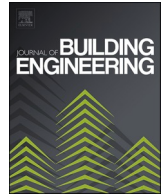




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## Space efficiency in timber office buildings

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## ABSTRACT

Timber offices indicate a growing field, principally thanks to their potential to offer noteworthy ecological and financial gains over their entire life. Like many other building types, space efficiency is a crucial design parameter in timber structures to ensure a project's feasibility. This factor is especially significant in office buildings, where maximizing rental income reflects effective planning. Currently, there is a lack of exhaustive inquiry providing a thorough insight of space efficiency in modern timber office buildings. This study fills this gap in the literature by collecting data from 33 buildings through literature reviews and case study method to investigate space efficiency with the key architectural and structural factors that influence it. The results showed that: (i) central cores stood out as the prevailing core layouts, while peripheral arrangements were noted as alternative preferences. Prismatic shapes emerged as the most favored options; (ii) timber was extensively used as a primary building material, closely followed by combinations of timber and concrete. Load-bearing systems mainly relied on shear walled frames and configurations; (iii) average space utilization across examined cases was 88 %, with variances ranging from 75 % to 95 % among different instances; (iv) average ratio of core area to GFA was 10 %, showing variations between 4 % and 19 % across various scenarios; and (v) there were no substantial variances noted in the effect of different core planning strategies on spatial efficiency. Similar conclusions were drawn regarding building forms and structural materials. Our paper will assist in crafting design principles customized for diverse stakeholders, including architectural designers of timber offices.

## List of abbreviations

CLT	Cross-laminated timber
T + C	Composite/hybrid structures combining timber and concrete
T + C + S	Composite/hybrid structures combining timber and concrete and steel
T + S	Composite/hybrid structures combining timber and steel
CTBUH	Council on Tall Buildings and Urban Habitat
EWPs	Engineered wood products
GFA	Gross floor area
NFA	Net floor area
UC	Under construction

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## 1. Introduction

### 1.1. Background

Developmental progression of modern city landscapes demonstrates a captivating storyline marked by a significant transition towards ecological balance and originality, prominently manifested in ascending formations of (high-rise) wooden constructions. These buildings, serving as representations of divergence from traditional building standards, arise as trailblazers in a trend that not only reshapes urban horizons but also questions preexisting beliefs concerning ecological influence and architectural potentials.

The emergence of these buildings transcends mere vertical presence, representing a blend of environmentally mindful design and technological progress [1]. By incorporating eco-friendly materials and construction methods, these structures not only reduce urban carbon emissions but also exemplify the alignment of contemporary architectural principles with ecological awareness [2]. In this transition, these edifices serve not just as physical entities but as symbols of a forthcoming era where urban centers seamlessly integrate visual splendor with environmental preservation, fostering a sustainable and inventive urban environment [3].

The evolution of timber office buildings relies on a thorough examination where advancements in technology, environmental responsibility, and innovative design intersect. Engineered wood products (EWPs), particularly cross-laminated timber (CLT), are at the forefront of this transition [4]. These materials, developed through sophisticated manufacturing techniques, liberate timber from its historical limitations in low-rise constructions, enabling it to rival traditional steel and concrete structures, thus signifying notable shift in urban development [5].

The incorporation of EWPs emphasizes timber's adaptability, robustness, and environmental friendliness in construction, consequently diminishing the carbon footprint [6]. Beyond their structural advantages, EWPs facilitate visually appealing designs, promoting a harmonious relationship with nature within timber office buildings, emblematic of progress and sustainability [7]. This progression denotes a pivotal move towards eco-conscious technologies, shaping a visually captivating urban landscape for the future.

Delving into the realm of timber office buildings involves a thorough investigation into the complexities of structure and design, with a particular emphasis on EWPs. This scrutiny unveils how EWPs redefine vertical architecture, granting architects unparalleled versatility in configuring office spaces and introducing a realm of novel design opportunities. Case studies such as Wellington in Australia and T3 Sterling Road Building 5 A in Canada serve as prime illustrations of timber's transformative capacity within urban office settings.

As a replenishable asset and a repository for carbon, timber assumes a crucial role in alleviating the ecological repercussions of swift urban expansion. A comprehensive evaluation of the life cycle, specifically directed at office environments, underscores the comprehensive environmental advantages associated with employing wood in tall constructions. This underscores the prospect for timber office buildings not solely to redefine urban panoramas but also to substantially foster sustainable urban growth, functioning as symbols of architectural environmental conscientiousness.

