/hybrid, such as timber + (reinforced) concrete, timber + steel, or timber + (reinforced concrete) + steel. In this context, this article has considered primary load-bearing components, such as columns, beams, shear trusses, and shear walls, excluding floor slabs. Furthermore, the material composition of the load-bearing structures on the first floor does not alter the categorization of the structural system or the definitions of the construction methods outlined below.

Furthermore, there is no consensus in the literature on the construction method classification of solid timber buildings [51], and the proposed classifications are grouped under the heading of structural systems (e.g., in Ref. [52]). In this paper, the following construction methods are used: (1) one-dimensional (1D) frame (Figure 3a), (2) two-dimensional (2D) panel (Figure 3b), and (3) three-dimensional (3D) volumetric (Figure 3c). A 1D frame refers to the method with frame members, i.e., post and beams, also called post-and-beam and post-and-slab-band. A 2D panel includes a prevalent panel or wall system, with smaller areas with other elements, also called cross-wall, honeycomb, and panel + external frame (balconies). A 3D volumetric points to the method with three-dimensional units, also called space modules. Furthermore, the authors use the term “party wall” for the fire compartment wall between two apartments.

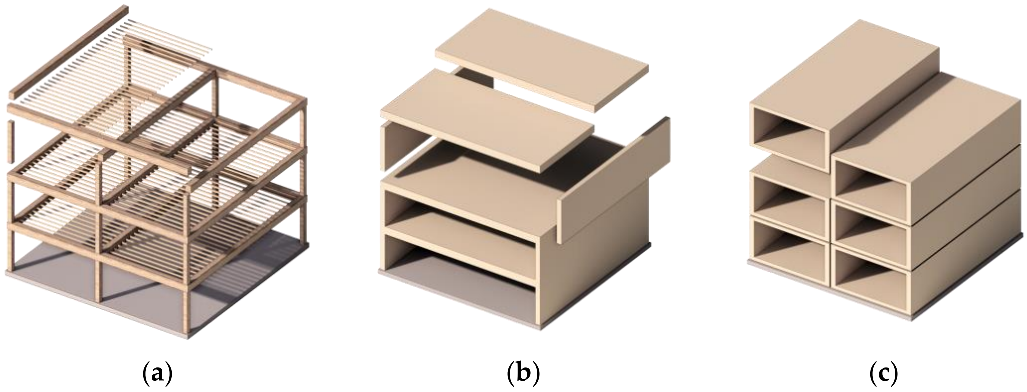


Figure 3. Construction methods: (**a**) 1D frame, (**b**) 2D panel, and (**c**) 3D volumetric.

In this study, space efficiency was defined as the ratio of net floor area (NFA) to gross floor area (GFA), which is primarily dependent on the structural system, construction method, structural materials, building form, and core typology. As depicted in Figure 4, the NFA is obtained by subtracting vertical circulation (i.e., elevator and staircases), technical spaces (including shafts), and structural elements from GFA. The floor plan diagrams of typical stories illustrating these areas are provided in Appendix A, Figures A1–A4. The space efficiency of the typical floor was analyzed because the typical floor has the greatest impact on the building's space efficiency. This is because, in timber construction, the structural walls tend to be positioned consistently across floors starting from the second floor.

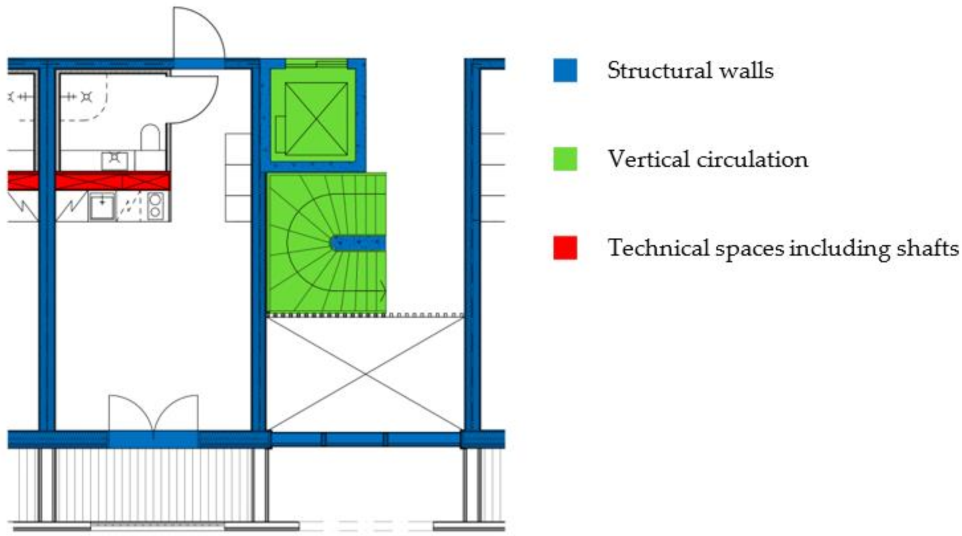


Figure 4. Structural walls, vertical circulation, and technical spaces including shafts, presented in a floor plan.

Figure 5 illustrates the systematic methodology employed for the identification and selection of the case studies, the data acquisition process from building control services, and the subsequent analysis of the interrelations between the design parameters and space efficiency. The researchers made a specific request for access to publicly accessible design documentation, including construction permission drawings, stored within the digital archives of the building control authorities. The authors ensured clear communication with the building control entities, emphasizing that their analysis covered all timber residential apartment buildings that underwent application and construction within the predefined time window. Following the acquisition of these design documents, 3D-modeling software was utilized to open the PDF drawings, converting them into a vector format. This approach facilitated precise measurements of both the buildings' dimensions and their structural elements.

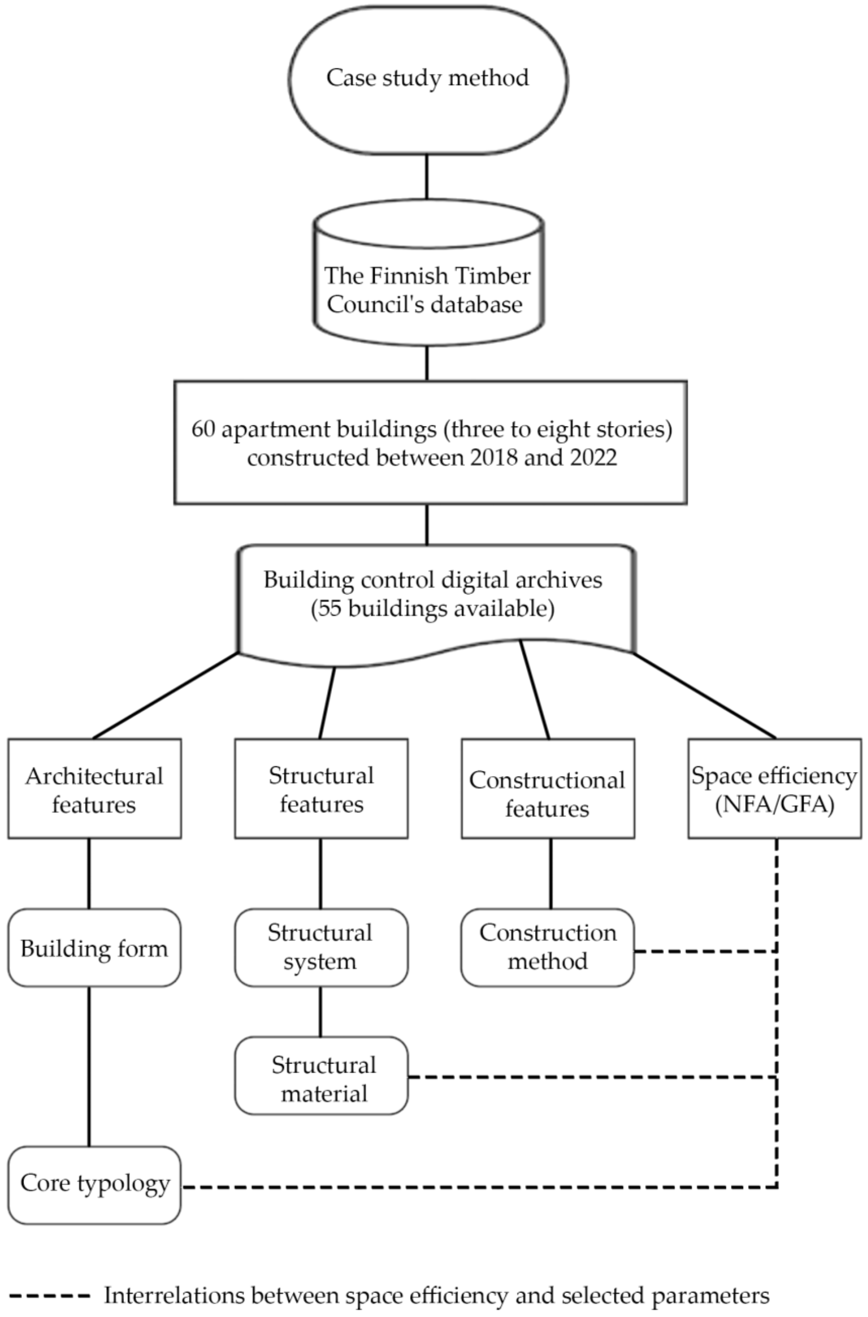


Figure 5. Flowchart of the methodology and process.

4. Results

4.1. Key Features

This section provides a description of the interrelations between space efficiency, structural and architectural features, and constructional features (see Appendix B). The primary features that influence space efficiency include: (1) the structural system, (2) the construction method, (3) the choice of structural materials, (4) the building form, and (5) the typology of the core. These parameters are influenced by the architectural goals, the necessary structural capacities, and the size and height of the building. As the only building form was the prismatic form and the only structural system was the shear wall system in the study sample, no analysis was conducted on these specific parameters. Having only prismatic forms in the sample group may be due to the speed of construction and prefabrication possibilities of prismatic forms. Between 2018 and 2022, the only structural system used was the shear wall system. Similarly, the reason for the high prevalence of this system may be because of its speed of construction with modular elements and its efficient resistance to the lateral loads at the heights achieved so far with timber.

4.1.1. Construction Method

Among the 55 case buildings, the most preferred construction method was 3D volumetric construction with more than 60%, followed by 2D panel construction with approximately 40%. The reason for the predominance of the 3D volumetric construction method may be due to improved working conditions and the shorter construction time on-site [53], especially when building with a few unique volumetric units [54]. Utilizing numerous same-sized and small volumetric units in construction may impact space efficiency, as in the cases of *Marinum* and *Terhikintie*. This effect arises from the fact that the wall elements of 3D volumetric units often possess load-bearing characteristics. Furthermore, in terms of production and transportation, the ideal size of a 3D volumetric unit is 30–33 m^2, having a weight of approximately 15–17 tons, enabling the use of conventional lifting devices on the construction site [55].

In Finland, the typical maximum dimensions of a single 3D volumetric unit are 12 × 4.2 × 3.2 m, where 12 m is the length, 4.2 m is the width, and 3.2 m is the height [56], which might influence the space efficiency. Similar maximum sizes for 3D volumetric units were also reported in [57], where a factory comparison of ten different factories was made based on the maximum size of 3D volumetric units. The factories were located in Europe and the United Kingdom, and the average maximum length and maximum width of the 3D volumetric unit were 11.09 m and 4.51 m, respectively.

4.1.2. Structural Materials

Typical shear wall material types found in the case studies are presented in Figure 6. LVL exhibits comparable compressive strength parallel to the grain when compared to concrete [58]. LVL has better load-bearing capabilities than CLT [59], followed by solid/sawn timber studs. On the other hand, solid timber studs may provide better cost-efficiency and less waste compared to EWPs [60,61], which might explain the high prevalence of them among the case studies. Solid timber studs (i.e., lightweight timber frame) were mostly utilized among the case studies, followed by CLT.

To meet acoustic and fire codes, it is necessary for the party walls between adjacent apartments to have sufficient sound insulation layers (Figure 6b,c,e,g). This, combined with the significant influence of party walls on space efficiency due to their repeated presence throughout the building, could potentially account for the finding that the use of different timber materials does not result in a significant difference in the average ratios of structural wall area to gross floor area, as demonstrated in Table 1.

Table 1. Structural wall area/GFA by material type.