One of the most critical aspects determining the viability of architectural projects is spatial efficiency, which becomes especially crucial in office buildings seeking to enhance their financial appeal by maximizing the useable area [8]. Despite limited exploration in academic literature on the topic, there has been extensive research on the technological, environmental, and economic aspects of timber buildings (e.g. Refs. [9–11]). However, there has been no examination of spatial efficiency in timber office construction.

Examining space efficiency in timber office buildings is crucial for several scientific, practical, and environmental reasons:

1. Resource conservation [12]: Wood is a renewable source and applying it efficiently in construction helps conserve other materials such as steel and reinforced concrete, which have a higher environmental impact during production. Efficient space utilization ensures minimal waste of these resources.
2. Carbon sequestration [13]: Wood has the unique ability to sequester carbon di-oxide from the atmosphere. By constructing wooden buildings and maximizing space efficiency, we can effectively store large amounts of carbon within the building's structure, thus mitigating the carbon footprint associated with construction and operation.
3. Energy efficiency [14]: Efficient space planning in wooden buildings can lead to better natural lighting, ventilation, and temperature regulation, reducing the dependency on artificial lighting and heating/cooling systems. This translates to lower energy use and greenhouse gas emissions over the structure's lifecycle.
4. Urban density and land use [15]: Space efficiency enables wooden buildings to accommodate more occupants and functions within a smaller footprint, contributing to urban density without sacrificing living or working quality. This optimizes land use in urban areas, preserving green spaces and reducing urban sprawl.
5. Health and well-being [16]: Well-designed, efficiently utilized spaces in wooden buildings can enhance occupants' physical and mental well-being by providing adequate daylight exposure, views of nature, and opportunities for social interaction. Research suggests that access to natural elements within built environments positively impacts human health and productivity.

### 1.2. Literature review

In research focused on space utilization in buildings, Tuure and Ilgin [17] investigated spatial efficiency in fifty-five mid-rise timber residences in Finland, revealing a range of efficiency from 78 % to 88 %. Ilgin [18–23] explored space efficiency in various types of high-rise buildings, including office towers, residential complexes, and mixed-use structures, as well as tapered skyscrapers. Common findings included the frequent adoption of outriggered frame systems and central cores, and a correlation between building height and space efficiency ratio. Okbaz and Sev [24] formulated a model for spatial effectiveness in eleven tall office buildings with unconventional layouts, indicating that building design significantly influences spatial efficiency, with conical configurations exhibiting the highest efficiency ratio. Ibrahimy et al. [25] assessed space utilization efficiency in residential buildings in Kabul City, noting

deviations from regulations due to inadequate attention to interior design and government directives. Goessler and Kaluarachchi [26] investigated the impact of smart technologies on compact urban residences, suggesting a two to threefold enhancement in space efficiency compared to conventional designs. Hamid et al. [27] observed that positioning buildings in corners maximizes land utilization efficiency in detached residences in Sudan. Suga [28] analyzed spatial effectiveness in hotels, emphasizing the benefits of prioritizing spatial efficiency. Arslan Kılınc [29] examined factors influencing core and load-bearing structures in box-shaped towers, noting an increase in core area with building height and no significant correlation between construction material and spatial efficiency. Von Both [30] introduced a stakeholder analysis approach to improve area and space efficiency in planning processes. Höjer and Mjörnell [31] proposed a four-phase construction guideline for understanding digitalization’s impact on interior space supply and demand. Nam and Shim [32] investigated lease duration and corner configurations in high-rise buildings, finding minimal impact of corner cuts on spatial efficiency but significant effects of lease duration. Zhang et al. [33] devised a free-form configuration to enhance solar radiation absorption in cold regions, resulting in improved radiation absorption with minimal compromise in spatial efficiency. Sev and Özgen [34] explored spatial effectiveness in office structures, emphasizing the influence of load-bearing systems and core configuration. Saari et al. [35] examined the interaction between spatial optimization and the overall expenditure of tall office buildings, revealing a substantial impact of improved spatial efficiency on achieving targeted benchmarks of indoor environmental comfort. Kim and Elnimeiri [36] evaluated spatial efficiency ratios in multi-use towers, emphasizing integration of optimal structural systems and forms to enhance spatial effectiveness. Overall, the current scholarly literature lacks sufficient exploration into the detailed analysis of space efficiency in the realm of timber office projects, which constitute a pointed subset of tall wooden structures.