Case Studies by Structural Wall Material	Structural Wall Area/GFA (%)		
	Min.	Max.	Average
Solid timber stud (twenty-nine buildings)	11.3	16.5	13.3
CLT (ten buildings)	9.4	17.0	12.6
Solid timber stud + CLT (nine buildings)	9.6	14.1	12.4
Solid timber stud + LVL (seven buildings)	11.1	13.9	12.7

Figures 7–9 illustrate the total thicknesses of the typical outer, party, and corridor walls in the case studies, respectively. To broaden the scope of the comparison among various timber materials, Figures 7–9 focus solely on the timber materials used, disregarding the distinction between single-framed, double-framed, or overlapped frame walls, as illustrated in Figure 6. In terms of outer walls, significant variations were not observed

when comparing different construction methods, except in the case of *Puumanni* (Figure 7b). In this particular case, the outer wall was constructed solely using CLT and had a thickness of 215 mm without the inclusion of any additional insulation layers.

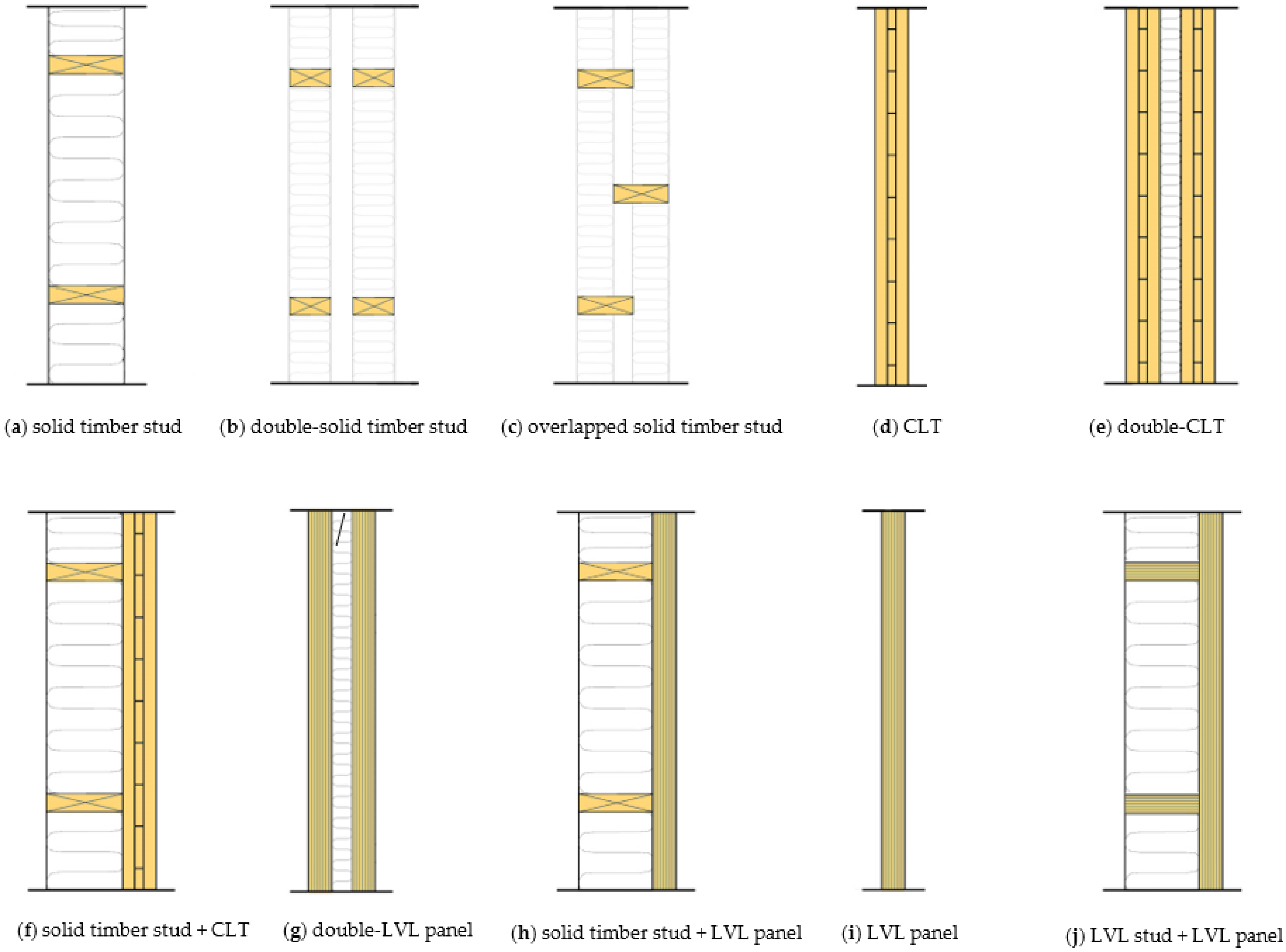
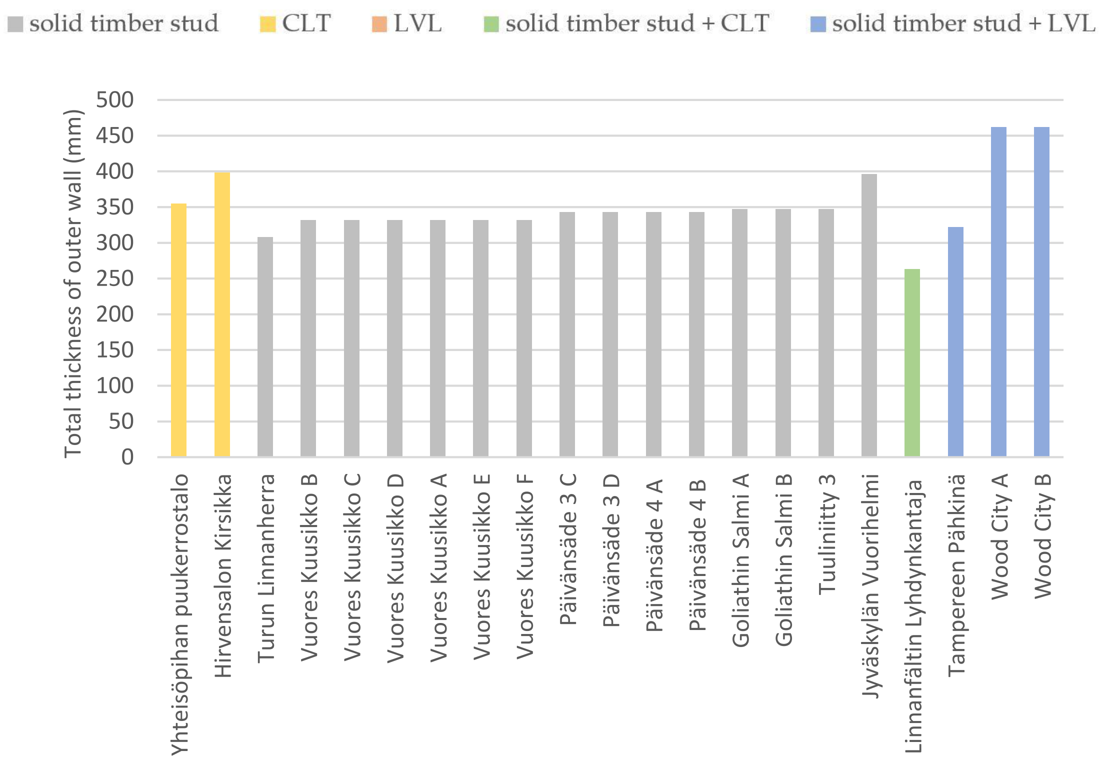


Figure 6. Typical shear wall material types (**a**–**j**). (Surface materials are not depicted in the figure).

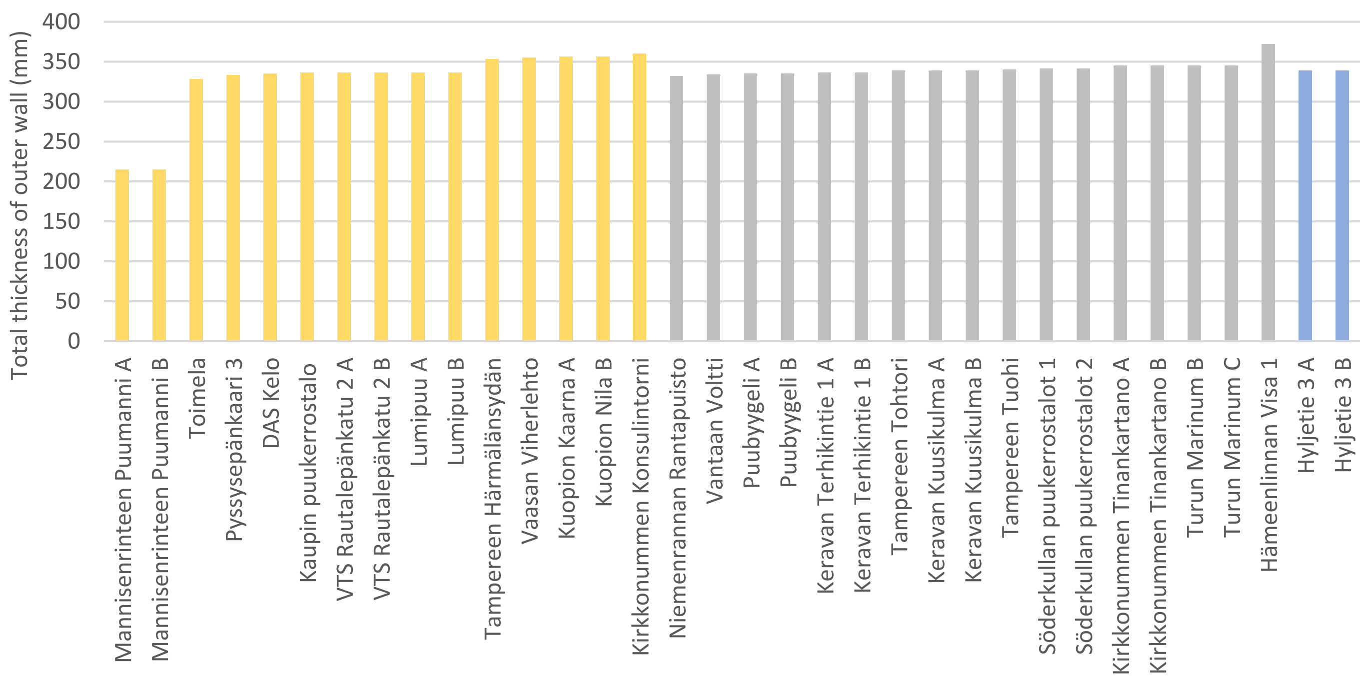
In terms of party walls, significant variations were not observed when comparing different construction methods or structural materials, except for the Wood City case study, which comprised eight stories and relatively long spans.

When comparing the two construction methods, the greatest disparities in total wall thickness are observed in corridor walls. Figure 9b shows that cases constructed using the 3D volumetric construction method exhibit numerous instances where the corridor wall thickness falls below 200 mm. In the case of the Toimela building, where CLT was utilized, the corridor wall had a thickness of 110 mm. In contrast, cases built with the 2D construction method typically have walls measuring around 250 mm (Figure 9a).

In case studies utilizing the 2D panel construction method, the average thickness of typical outer walls and corridor walls was higher. On the other hand, in case studies employing the 3D volumetric construction method, the average thickness of typical party walls was greater (Figure 10). Across all case studies, the average total thickness of all typical shear walls was 295 mm for the 2D panel construction method and 276 mm for the 3D volumetric construction method.



(**a**)



(**b**)

Figure 7. Total thicknesses of typical outer walls in the case studies constructed with (**a**) 2D construction method and (**b**) 3D volumetric construction method.