1.3. Research objectives

Drawing from data derived from 33 case studies, this research aims to analyze space efficiency by exploring critical architectural and structural design factors in contemporary timber office buildings. Our paper seeks to determine how various planning considerations impact space efficiency. The analysis focuses on four key aspects: (1) main architectural design parameters: core planning and building form, (2) main structural design parameters: structural material and structural system, (3) space efficiency, and (4) interrelation of space efficiency and above-mentioned design parameters. Through this analysis, our study, which represents the state of the art in these building applications, will provide information that can guide more informed decisions in the design of future timber office towers.

In our study, the terminologies “low-rise building”, “multi-story building”, “mid-rise building”, “tall building” are delineated to represent buildings with 1–2 stories, over 2 stories, 3-8 stories, and over 8 stories, respectively. Within the context of this paper, the analysis focuses on mid-rise and tall buildings.

The subsequent sections followed this order: first, the research methodology used in the study was explained. Then, an examination of 33 timber office case studies, offering relevant insights into the key characteristics and space efficiency considerations. This was

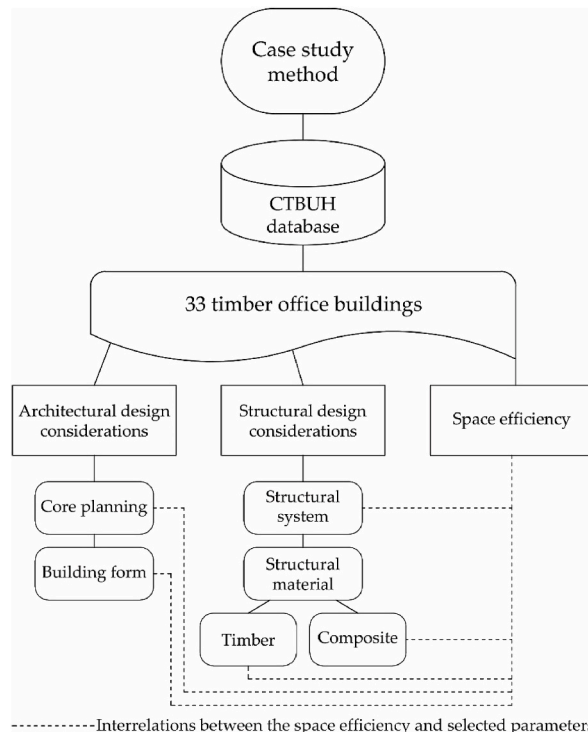


Fig. 1. Research method (image created by authors).

followed by comprehensive discussion section, Finally, a conclusion was drawn, including recommendations, suggestions for future research and the study’s limitations.

## 2. Research method

Case study method was employed to categorize and consolidate data on contemporary 33 office timber projects, as depicted in Fig. 1. This method is commonly employed in research when studies are recorded for qualitative and quantitative data, along with an extensive literature review [37,38] to categorize and consolidate data on contemporary office timber projects, enabling a structured examination of their architectural and structural characteristics. This approach offers a detailed analysis of specific cases within a real-world context, providing a comprehensive understanding of the unique features and trends in modern timber-based office designs. By focusing on individual cases, researchers can gain in-depth insights into the design and structure of each project, revealing common themes and variations among them. The use of case studies also allows for flexibility in data collection, incorporating various sources such as drawings and documents to build a well-rounded perspective. Additionally, this method supports the consolidation and categorization of data, leading to a structured analysis that can identify key trends and inform broader conclusions about contemporary office timber projects. This structured approach helps to understand the complexity and context of these projects, allowing researchers to draw meaningful insights from real-world examples and make informed evaluations of the built environment.

This study conducted a comprehensive analysis, encompassing a collection of 33 case studies. Examined structures were either built or under construction, with a focus on structures predominantly constructed with wooden framework. Selection criteria included buildings with eight or more stories, with data sourced from documentation provided by Council on Tall Buildings and Urban Habitat (CTBUH) [39]. These selected offices were situated in various locations globally: six from Canada, six from the United States, six from Australia, four from France, three from Switzerland, three from Germany, and one each from Norway, Denmark, UK, Japan, and Singapore, as seen in Fig. 2, as well as outlined in Appendix A.

In the domain of wooden office construction, decision-making primarily revolves around architectural and structural needs driven by necessity, besides the fundamental purpose of the structure. The key elements include the following factors, as outlined in Appendix B:

Architecturally:

- o arrangement of the core, which impacts the layout of vertical transportation and the allocation of shafts.
- o form of the structure, which influences sizes and patterns of the floor slabs.

Structurally:

- o structural system, which influences the arrangement and sizes of the load-bearing components.
- o structural material, which influences the proportions of the load-bearing members.

Core planning framework proposed by Ref. [17] is chosen for execution due to its thorough organization, which encompasses the following categories: (1) central, (2) atrium, (3) external, and (4) peripheral. Forms are categorized as: (a) prismatic, (b) setback, (c) tapered, (d) twisted, (e) tilted, and (f) free building forms.

In the realm of structural materials, there are primarily two main categories: (a) timber, and (b) composite or hybrid materials, which encompass combinations such as wood with concrete or steel, or mixtures of wood, concrete, and steel. The focus of our article is main structural elements like columns, omitting discussion of horizontal building elements. It’s crucial to note that changes in the



Fig. 2. Case study buildings located across diverse geographical regions worldwide.

composition of materials at the basement level don't impact the classification of the overall load-bearing framework.

Based on the categorization of structural materials, a key constraint for grouping a structure as 'timber' is that its primary vertical and horizontal load-bearing members are exclusively made of timber [39]. However, it's remarkable that in some in-stances, a 'timber' building may incorporate non-timber connections within timber members.

Conversely, in composite structures involving timber, a considerable part of the structural framework incorporates materials other than timber, such as steel, concrete, or an amalgamation of both. In buildings that integrate timber and concrete, it's frequent to find a concrete core supporting wooden structure. In buildings merging timber and steel, a considerable share of the structure relies on steel. Analogously, hybrid constructions combine timber, concrete, and steel to withstand primary forces. A conventional approach engages a concrete service core working alongside steel beams and pillars, whereas wood is employed in separation walls.

In the sense of bolstering horizontal rigidity especially in tall towers, particularly in addressing issues posed by wind and seismic forces, various load-bearing method-ologies and classifications have been implemented and analyzed in practical scenarios as documented in prior research [40]. This study adopts structural system categorization introduced by Ref. [17] owing to its complete nature, comprising: (i) rigid frame system; (ii) shear frame system encompassing shear trussed frame and shear walled frame configurations; and (iii) shear wall system.

Space efficiency refers to how effectively net floor area (NFA) is utilized in relation to gross floor area (GFA). This aspect holds significant significance, principally for stakeholders, as it entails optimizing the use of floor areas to achieve maximum returns on financial investments. The degree of spatial effectiveness mostly relies on numerous considerations, encompassing the choice of structural frameworks and architectural design.

We assessed spatial effectiveness by calculating the ratio of NFA to GFA, offering a quantitative measure of space utilization efficiency. Additionally, we determined the core relative to GFA by evaluating the proportion of the service core to GFA, offering insights into how space is allocated proportionally to essential structural and service elements within the overall building framework.

The assessment of spatial efficiency involves two main comparisons [17]: the ratio of NFA to GFA, and the ratio of core area to GFA. NFA is computed by subtracting the service core area from GFA, which helps in delineating functional zones where activities take place, excluding areas designated for infrastructure and support services. The NFA to GFA ratio provides a quantitative measure of how effectively the available floor area is utilized for practical purposes, indicating the efficiency of space allocation.

For comprehensive details and accurate outcomes of these analyses, readers are encouraged to refer to Appendix C. This section provides a deeper understanding of the methodology used, ensuring transparency, and enabling stakeholders to assess the credibility and reliability of the spatial efficiency measurements presented.

### 3. Results

In this section, fundamental elements of architectural design such as core planning and form, critical structural design factors encompassing materials and systems, and spatial efficiency, along with its interplay with various design considerations, are outlined.

#### 3.1. Main architectural design parameters: core planning and building form

Upon assessing Fig. 3, it is evident that central core formation is the most employed, accounting for 67 %, followed by the peripheral arrangement, making up 27 %.