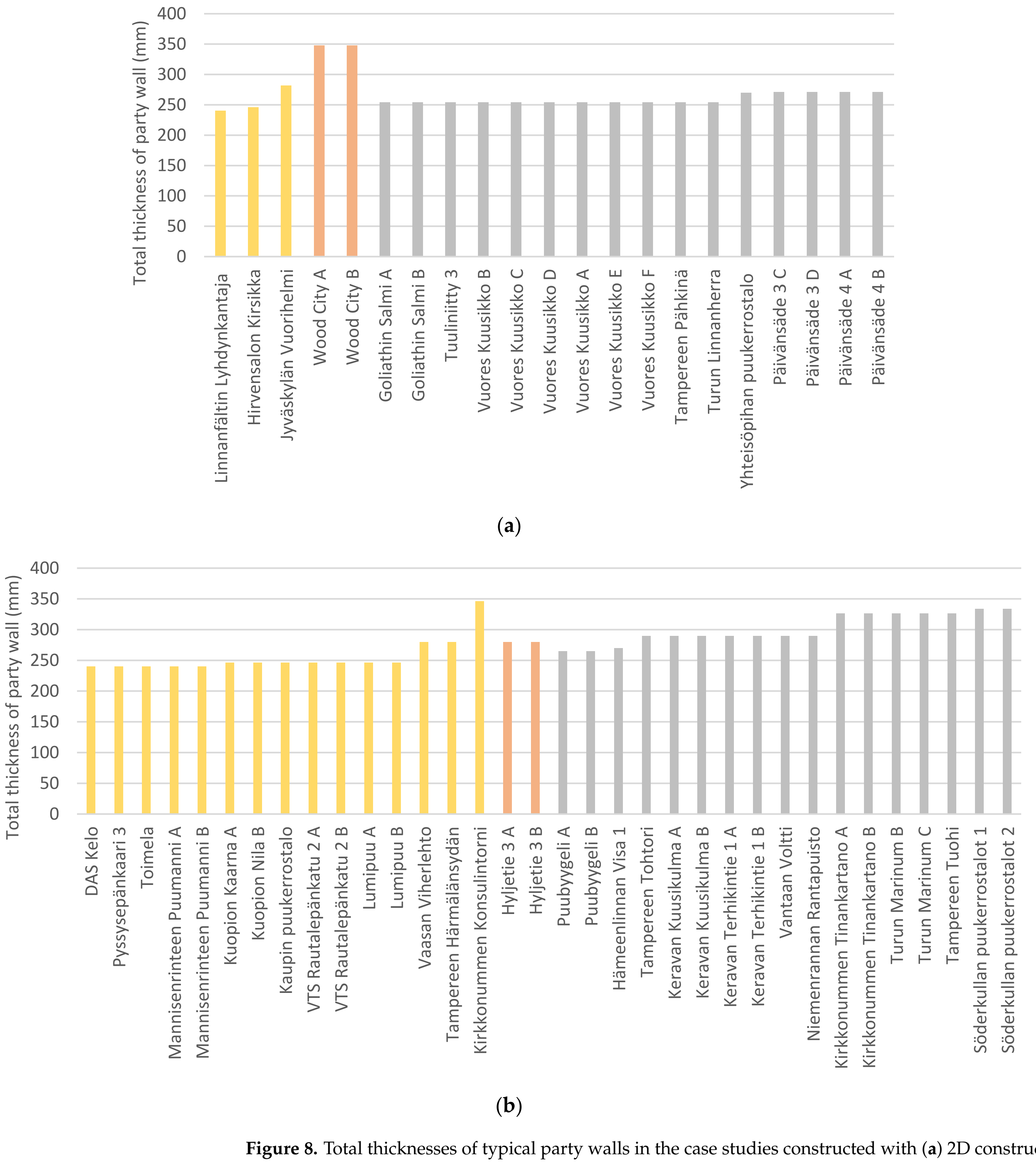
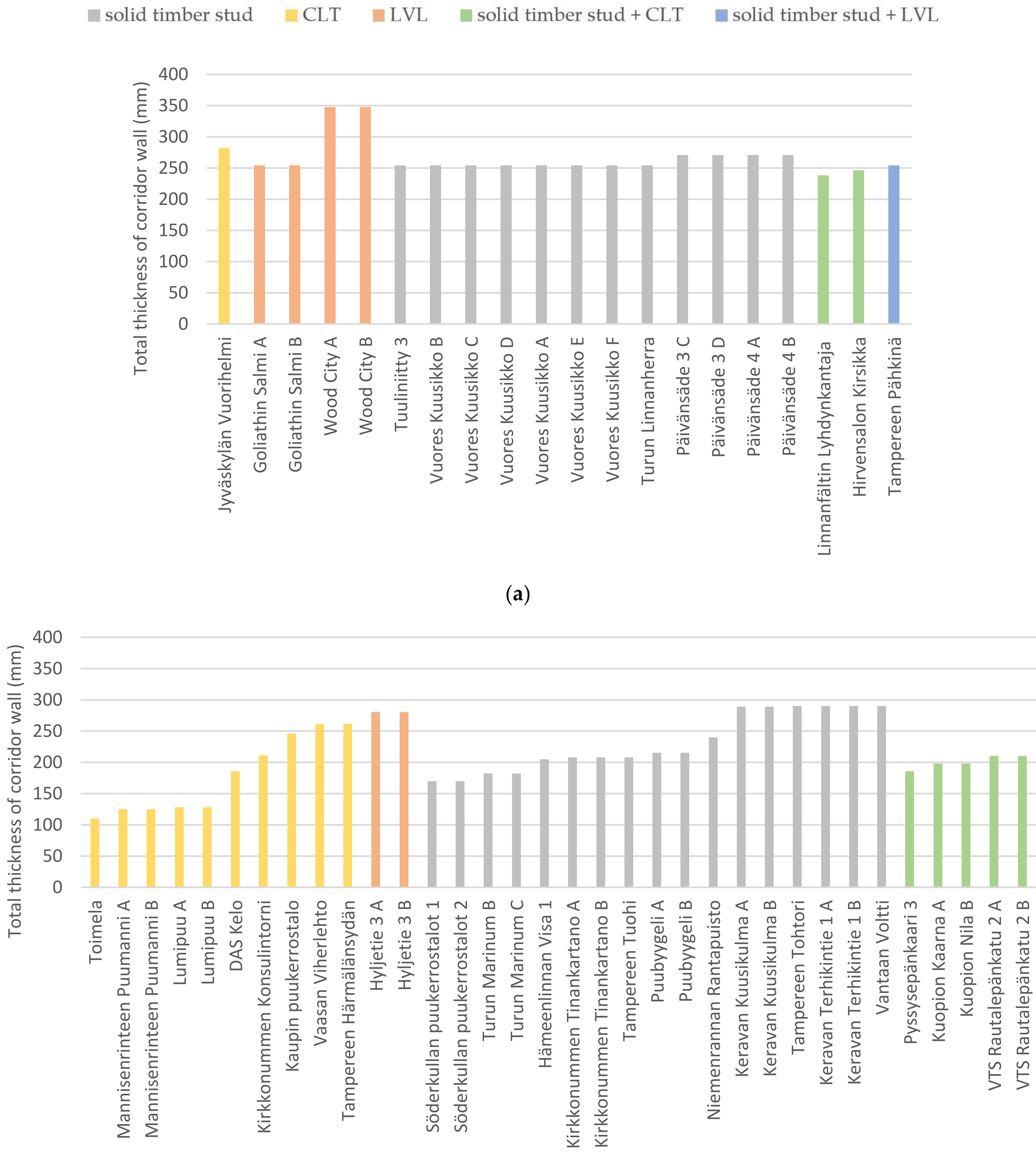


Figure 8. Total thicknesses of typical party walls in the case studies constructed with (**a**) 2D construction method and (**b**) 3D volumetric construction method.



(**a**)

(**b**)

Figure 9. Total thicknesses of typical corridor walls in the case studies constructed with (**a**) 2D construction method and (**b**) 3D volumetric construction method.

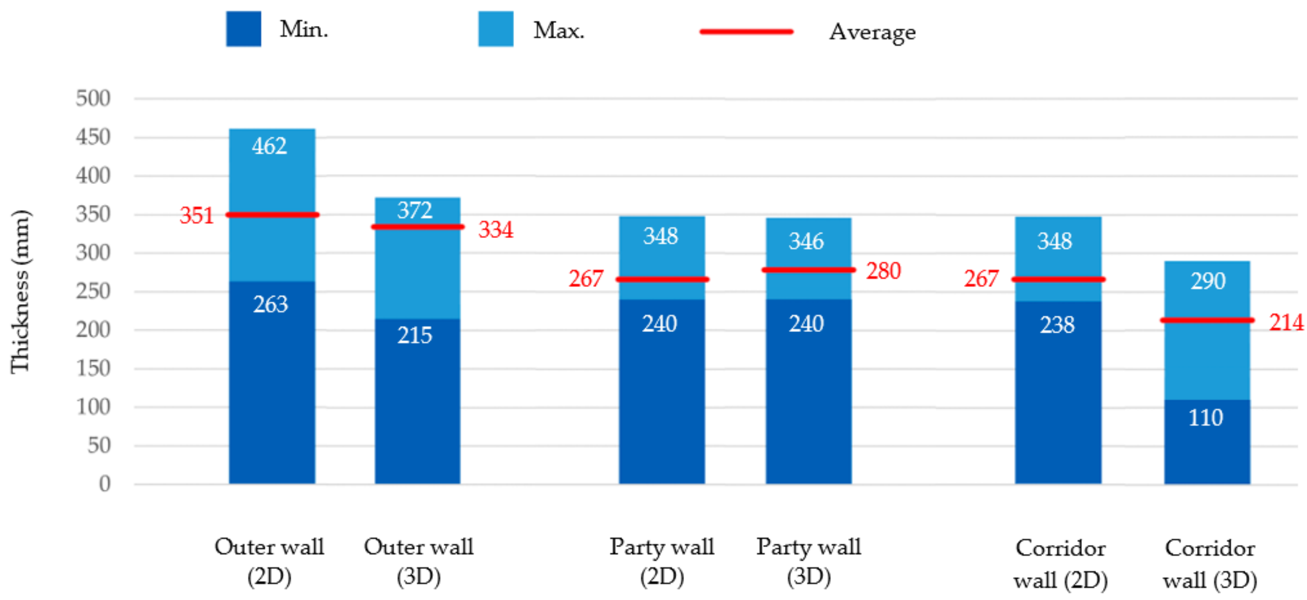


Figure 10. Total thicknesses of the typical shear walls by construction method.

4.1.3. Core Typology

As seen in Figure 11, the most dominant core type was the peripheral core (>50%). In most cases, the building depth was narrow, with the core in the peripheral area adjacent to the building envelope, providing an efficient floor plan, which may explain the dominance of the peripheral core. Among the case buildings, the central core was mostly used in squarish floor plans. The central core enables the placing of apartments at the periphery of the building, with more light and views, and the central core often enables shorter fire escape routes, which may have contributed to the high prevalence of this typology.

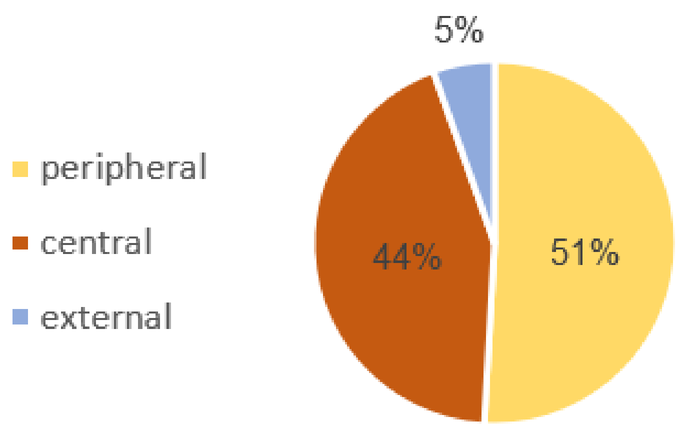


Figure 11. Case studies by core type.

4.2. Space Efficiency

In addition to the abovementioned parameters, space efficiency is affected by structural wall area, vertical circulation area, and technical spaces, including shafts. Lyhdynkantaja had the largest space efficiency, with 87.9%, and one of the smallest structural wall area/GFA ratios in the study sample. Lyhdynkantaja was built with a 2D panel construction method, and it had relatively large spans to further enhance its space efficiency. Among the case studies, the space efficiency ranged from 77.8% to 87.9%, and the average was 83%. As depicted in Figure 12, there was no substantial difference observed among construction methods regarding the average distribution of area for structural walls, vertical circulation, and technical spaces (including shafts).