Employing a central core within timber office constructions can yield various advantages [41]:

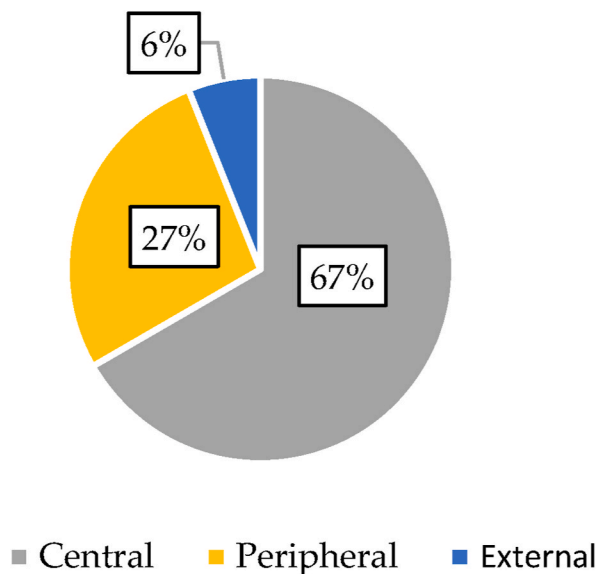


Fig. 3. Cases by core planning.

1. **Structural stability:** A central core lends strong structural component to the building, particularly in taller edifices, effectively withstanding lateral forces like wind and seismic loads, thus ensuring the building's safety and steadiness.
2. **Optimal space utilization:** By centralizing crucial amenities such as elevators, staircases, and utilities, more floor area becomes available for office functions. This configuration maximizes the useable space within the building, improving its efficiency and utility.
3. **Interior design flexibility:** The central core design offers greater freedom in organizing office layouts. As the core manages essential services, internal partitions can be easily adjusted without compromising the building's structural integrity.
4. **Enhanced natural lighting and ventilation:** Situating amenities like elevators and staircases within a central core can facilitate better dispersion of natural light and airflow throughout the office areas, contributing to a more pleasant and eco-friendly indoor environment.
5. **Economical construction:** Incorporating a central core can potentially reduce construction expenses by simplifying the structural system and optimizing construction processes. Furthermore, efficient space utilization can lead to overall cost savings.
6. **Visual allure:** A thoughtfully designed central core can serve as a focal point in the building's interior architecture. Architects often employ innovative designs and materials to craft visually captivating central cores, elevating the overall aesthetic appeal of the office building.
7. **Environmental sustainability:** Timber, being renewable and eco-friendly, serves as an ideal building material. Utilizing timber for the central core and other structural elements helps achieve sustainability objectives by curbing carbon emissions associated with construction and operation.
8. **Seismic resilience:** When appropriately designed and engineered, timber structures demonstrate commendable seismic performance. A central core contributes to structure's overall stability during seismic events, bolstering occupant safety.

The low frequency of external core arrangements, such as staircases and elevators on the outer edges of structures, is linked to the operational and safety challenges they create [19]. External cores increase internal circulation routes, leading to longer fire evacuation paths. This extended evacuation distance raises safety risks during emergencies, potentially delaying the safe exit of occupants and complicating emergency response.

Prismatic configuration stands out as the predominant architectural preference, representing 91 % of instances. In contrast, unbounded configurations make up 9 % of the total, as illustrated in Fig. 4.

Prismatic form usage in timber office constructions offers several advantages [17]:

1. **Aesthetic appeal:** Prismatic forms can create visually striking and modern architectural designs. They often stand out in urban landscapes, offering a unique and attractive appearance.
2. **Efficient use of space:** Prismatic forms allow for efficient use of space, both vertically and horizontally. This can be particularly advantageous in office constructions where maximizing floor space is crucial for accommodating workspaces, meeting rooms, and common areas.
3. **Structural strength:** Prismatic forms can provide inherent structural strength, especially when constructed using timber. Timber is a strong and versatile building material that, when used in prismatic forms, can create buildings capable of withstanding various loads and environmental conditions.
4. **Natural light and ventilation:** The shape of prismatic forms can be optimized to allow for better natural light penetration and ventilation throughout the building. This not only enhances the indoor environment but also reduces the need for artificial lighting and mechanical ventilation, contributing to energy efficiency.
5. **Sustainability:** Timber is an eco-friendly construction material. Utilizing timber in prismatic forms promotes sustainability by lowering dependence on non-renewable resources and reducing carbon footprint compared to traditional construction materials like concrete or steel.
6. **Cost-effectiveness:** Timber construction, particularly in prismatic forms, can be cost-effective compared to other construction methods. Timber is often lighter and easier to work with, leading to shorter construction times and lower labor costs. Additionally, the prefabrication of timber components can further reduce construction time and expenses.