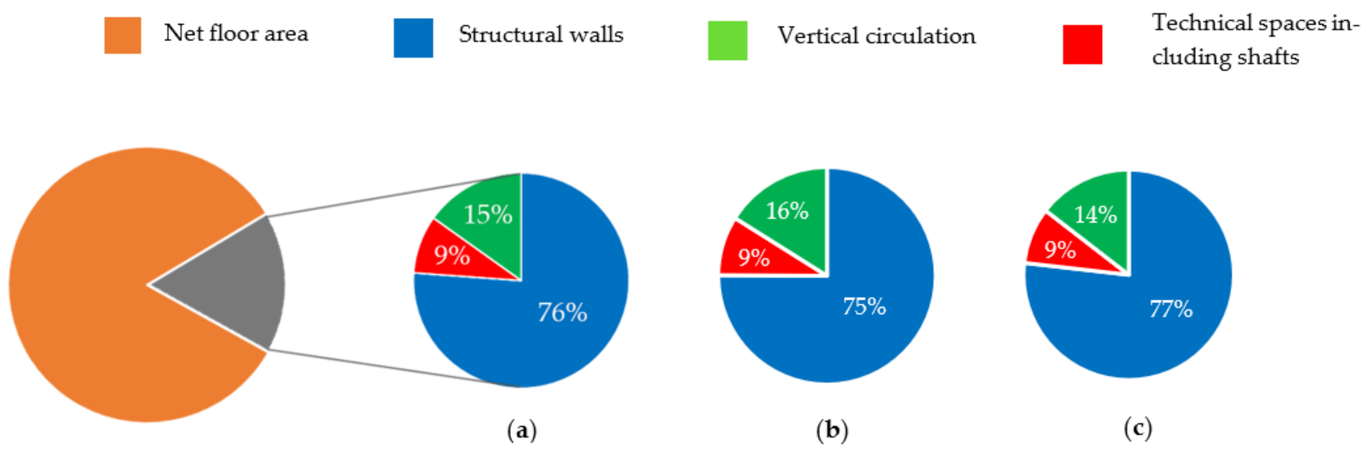


Figure 12. Average distribution of area for structural walls, vertical circulation, and technical spaces (including shafts) in (**a**) all case studies; (**b**) 2D panel construction method; (**c**) 3D volumetric construction method.

As seen in Table 2, there is no significant scientific correlation between the area ratios and construction methods. In buildings constructed using the 3D volumetric construction method, there appears to be a tendency for the average sizes of structural wall areas to be larger. (Table 2). This phenomenon may be attributed to the characteristics of 3D volumetric construction, which typically involve the creation of relatively small volumetric units (Appendix A, Figures A1–A4).

Table 2. Averages of area ratios by construction method.

	2D Panel	3D Volumetric	All Case Studies
Average structural wall area/GFA	11.9%	13.6%	12.9%
Average shaft areas and technical spaces/GFA	1.3%	1.6%	1.5%
Average vertical circulation area/GFA	2.6%	2.7%	2.6%

The data presented in Table 3 indicates the absence of a scientific correlation between the number of stories and average space efficiency. This can be attributed to the fact that there is no requirement in the fire code to increase the size of load-bearing structures in mid-rise buildings, ranging from three to eight stories, as they all belong to the P2 fire class category. Additionally, at these heights, there is no need for an additional staircase in terms of fire escape routes.

Table 3. Average space efficiency of case studies grouped by number of stories and construction methods.

# of Stories	2D Panel Construction Method		3D Volumetric Construction Method		All Case Studies	
	Average Space Efficiency	# of Buildings	Average Space Efficiency	# of Buildings	Average Space Efficiency	# of Buildings
3	83.4%	4	80.4%	4	81.9%	8
4	84.8%	7	82.1%	16	82.9%	23
5	84.3%	7	83.4%	6	83.9%	13
6	84.6%	1	81.8%	4	82.3%	5
7	-	0	83.4%	2	83.4%	2
8	82.8%	2	82.7%	2	82.7%	4

4.3. Interrelations of Space Efficiency and Key Features

The interrelations of space efficiency and the key features, such as construction method, structural materials, and core typology, were examined in this section.

4.3.1. Interrelation of Construction Method and Space Efficiency

Figure 13 displays a set of markers symbolizing the case buildings, organized in ascending order based on their space efficiency. The average space efficiency in 2D panel and 3D volumetric projects were 84.2% and 82.6%, respectively.

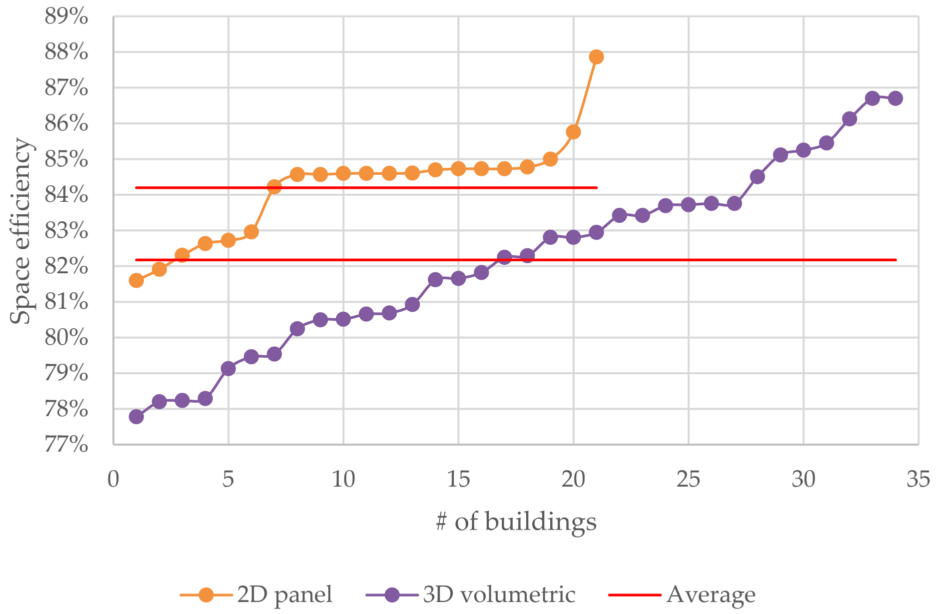


Figure 13. Interrelation of average space efficiency and construction method.

The data indicate that there is no significant difference in the average space efficiency between the 2D panel and 3D volumetric construction methods. This observation may be attributed to the prevalence of numerous small apartments, which is more commonly associated with the 3D panel construction method, as indicated in Figures A1–A4. However, this impact is compensated by the utilization of thicker outer and corridor walls, on average, in the 2D panel construction method (Figure 10).

4.3.2. Interrelation of Structural Materials and Space Efficiency

Typical shear wall material types among the case studies are listed in Table 4. There was not a significant difference between shear wall material and average space efficiency among the case studies.

Table 4. Space efficiency by shear wall material.

Case Studies by Shear Wall Material	Space Efficiency% (NFA/GFA)		
	Min.	**Max.**	**Average**
Solid timber stud (twenty-nine buildings)	77.8	86.1	82.4
CLT (ten buildings)	79.5	86.7	83.0
Solid timber studs + CLT (nine buildings)	82.3	87.9	84.4
Solid timber studs + LVL (seven buildings)	81.6	84.6	83.4

Improving space efficiency can be accomplished by utilizing different combinations of timber materials, such as employing solid timber studs with CLT or solid timber studs alongside LVL. The use of these timber material combinations can result from material optimization to enable thinner shear wall structures and the reduction of the overall size of structural wall area. This approach has the potential to achieve optimal material use and space efficiency (Figure 14). Moreover, in some projects, small parts of the shear walls were reinforced with LVL panels, the use of which could also be due to material optimization, not only enhancing the load-bearing properties of the building.

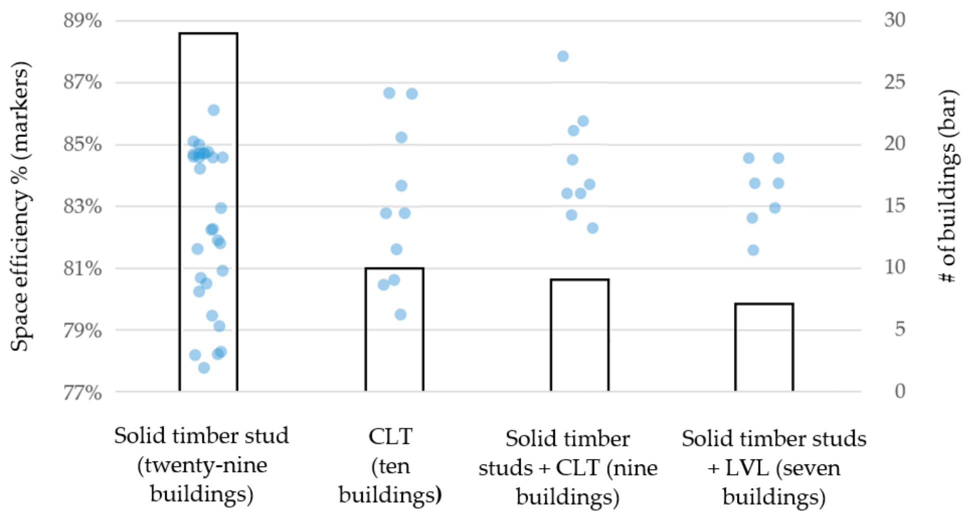


Figure 14. Interrelation of average space efficiency and structural wall material.

4.3.3. Interrelation of Core Typology and Space Efficiency

Case studies featuring a central core achieved the highest level of space efficiency, despite not being the most utilized core type. Their space efficiency started at over 80%. (Figure 15).

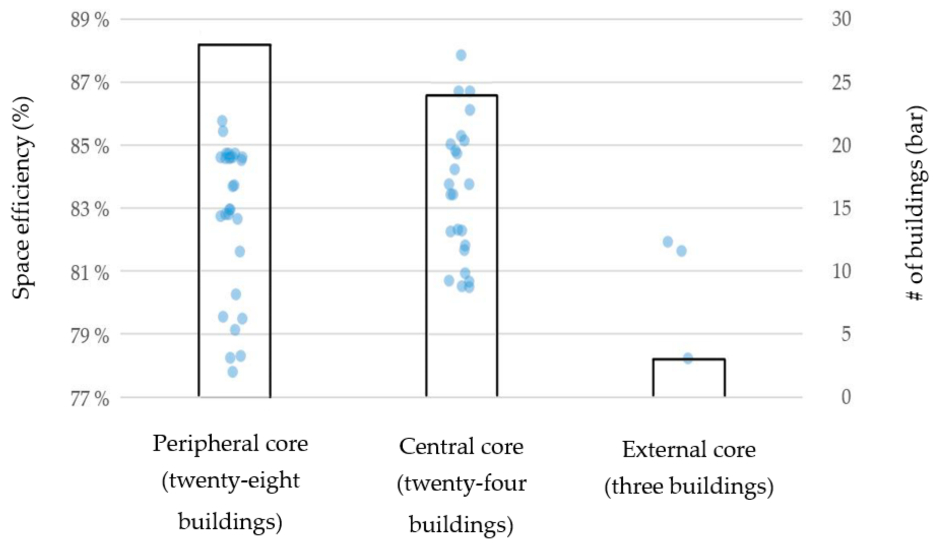


Figure 15. Interrelation of average space efficiency and core type.

Table 5 shows that the best average space efficiency was achieved with central core type, followed by peripheral core type. However, there is not a significant difference between core type and average space efficiency.

Table 5. Average space efficiency by core type.

Core Type	Average Space Efficiency
Central (twenty-four buildings)	83.5%
Peripheral (twenty-eight buildings)	82.7%
External (three buildings)	80.6%

5. Discussion

To date, no study has comprehensively examined the concept of space efficiency in timber apartment buildings. Thus, it was not possible to discuss the effects of different types of timber shear wall materials or different construction methods on space efficiency. Given the scarcity of the available literature, a comprehensive examination of the similarities and differences in space efficiency between Finnish mid-rise timber construction and other countries could not be conducted. Similarly, the absence of relevant studies in the literature on the space efficiency of non-wooden buildings of comparable scale prevented making a comparison in this context. Nevertheless, the following comparisons were drawn based on space efficiency-focused studies discussed in the literature review section.

The analysis revealed that among the examined case studies, the sole structural system identified was the shear wall system. Similarly, Ref. [36] 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. These findings differ from the findings of [28,29,40], which indicated that the super-tall (300 m or taller) buildings used an outriggered frame system predominantly. As stated in Ref. [28], the prevalence of an outriggered frame system might be due to its flexible properties regarding the perimeter column arrangement for providing relatively more freedom in the building's façade design as well as the ability to reach greater heights. In this paper, the case study buildings mostly utilized the shear wall system as the structural system, and it may be because of its ease of construction with modular elements, also accompanied by effective lateral stiffness at the heights of mid-rise timber apartment buildings. According to [48], the reasons behind this prevalence may be due to the advantages of shear wall systems, such as the speed of construction, compatibility with prefabrication techniques, efficiency, and sufficient stiffness to resist lateral loads in buildings up to about 35 stories. Furthermore, the shear wall system's effectiveness in providing lateral stiffness is particularly crucial in mid-rise timber apartment buildings. These structures often need to contend with lateral forces arising from wind loads and other external factors, and the shear wall system offers a reliable solution to resist these forces. Its effectiveness in mitigating lateral movements and enhancing overall stability is essential, especially given the height range of these buildings. The choice of the shear wall system could also be influenced by the structural and material properties of the timber used in the construction. Timber, as a natural material, has inherent qualities that make it suitable for shear resistance, especially when engineered products such as CLT or LVL are employed. These materials offer both strength and flexibility, making them well-suited for the demands of mid-rise construction. The synergistic combination of ease of construction, lateral stiffness, material properties, and sustainability considerations likely contributes to the prevalence of the shear wall system in mid-rise timber apartment buildings.

Within this research paper, the study sample exclusively consisted of buildings with a prismatic form. The findings of [28] showed that prismatic forms were mostly used. The high prevalence of prismatic forms can be explained by the ease of construction compared to more complex shapes. One significant rationale for the high occurrence of prismatic forms is the inherent ease of construction when compared to more intricate or irregular shapes. The architectural detailing and construction methods involved in creating complex geometries can introduce challenges that may increase the overall construction time and costs. Prismatic forms, with their regularity and uniformity, align more harmoniously with conventional construction techniques, leading to smoother project execution. The practicality of prismatic-shaped buildings further enhances their appeal. The emphasis on rectangular floor plans, which is a common manifestation of prismatic forms, offers notable advantages in terms of space utilization and functional efficiency. The uniformity of interior spaces enables the efficient arrangement of rooms and layout consistency, making it easier to allocate living spaces, utilities, and amenities. This design approach fosters a sense of functional organization within the building, promoting convenience and adaptability for future occupants. The modular nature of prismatic shapes contributes to optimizing construction materials and resources. The regularity in design often translates into standardized components, which can be prefabricated, thereby streamlining the construction process and minimizing waste. This alignment with prefabrication and modular construction methods not only accelerates the building process but also aligns with sustainable construction practices by reducing material waste and energy consumption. In contrast, the studies of Refs. [29,40] reported that among super-tall office buildings, other forms, such as tapered and free forms, were most employed. In super-tall buildings, the high prevalence of the tapered form could be for its aerodynamic and structural efficiency [49].

The average area of the apartments is typically determined at the early stages of the project's goals, which means that space efficiency typically cannot be improved with longer spans. As mentioned in Ref. [40], the implementation of tapered forms to reduce the upper floor area in buildings may be suitable for planning a mixed-use building, as it can offer diverse possibilities for span configurations. In the case studies examined, there were some variations in the positioning of structural walls at the highest floor compared to the typical floor in the cases of Pähkinä and Lyhdynkantaja. These variations were achieved by removing or moving the position of party walls between apartments. These variations could potentially arise from the client's requirement to diversify the distribution of apartments, with the top floor offering the most advantageous opportunity for implementing a distinct apartment arrangement due to structural considerations.

Among the case studies, central core was the most used core type. Similarly, the findings of Refs. [28,29,40] showed that among contemporary super-tall office, residential, and mixed-use buildings, the central core was the most preferred core type. Placing the core centrally allows for more apartments to be situated along the building's outer perimeter, thereby ensuring that a larger number of units can benefit from ample natural light and potentially offer scenic views of the surrounding environment. From a safety perspective, the central core configuration plays a crucial role. It allows for a more efficient escape route, which is particularly significant in compliance with fire code regulations. The shorter distance from apartments to the central core can expedite evacuation in case of emergencies. This aspect has likely contributed to the prevalence of the central core typology. Moreover, the architectural advantages of the central core are noteworthy. Compared to peripheral or exterior core arrangements, where staircases often intersect with the façade, the central core offers greater design flexibility for the building's exterior appearance. The absence of a staircase disrupting the façade design in the central core configuration enables a more harmonious and continuous aesthetic. Architects can explore a wider range of façade treatments, materials, and features, resulting in a more visually appealing building. This creative freedom enhances the architectural expression of the building while maintaining a functional and efficient core layout. The absence of atrium core configurations in the sample can be accounted for by the relatively larger construction area typically needed for atrium buildings. Additionally, having an atrium core could result in an expansion of the façade area due to the presence of the atrium, potentially resulting in increased energy consumption.

Among the case studies of this paper, there was no scientific correlation between building height and space efficiency. However, Refs. [28,29,40] reported that as the height of the building increased, space efficiency decreased, which was explained by the fact that the taller the structures, the larger the dimensions of load-bearing components. Nevertheless, empirical evidence from timber buildings in Europe indicates the feasibility of reducing the cross-sectional area of CLT structural walls on higher floors as the building increases in height.

The space efficiency and material utilization of a building are notably impacted by the repeated occurrence of party walls throughout the structure, underscoring the importance for designers to thoroughly evaluate diverse alternatives and thicknesses for these party walls. Regarding the corridor walls, designers could consider alternatives, such as the feasibility of attaching the corridor slab to the neighboring apartment wall using short vertical supports affixed by diagonal screws or evaluating whether the corridor slab must be independently supported, extending all the way to the foundations as a distinct vertical wall structure. The choice between these assembly methods significantly impacts both material utilization and space efficiency. Furthermore, not all projects applied the understanding that the wall separating the building's corridor from the apartment can be narrower in areas of the apartment that are not designated as actual living spaces, such as hallways. The differences of these wall thicknesses arise from dissimilar sound insulation specifications designated for the apartment's hallway compared to the actual living areas. While designers could consider these options in their plans, it is essential not to rely solely on this factor to dictate the overall design.

6. Conclusions

This study mapped out the current state of the art regarding space efficiency of mid-rise (three to eight story) timber apartment buildings in the Finnish context. The case studies were examined regarding their structural, architectural, and constructional features to find interrelations to space efficiency.

The findings are summarized as follows:

- Among the case studies, the space efficiency ranged from 77.8% to 87.9%, and the average was 83%.
- The mean values of the ratios of structural wall area to gross floor area, vertical circulation area to gross floor area, and technical spaces (including shafts) to gross floor area were found to be 12.9%, 2.6%, and 1.5%, respectively.
- Construction methods or shear wall materials make no significant difference in terms of space efficiency, and there is no scientific correlation between the number of stories and space efficiency.
- The best average space efficiency was achieved with the central core type, followed by peripheral core arrangement.

This research significantly contributes to the understanding of space efficiency in mid-rise timber apartment buildings. By analyzing data from 55 Finnish mid-rise timber apartment buildings constructed within a specific time frame, the study offers insights into the factors and design parameters that influence space efficiency in this context. The findings provide valuable information for improving the design, planning, and construction of mid-rise timber apartment buildings, ultimately enhancing their feasibility and functionality.

The methodology employed in this research is innovative in its holistic approach to assessing space efficiency. By examining a wide range of factors, including structural wall area, vertical circulation area, technical spaces (including shafts), and core arrangements, the study offers a comprehensive understanding of the complex interplay that affects space efficiency in mid-rise timber apartment buildings. This multidimensional methodology adds depth to the analysis and contributes to a more robust evaluation of space efficiency determinants.

While this study provides valuable insights into space efficiency in mid-rise timber apartment buildings, it also has certain limitations. The dataset was constrained to the specific Finnish setting, encompassing the applicable Land Use and Building Act, within the time frame of 2018 to 2022. Thus, further studies could explore buildings governed by different Building Acts over an extended time frame. Future studies could also concentrate on the assessment of space efficiency in buildings featuring diverse structural systems, such as the rigid frame system. This system is acknowledged for its capacity to deliver heightened spatial flexibility and extended spans owing to its constructional attributes involving the on-site utilization of posts and beams. Moreover, the inclusion of additional nations (e.g., Nordic countries or Central Europe) within the sample group could offer valuable insights.

The primary objective of this article is not to prescribe specific construction methods or materials, given the uniqueness of each project and the variation in apartment layout requirements. Instead, the results offer valuable insights for refining the space efficiency of the building during the planning phase, considering the diverse selection criteria associated with structural, architectural, and constructional features. Considering our research findings, it can be discerned that the employment of the 2D panel construction method with a central core configuration may potentially lead to advantageous outcomes regarding space efficiency. The outcomes of our study suggest that these construction choices could offer substantial benefits in optimizing the utilization of available space within the built environment. To further enhance space efficiency, the utilization of timber material combinations, such as solid timber studs combined with either CLT or LVL, can be implemented. This can be performed specifically on the lower floors or strategically placed throughout the building. By employing these timber material combinations, the overall shear wall structures can be made thinner, leading to an optimized use of space.

Timber constructions possess distinct constraints concerning the preferred distribution of apartments, span lengths, and load-bearing capacities. These restrictions influence the layout and configuration of interior spaces, affecting space efficiency. Moreover, many small apartments can lead to suboptimal space utilization within the building. By understanding and navigating technical, regulatory, design, and cost-related limitations, designers can develop effective strategies to overcome these obstacles.

Finding the right balance between space efficiency, safety, aesthetics, functionality, and sustainability is key to creating successful timber apartment buildings that maximize usable space while meeting the diverse needs of occupants. Therefore, effective communication and interdisciplinary collaboration among various stakeholders at the early stages of timber apartment building design are needed. The outcomes of this research will be helpful for architects and structural designers regarding space efficiency in the preliminary design phase of a mid-rise timber apartment building.

Building upon the current research, future investigations can expand the scope to include a more diverse range of geographic regions and building contexts. Comparative studies across different regulatory environments, construction methods, and materials can provide a more comprehensive understanding of the factors influencing space efficiency. Additionally, exploring the integration of sustainable practices and innovative technologies in mid-rise timber apartment buildings could further enhance their space efficiency and overall sustainability. Overall, this research significantly advances the understanding of space efficiency in mid-rise timber apartment buildings, offering valuable insights to guide design decisions and inform the practices of various stakeholders in the construction industry.

As mentioned, the research findings are primarily limited to the context of Finnish mid-rise timber apartment buildings constructed under the Finnish Land Use and Building Act between 2018 and 2022. However, in further studies, a sensitivity analysis could be conducted to assess the potential repercussions of alterations in the context, encompassing diverse regulatory frameworks, building practices, and environmental conditions on the observed space efficiency outcomes. By conducting this analysis, the research could assess the extent to which the findings are transferable to other regions and contexts. Sensitivity analysis could involve comparing the results with data from different countries or regions to determine the robustness and generalizability of the findings. Furthermore, in future research endeavors, it may be worthwhile to perform an uncertainty analysis. The ensuing aspects can be noted. The uncertainty of the research results can stem from several sources. The limited time frame of data collection (2018–2022) may not fully capture long-term trends and changes in construction practices. Additionally, the study’s focus on a specific legal framework and construction period introduces uncertainties about the applicability of the findings to different regulatory environments or time periods. The potential variability in data accuracy, data collection methods, and measurement errors may also contribute to uncertainty.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A