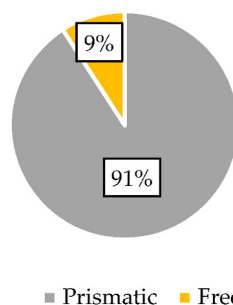


Fig. 4. Cases by building form.

7. Flexibility and adaptability: Prismatic forms offer flexibility in design, allowing architects and interior designers to create versatile office spaces that can be easily adapted to changing needs and preferences. This adaptability is essential in modern office environments where flexibility and innovation are highly valued.
8. Biophilic design: The use of timber and prismatic forms can contribute to biophilic design principles, which seek to connect building occupants with nature. Timber's natural aesthetics and the incorporation of ample natural light and ventilation can enhance occupant well-being, productivity, and overall satisfaction in the workplace.

### 3.2. Main structural design parameters: structural material and structural system

Fig. 5 emphasizes a notable occurrence of composite structures, comprising 73 % of the dataset, followed by pure timber assembly with 27 %.

Fig. 6 shows hybrid arrangements organized based on the arrangement of load-bearing elements. The predominant preference was observed for timber combined with concrete, constituting 75 %. Following this, timber utilized alongside both concrete and steel was identified in 21 %.

As shown in Fig. 7, shear-frame systems were favored, being used at a ratio of 97 %. Within the category of shear-frame systems, shear walled frames were primarily utilized, totaling 25 instances, indicating a significant preference for this particular configuration. There was only one case employing tube system.

In shear-frame systems, which incorporate both shear trussed frame and shear walled frame configurations, the interaction between these structural elements plays a critical role in enhancing the total performance of the system. Shear trussed frames and shear walled frames each possess distinct advantages and limitations. For instance, rigid frames offer considerable stiffness but may exhibit limitations in their ability to dissipate lateral forces efficiently. Conversely, shear truss or wall systems excel in dissipating lateral loads but may lack the stiffness provided by rigid frames. By integrating these components within a shear-frame system, the inherent disadvantages of each are mitigated through synergistic effects. The rigid frame component enhances the lateral load resistance of the shear truss or wall systems in upper levels, where lateral forces are more significant. Simultaneously, the shear truss or wall component enhances the stiffness and load-carrying capacity of the rigid frame in lower floors, where vertical loads predominate. This intricate interplay between structural elements results in a system that demonstrates superior resilience against lateral forces compared to structures relying solely on a 'shear wall' or 'rigid frame' approach. Furthermore, this enhanced resilience is vital for ensuring structural integrity and occupant safety, particularly in regions prone to seismic activity or high wind loads. Hence, the prevalence of shear-frame arrangements might be attributed to their capacity to optimize structural performance by leveraging the complementary strengths of each constituent element.

### 3.3. Space efficiency in timber office buildings

In our study, through the analysis of 33 instances, we established that the average spatial efficiency and the proportion of core area to GFA were around 88 % and 10 % respectively. The spectrum of measurements extended from a minimum of 75 %–4 % and reached a maximum of 95 %–19 %, as illustrated in Appendix C.

#### 3.3.1. Interrelation of space efficiency and core planning

Fig. 8 presents data pertaining to specific buildings, emphasizing their core planning approaches. The diagram shows bars on the right side, representing the over-all count of the cases categorized by their core types. Moreover, orange dots are employed to denote space efficiency of these buildings for each corresponding core type. Additionally, a gray bar is incorporated in the graph to depict the prevalence of structures within the analyzed sample sharing the same core typology.

In core configurations employed in cases, the central type has occurred as the leading choice, comprising 22 buildings. These instances have demonstrated spatial efficiency levels varying from 75 % to 95 %, with an average of 88 %. On the other hand, studies featuring the peripheral core type, totaling 9, have shown spatial efficiency ranging from 81 % to 91 %, averaging 87 %. Consequently, there is minimal disparity in the average spatial efficiency observed between various core types in this analysis.

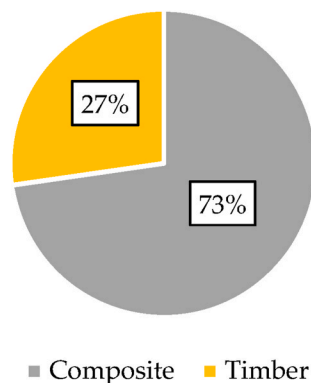


Fig. 5. Cases by structural material.