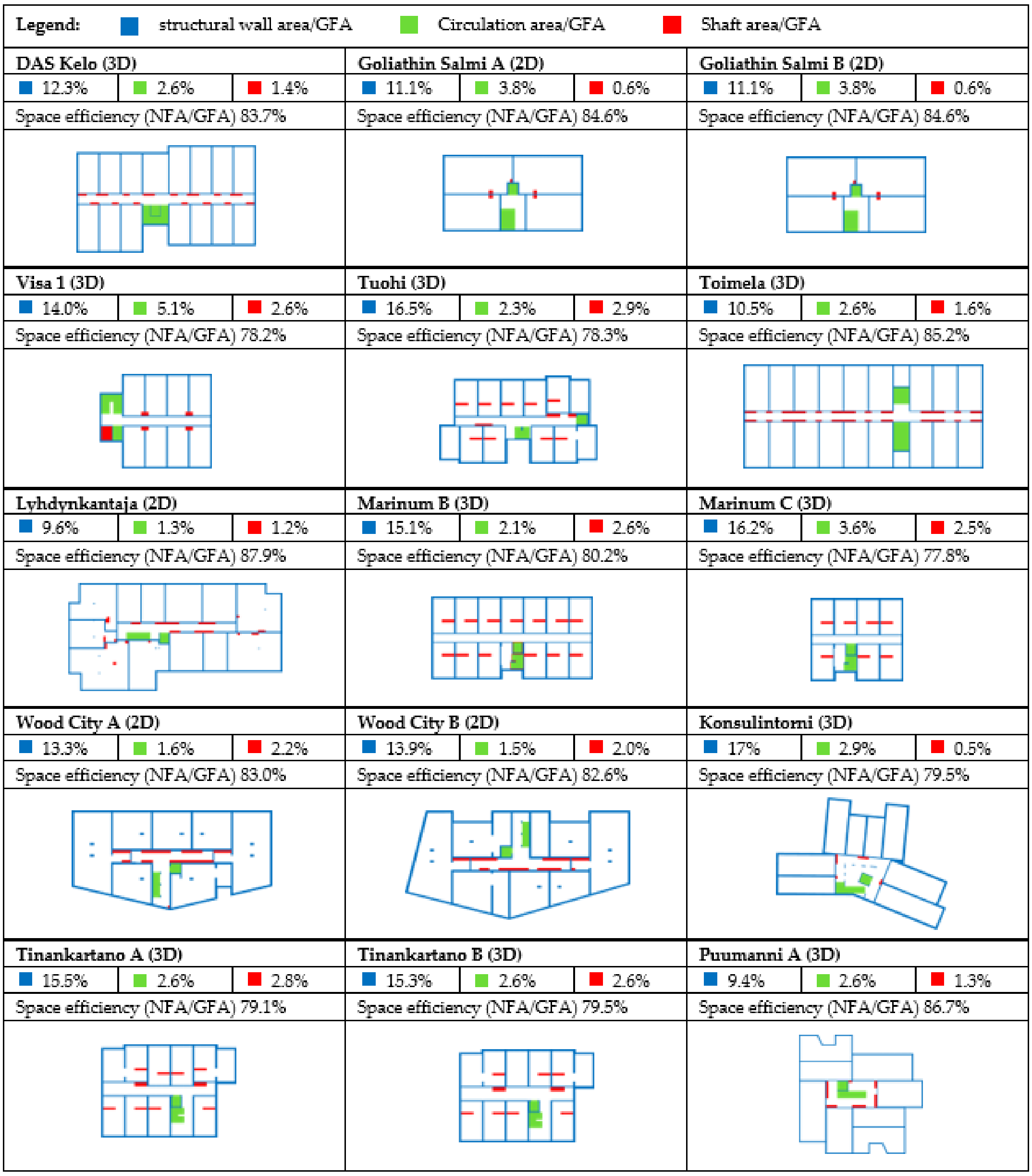

Figure A1. Floor plan diagrams of typical stories 1:1000 (1).

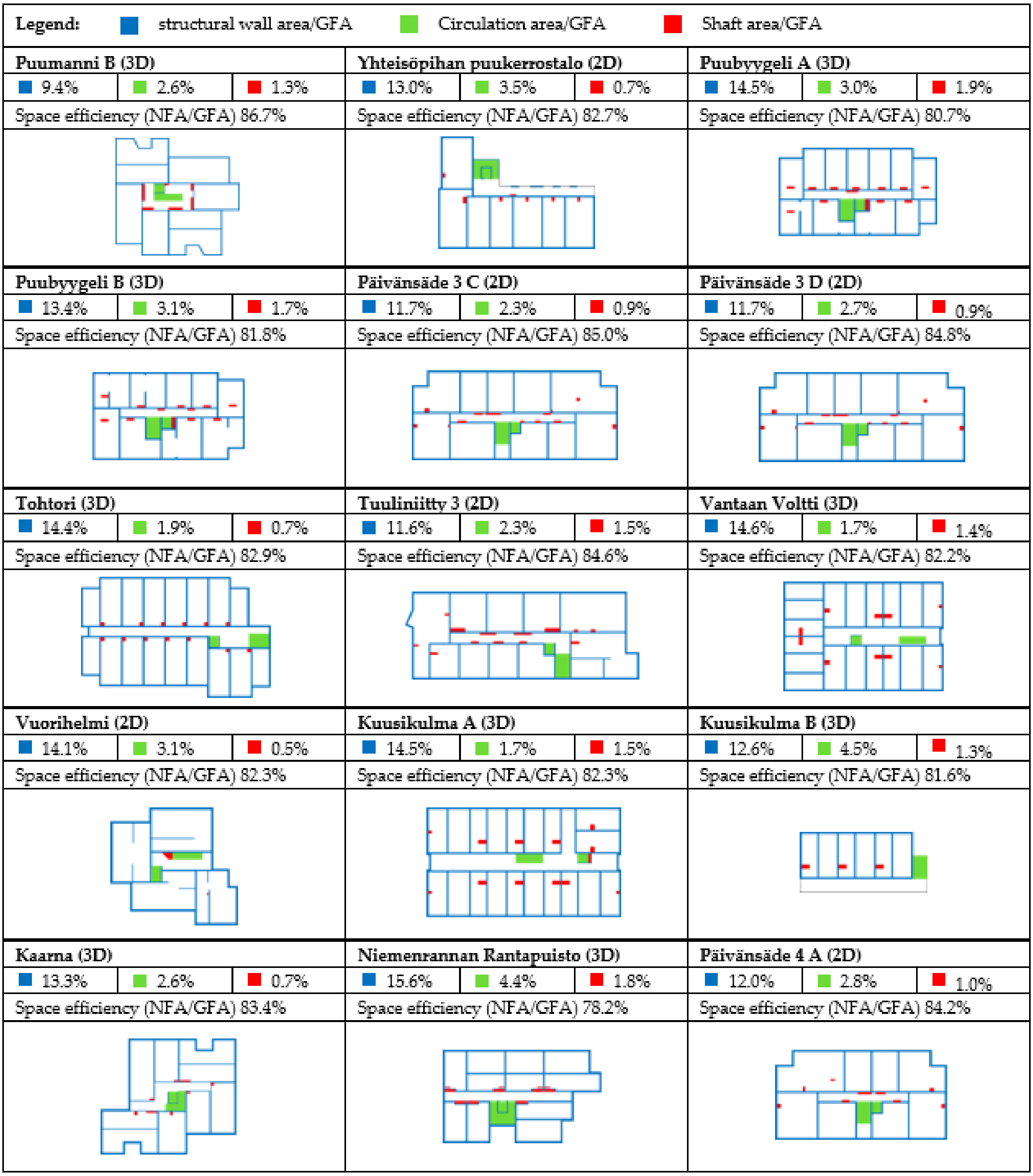

Figure A2. Floor plan diagrams of typical stories 1:1000 (2).

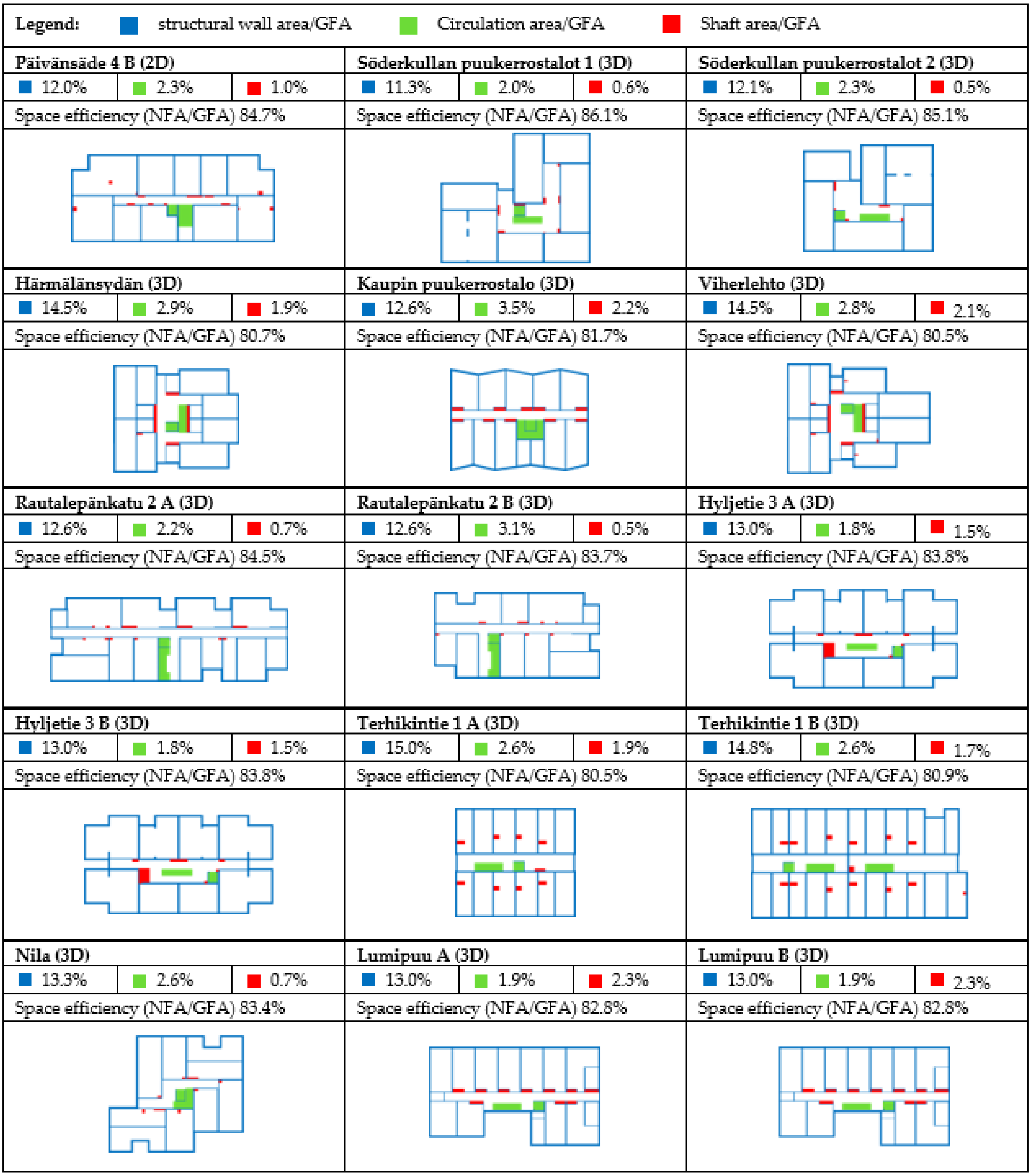

Figure A3. Floor plan diagrams of typical stories 1:1000 (3).

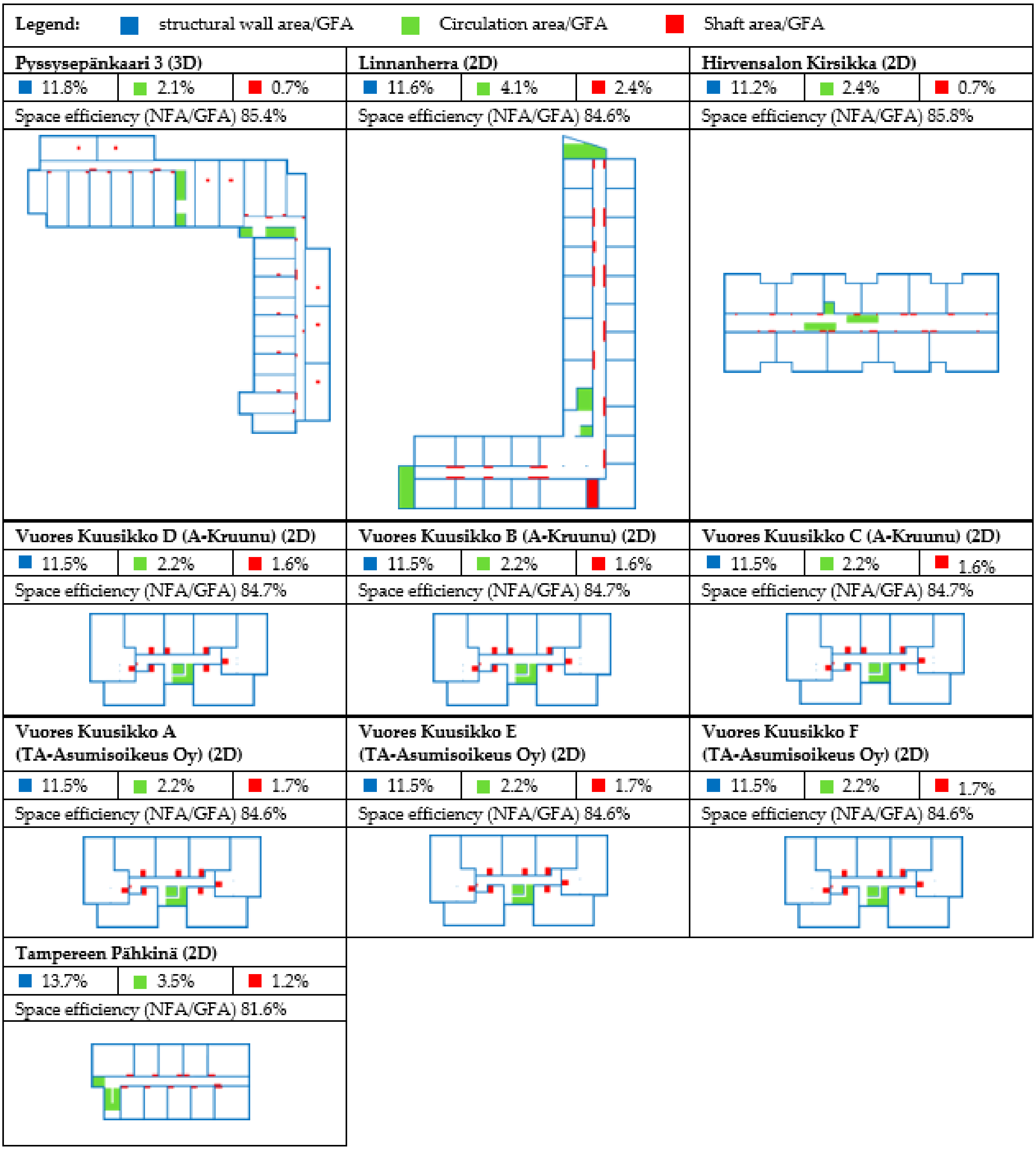

Figure A4. Floor plan diagrams of typical stories 1:1000 (4).

Appendix B

General information of the case studies.

Building Name City	Completion Year	Building Height (mm) [1]	# of Stories	Construction Method	GFA (m^2)	NFA (m^2)	Space Efficiency	Structural Wall Material Type	Core Type
DAS Kelo Rovaniemi	2019	26,632	8	3D Volumetric	572.8	479.4	83.7%	CLT	peripheral
Goliathin Salmi, Building A Turku	2019	14,420	4	2D Panel	348.5	294.7	84.6%	solid timber stud + LVL	peripheral

Building Name City	Completion Year	Building Height (mm) [1]	# of Stories	Construction Method	GFA (m^2)	NFA (m^2)	Space Efficiency	Structural Wall Material Type	Core Type
Goliathin Salmi, Building B Turku	2019	14,000	4	2D Panel	348.5	294.7	84.6%	solid timber stud + LVL	peripheral
Hämeenlinnan Visa 1 Hämeenlinna	2019	12,730	4	3D Volumetric	312.8	244.6	78.2%	solid timber stud	external
Tampereen Tuohi Tampere	2019	15,295	4	3D Volumetric	376.9	295.1	78.3%	solid timber stud	peripheral
Toimela Nurmijärvi	2019	14,155	4	3D Volumetric	830.8	708.2	85.2%	CLT	central
Turun Linnanfältin Lyhdynkantaja Turku	2019	17,496	5	2D Panel	655.4	575.8	87.9%	solid timber stud + CLT	central
Turun Marinum, Building B Turku	2019	12,557	3	3D Volumetric	438.1	351.6	80.2%	solid timber stud	peripheral
Turun Marinum, Building C Turku	2019	12,527	3	3D Volumetric	250.4	194.8	77.8%	solid timber stud	peripheral
Wood City, Building A Helsinki	2019	26,012	8	2D Panel	576.7	478.4	83.0%	solid timber stud + LVL	peripheral
Wood City, Building B Helsinki	2019	25,876	8	2D Panel	633	523.1	82.6%	solid timber stud + LVL	peripheral
Kirkkonummen Konsulintorni Kirkkonummi	2020	14,814	4	3D Volumetric	371	295.1	79.5%	CLT	peripheral
Kirkkonummen Tinankartano, Building A Kirkkonummi	2020	13,933	4	3D Volumetric	357.7	283.0	79.1%	solid timber stud	peripheral
Kirkkonummen Tinankartano, Building B Kirkkonummi	2020	13,933	4	3D Volumetric	357.7	284.2	79.5%	solid timber stud	peripheral
Mannisenrinteen Puumanni, Building A Jyväskylä	2020	16,274	4	3D Volumetric	376.4	326.3	86.7%	CLT	central
Mannisenrinteen Puumanni, Building B Jyväskylä	2020	15,206	4	3D Volumetric	376.4	326.3	86.7%	CLT	central
Nurmeksen Yhteisöpihan puukerrostalo Nurmes	2020	10,364	3	2D Panel	397.2	328.6	82.7%	solid timber stud + CLT	peripheral
Puubyygeli, Building A Turku	2020	14,517	4	3D Volumetric	437	352.6	80.7%	solid timber stud	central
Puubyygeli, Building B Turku	2020	11,264	3	3D Volumetric	428.5	350.6	81.8%	solid timber stud	central
Päivänsäde 3, Building C Turku	2020	13,925	4	2D Panel	574	487.9	85.0%	solid timber stud	central
Päivänsäde 3, Building D Turku	2020	10,426	3	2D Panel	505	428.1	84.8%	solid timber stud	central
Tampereen Tohtori Tampere	2020	18,692	5	3D Volumetric	635.7	527.3	82.9%	solid timber stud	peripheral
Tuuliniitty 3 Espoo	2020	19,003	5	2D Panel	628.3	531.6	84.6%	solid timber stud	peripheral
Vantaan Voltti Vantaa	2020	16,905	5	3D Volumetric	567.1	466.4	82.2%	solid timber stud	central
Jyväskylän Vuorihelmi Jyväskylä	2021	16,503	5	2D Panel	365.7	301.0	82.3%	solid timber stud + CLT	central
Keravan Kuusikulma, Building A Kerava	2021	17,581	5	3D Volumetric	673.8	554.5	82.3%	solid timber stud	central
Keravan Kuusikulma, Building B Kerava	2021	10,900	3	3D Volumetric	241.2	196.9	81.6%	solid timber stud	external
Kuopion Kaarna, Building A Kuopio	2021	22,994	7	3D Volumetric	411.4	343.2	83.4%	solid timber stud + CLT	central
Niemenrannan Rantapuisto Tampere	2021	15,194	4	3D Volumetric	398.7	311.9	78.2%	solid timber stud	peripheral
Päivänsäde 4, Building A Turku	2021	10,563	3	2D Panel	473	398.4	84.2%	solid timber stud	central
Päivänsäde 4, Building B Turku	2021	13,400	4	2D Panel	574	486.2	84.7%	solid timber stud	central
Söderkullan puukerrostalot. Building 1 Sipoo	2021	13,227	4	3D Volumetric	515.3	443.8	86.1%	solid timber stud	central
Söderkullan puukerrostalot. Building 2 Sipoo	2021	13,229	4	3D Volumetric	430.3	366.3	85.1%	solid timber stud	central
Tampereen Härmälänsydän Tampere	2021	14,700	4	3D Volumetric	385	310.5	80.7%	CLT	central
Tampereen Kaupin puukerrostalo Tampere	2021	27,718	8	3D Volumetric	446.5	364.6	81.7%	CLT	central
Vaasan Viherlehto Vaasa	2021	19,891	6	3D Volumetric	402.5	324.0	80.5%	CLT	central
VTS Rautalepänkatu 2. Building A Tampere	2021	15,585	4	3D Volumetric	599.6	506.7	84.5%	solid timber stud + CLT	peripheral
VTS Rautalepänkatu 2. Building B Tampere	2021	14,630	4	3D Volumetric	424.9	355.7	83.7%	solid timber stud + CLT	peripheral

Building Name City	Completion Year	Building Height (mm) [1]	# of Stories	Construction Method	GFA (m^2)	NFA (m^2)	Space Efficiency	Structural Wall Material Type	Core Type
Hyljetie 3, Building A Espoo	2022	18,712	5	3D Volumetric	557.5	466.9	83.8%	solid timber stud + LVL	central
Hyljetie 3, Building B Espoo	2022	18,582	5	3D Volumetric	557.5	466.9	83.8%	solid timber stud + LVL	central
Keravan Terhikintie 1, Building A Kerava	2022	15,484	4	3D Volumetric	420.5	338.5	80.5%	solid timber stud	central
Keravan Terhikintie 1, Building B Kerava	2022	22,939	6	3D Volumetric	725.1	586.8	80.9%	solid timber stud	central
Kuopion Nila, Building B Kuopio	2022	22,878	7	3D Volumetric	411.4	343.2	83.4%	solid timber stud + CLT	central
Lumipuu, Building A Tampere	2022	20,581	6	3D Volumetric	482.1	399.2	82.8%	CLT	peripheral
Lumipuu, Building B Tampere	2022	20,597	6	3D Volumetric	482.1	399.2	82.8%	CLT	peripheral
Pyssysepänkaari 3 Kirkkonummi	2022	16,298	5	3D Volumetric	1195.3	1021.4	85.4%	solid timber stud + CLT	peripheral
Tampereen Pähkinä Tampere	2022	19,280	5	2D Panel	379.1	309.3	81.6%	solid timber stud + LVL	peripheral
Turun Hirvensalon Kirsikka Turku	2022	14,563	4	2D Panel	783	671.5	85.8%	solid timber stud + CLT	peripheral
Turun Linnanherra Turku	2022	12,500	3	2D Panel	1234.6	1011.3	81.9%	solid timber stud	external
Vuores Kuusikko (A-Kruunu Oy) Building B Tampere	2022	17,348	5	2D Panel	492.3	417.1	84.7%	solid timber stud	peripheral
Vuores Kuusikko (A-Kruunu Oy) Building C Tampere	2022	17,484	5	2D Panel	492.3	417.1	84.7%	solid timber stud	peripheral
Vuores Kuusikko (A-Kruunu Oy) Building D Tampere	2022	14,369	4	2D Panel	492.3	417.1	84.7%	solid timber stud	peripheral
Vuores Kuusikko (TA-Asumisoikeus Oy) Building A Tampere	2022	20,849	6	2D Panel	492.3	416.5	84.6%	solid timber stud	peripheral
Vuores Kuusikko (TA-Asumisoikeus Oy) Building E Tampere	2022	17,578	5	2D Panel	492.3	416.5	84.6%	solid timber stud	peripheral
Vuores Kuusikko (TA-Asumisoikeus Oy) Building F Tampere	2022	14,876	4	2D Panel	492.3	416.5	84.6%	solid timber stud	peripheral

[1] Building height is measured according to the Finnish building code.

References

1. Jia, N.; Li, Y.; Chen, R.; Yang, H. A Review of Global PM2.5 Exposure Research Trends from 1992 to 2022. *Sustainability* **2023**, *15*, 10509. [CrossRef]
2. Shen, L.; Ochoa, J.J.; Bao, H. Strategies for Sustainable Urban Development—Exploring Innovative Approaches for a Liveable Future. *Buildings* **2023**, *13*, 764. [CrossRef]
3. Koomen, E.; van Bemmel, M.S.; van Huijstee, J.; Andrée, B.P.J.; Ferdinand, P.A.; van Rijn, F.J.A. An integrated global model of local urban development and population change. *Comput. Environ. Urban Syst.* **2023**, *100*, 101935. [CrossRef]
4. Rek-Woźniak, M. Discourses of growth in megaproject-based urban development: A comparative study of Poland and Finland. *Policy Soc.* **2023**, *42*, 245–258. [CrossRef]
5. Liu, Y.; Sang, M.; Xu, X.; Shen, L.; Bao, H. How Can Urban Regeneration Reduce Carbon Emissions? A Bibliometric Review. *Land* **2023**, *12*, 1328. [CrossRef]
6. Talvitie, I.; Kinnunen, A.; Amiri, A.; Junnila, S. Can future cities grow a carbon storage equal to forests? *Environ. Res. Lett.* **2023**, *18*, 044029. [CrossRef]
7. Suomala, T. Understanding the Perceptions of Urban Citizens Concerning a Forest-Based Bioeconomy. Master's Thesis, University of Helsinki, Helsinki, Finland, 2019.
8. Dahlbo, H.; Bacher, J.; Lähtinen, K.; Jouttijärvi, T.; Suoheimo, P.; Mattila, T.; Sironen, S.; Myllymaa, T.; Saramäki, K. Construction and demolition waste management—A holistic evaluation of environmental performance. *J. Clean. Prod.* **2015**, *107*, 333–341. [CrossRef]
9. Finnish Ministry of Environment. Wood Building Program. 2020. Available online: https://ym.fi/en/wood-building (accessed on 19 July 2023).
10. European Commission. *A Sustainable Bioeconomy for Europe: Strengthening the Connection between Economy, Society and the Environment*; Publications Office of the European Union: Luxembourg, Luxembourg, 2018.
11. Ghobadi, M.; Sepasgozar, S.M.E. Circular economy strategies in modern timber construction as a potential response to climate change. *J. Build. Eng.* **2023**, *77*, 107229. [CrossRef]

12. Tupenaite, L.; Kanapeckiene, L.; Naimaviciene, J.; Kaklauskas, A.; Gecys, T. Timber Construction as a Solution to Climate Change: A Systematic Literature Review. *Buildings* **2023**, *13*, 976. [CrossRef]
13. Giurcaki, A.; Befort, N. Deconstructing substitution narratives: The case of bioeconomy innovations from the forest-based sector. *Ecol. Econ.* **2023**, *207*, 107753. [CrossRef]
14. Ingrao, C.; Bacenetti, J.; Bezama, A.; Blok, V.; Goglio, P.; Koukios, E.G.; Lindner, M.; Nemecek, T.; Siracusa, V.; Zabaniotou, A.; et al. The potential roles of bio-economy in the transition to equitable, sustainable, post fossil-carbon societies: Findings from this virtual special issue. *J. Clean. Prod.* **2018**, *204*, 471–488. [CrossRef]
15. Kazulis, V.; Muizniece, I.; Zihare, L.; Blumberga, D. Carbon storage in wood products. *Energy Procedia* **2017**, *128*, 558–563. [CrossRef]
16. Abed, J.; Rayburg, S.; Rodwell, J.; Neave, M. A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures. *Sustainability* **2022**, *14*, 5570. [CrossRef]
17. Petrović, B.; Eriksson, O.; Zhang, X. Carbon assessment of a wooden single-family building—A novel deep green design and elaborating on assessment parameters. *Build. Environ.* **2023**, *233*, 110093. [CrossRef]
18. Arehart, J.H.; Hart, J.; Pomponi, F.; D'Amico, B. Carbon sequestration and storage in the built environment. *Sustain. Prod. Consum.* **2021**, *27*, 1047–1063. [CrossRef]
19. Sakuragawa, S.; Miyazaki, Y.; Kaneko, T.; Makita, T. Influence of wood wall panels on physiological and psychological responses. *J. Wood Sci.* **2005**, *51*, 136–140. [CrossRef]
20. Gold, S.; Rubik, F. Consumer attitudes towards timber as a construction material and towards timber frame houses—Selected findings of a representative survey among the German population. *J. Clean. Prod.* **2009**, *17*, 303–309. [CrossRef]
21. Kim, S.; Yun, B.Y.; Choi, J.Y.; Kim, Y.U.; Kim, S. Quantification of visual thermal perception changes in a wooden interior environment using physiological responses and immersive virtual environment. *Build. Environ.* **2023**, *240*, 110420. [CrossRef]
22. Rhee, P. Beyond green: Environmental building technologies for social and economic equity. *Arch. Des.* **2018**, *88*, 94–101. [CrossRef]
23. Ilgın, H.E.; Karjalainen, M. *Massive Wood Construction in Finland: Past, Present, and Future*; IntechOpen: London, UK, 2022. [CrossRef]
24. The National Building Code of Finland—Structural Fire Safety, Decree of the Ministry of the Environment. 2017. Available online: https://ym.fi/en/the-national-building-code-of-finland (accessed on 19 July 2023).
25. Ilgın, H.E.; Karjalainen, M. *Tallest Timber Buildings: Main Architectural and Structural Design Considerations*; IntechOpen: London, UK, 2022. [CrossRef]
26. Karjalainen, M.; Ilgın, H.E. A Statistical Study on Multi-story Timber Residential Buildings (1995–2020) in Finland. In Proceedings of the LIVENARCH VII Livable Environments & Architecture 7th International Congress OTHER ARCHITECT/URE(S), Trabzon, Turkey, 28–30 September 2021; Volume 1, pp. 82–94.
27. Ilgın, H.E. Core Design and Space Efficiency in Contemporary Supertall Office Buildings. In *Sustainable High-Rise Buildings: Design, Technology, and Innovation*; Al-Kodmany, K., Du, P., Ali, M.M., Eds.; The Institution of Engineering and Technology: London, UK, 2022.
28. Ilgın, H.E. Space Efficiency in Contemporary Supertall Residential Buildings. *Architecture* **2021**, *1*, 25–37. [CrossRef]
29. Ilgın, H.E. Space Efficiency in Contemporary Supertall Office Buildings. *J. Archit. Eng.* **2021**, *27*, 04021024. [CrossRef]
30. Lin, C.L.; Chiang, W.H.; Weng, Y.S.; Wu, H.P. Assessing the anthropogenic carbon emission of wooden construction: An LCA study. *Build. Res. Inf.* **2023**, *51*, 138–157. [CrossRef]
31. Ilgın, H.E.; Karjalainen, M.; Koponen, O. *Review of the Current State-of-the-Art of Dovetail Massive Wood Elements*; IntechOpen: London, UK, 2021. [CrossRef]
32. Ilgın, H.E.; Karjalainen, M.; Koponen, O. *Various Geometric Configuration Proposals for DovetailWooden Horizontal Structural Members in Multistory Building Construction*; IntechOpen: London, UK, 2022. [CrossRef]
33. Jayawardana, J.; Kulatunga, A.K.; Jayasinghe, J.A.S.C.; Sandanayake, M.; Zhang, G. Environmental Sustainability of Off-Site Construction in Developed and Developing Regions: A Systematic Review. *J. Archit. Eng.* **2023**, *29*, 04023008. [CrossRef]
34. Bahrami, A.; Jakobsson, J.; Söderroos, T. Factors Influencing Choice of Wooden Frames for Construction of Multi-Story Buildings in Sweden. *Buildings* **2023**, *13*, 217. [CrossRef]
35. The Finnish Timber Council, 2023. Timber Apartment Buildings Built in Finland. Available online: https://puuinfo.fi/arkkitehtuuri/asuinkerrostalot/suomessa-toteutetut-puukerrostalot/ (accessed on 19 July 2023).
36. Ilgın, H.E.; Karjalainen, M.; Pelsmakers, S. Contemporary Tall Timber Residential Buildings: What are the Main Architectural and Structural Design Considerations? *Int. J. Build. Pathol. Adapt.* **2022**, *in press*. [CrossRef]
37. Okbaz, F.T.; Sev, A. A model for determining the space efficiency in non-orthogonal high rise office buildings. *J. Fac. Eng. Archit. Gazi Univ.* **2023**, *38*, 113–125. [CrossRef]
38. Hamid, G.M.; Elsawi, M.; Yusra, O. The Impacts of Spatial Parameters on Space Efficiency in Hybrid Villa-Apartments in Greater Khartoum, Sudan. *J. Archit. Plan.* **2022**, *34*, 425–440. [CrossRef]
39. Suga, R. Space Efficiency in Hotel Development. Master's Thesis, MODUL University Vienna, Vienna, Austria, 2021.
40. Ilgın, H.E. A study on space efficiency in contemporary supertall mixed-use buildings. *J. Build. Eng.* **2023**, *69*, 106223. [CrossRef]
41. Arslan Kılınç, G. Improving a Model for Determining Space Efficiency of Tall Office Buildings. Ph.D. Thesis, Mimar Sinan Fine Art University, Istanbul, Turkey, 2019. (In Turkish).

42. Nam, H.J.; Shim, J.H. An analysis of the change in space efficiency based on various tall building corner shapes and lease spans. *J. Archit. Inst. Korea Plann* **2016**, *32*, 13–20. [CrossRef]
43. Sev, A.; Özgen, A. Space Efficiency in High-rise Office Buildings. *Metu JFA* **2009**, *26*, 69–89. [CrossRef]
44. Saari, A.; Tissari, T.; Valkama, E.; Seppänen, O. The effect of a Redesigned Floor Plan, Occupant Density and the Quality of Indoor Climate on the Cost of Space, Productivity and Sick Leave in an Office Building–A Case Study. *Build. Environ.* **2006**, *41*, 1961–1972. [CrossRef]
45. Kim, H.I.; Elnimeiri, M. Space Efficiency in Multi-Use Tall Building. In *Tall Buildings in Historical Cities—Culture and Technology for Sustainable Cities*; CTBUH: Chicago, IL, USA, 2004; pp. 748–755.
46. Carapellucci, F.; Conti, V.; Lelli, M.; Liberto, C.; Orchi, S.; Valenti, G.; Valentini, M.P. Tools and Methodologies for the Analysis of Home-to-Work Shuttle Service Impacts: The ENEA "Casaccia" Case Study. *Future Transp.* **2023**, *3*, 901–917. [CrossRef]
47. Kuzmanovska, I.; Gasparri, E.; Monne, D.T.; Aitchison, M. Tall timber buildings: Emerging trends and typologies. In Proceedings of the 2018 World Conference on Timber Engineering (WCTE 2018), Seoul, August, 20–23 August 2018; pp. 20–23.
48. Günel, M.H.; Ilgin, H.E. *Tall Buildings: Structural Systems and Aerodynamic Form*; Routledge: London, UK; New York, NY, USA, 2014.
49. Ilgın, H.E. Use of aerodynamically favorable tapered form in contemporary supertall buildings. *J. Des. Resil. Archit. Plan.* **2022**, *3*, 183–196. [CrossRef]
50. Tupėnaitė, L.; Žilėnaitė, V.; Kanapeckienė, L.; Sajjadian, S.M.; Gečys, T.; Sakalauskienė, L.; Naimavičienė, J. Multiple criteria assessment of high-rise timber buildings. *Eng. Struct. Technol.* **2019**, *11*, 87–94. [CrossRef]
51. Svatoš-Ražnjević, H.; Orozco, L.; Achim, M. Advanced Timber Construction Industry: A Review of 350 Multi-Story Timber Projects from 2000–2021. *Buildings* **2022**, *12*, 404. [CrossRef]
52. Wiegand, E.; Ramage, M. The Impact of Policy Instruments on the First Generation of Tall Wood Buildings. *Build. Res. Inf.* **2022**, *50*, 255–275. [CrossRef]
53. Hough, M.J.; Mark Lawson, R. Design and Construction of High-Rise Modular Buildings Based on Recent Projects. *Proc. Inst. Civ. Eng. Civ. Eng.* **2019**, *172*, 37–44. [CrossRef]
54. Bhandari, S.; Riggio, M.; Jahedi, S.; Fischer, E.C.; Muszynski, L.; Luo, Z. A Review of Modular Cross Laminated Timber Construction: Implications for Temporary Housing in Seismic Areas. *J. Build. Eng.* **2023**, *63*, 105485. [CrossRef]
55. The Finnish Timber Council. Productivity Leap in Industrial Wood Construction. 2022. p. 37. Available online: https://puuinfo.fi/wp-content/uploads/2022/08/Teollisen-puurakentamisen-tuottavuusloikka_Puu-lehden-erikoisnumero-2022.pdf (accessed on 19 July 2023).
56. The Finnish Timber Council. The Most Common Structural Systems. 2022. Available online: https://puuinfo.fi/puutieto/kayttokohteet/yleisimmat-rakennejarjestelmat/ (accessed on 19 July 2023).
57. Duncheva, T.; Bradley, F.F. Multifaceted Productivity Comparison of Off-Site Timber Manufacturing Strategies in Mainland Europe and the United Kingdom. *J. Constr. Eng. Manag.* **2019**, *145*, 04019043. [CrossRef]
58. Evison, D.; Kremer, P.; Guiver, J. Mass Timber Construction in Australia & New Zealand—Status, and Economic and Environmental Influences on Adoption. *Wood Fiber Sci.* **2018**, *50*, 128–138. [CrossRef]
59. Pilon, D.S.; Palermo, A.; Sarti, F.; Salenikovich, A. Benefits of Multiple Rocking Segments for CLT and LVL Pres-Lam Wall Systems. *Soil. Dyn. Earthq. Eng.* **2019**, *117*, 234–244. [CrossRef]
60. Gong, M. Wood and Engineered Wood Products: Stress and Deformation. In *Engineered Wood Products for Construction*; IntechOpen: London, UK, 2021. [CrossRef]
61. Hurmekoski, E.; Jonsson, R.; Nord, T. Context, drivers, and future potential for wood-frame multi-story construction in Europe. *Technol. Forecast. Soc. Chang.* **2015**, *99*, 81–196. [CrossRef]