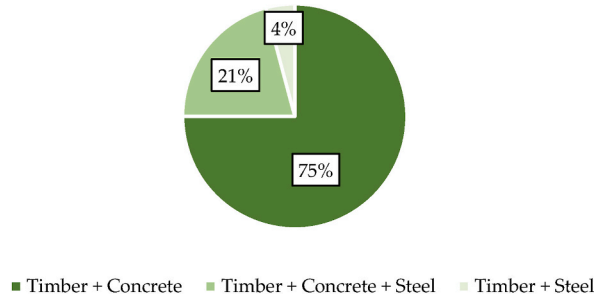


Fig. 6. Composite cases by structural material combinations.

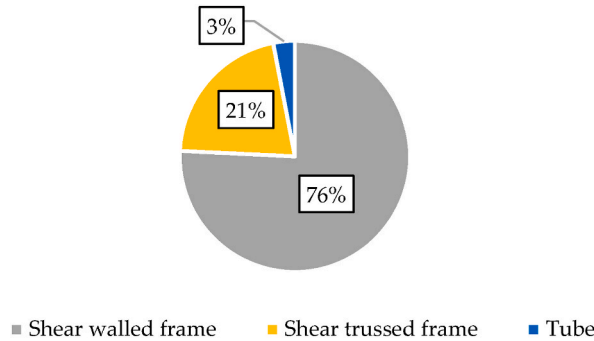


Fig. 7. Cases by structural system.

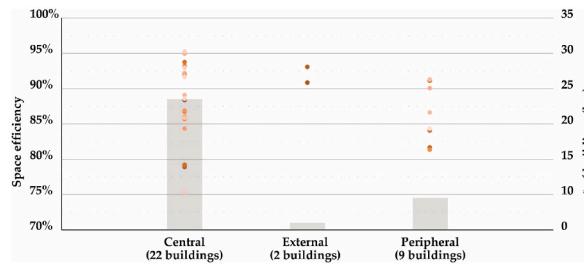


Fig. 8. Interrelation between space efficiency and core planning (figure by authors).

3.3.2. Interrelation of space efficiency and building form

Fig. 9 gives data pertaining to the analyzed case studies, with a specific emphasis on their forms. The diagram illustrates bars on the right side, indicating the overall number of these structures categorized by their forms. Moreover, blue dots are employed to indicate the spatial efficiency of these case study buildings corresponding to each particular form. Additionally, a gray bar is included in the graph to visually represent the frequency of examined buildings within the examined sample that exhibit the same architectural form.

In the domain of building forms utilized in case study structures, prismatic forms have emerged as the predominant selection, noted in 30 instances. These configurations have showcased spatial efficiency ratios ranging from 75 % to 95 %, averaging at 88 %.

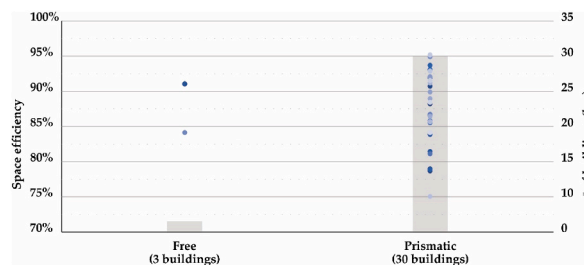


Fig. 9. Interrelation between space efficiency and building form (figure by authors).

Conversely, instances featuring free forms, totaling only 3 cases.

3.3.3. Interrelation of space efficiency and structural system

Fig. 10 shows data pertaining to the examined cases, with a particular focus on their load-bearing systems. The diagram displays bars on the right side, representing the total number of cases categorized by their structural systems. Additionally, orange dots are utilized to denote the spatial efficiency of these buildings for each respective structural system. Furthermore, a gray bar is incorporated into the graph to visually depict the frequency of buildings with identical structural systems within the sample set.

In our study of tower structures, shear walled frame has emerged as the most chosen structural system, observed in 25 instances. These designs have exhibited spatial efficiency levels spanning from 75 % to 95 %, with an average of 87 %. Conversely, structures employing the second most popular system, namely shear trussed frame, totaling 7 cases, have shown spatial efficiency ranging from 84 % to 95 %, averaging at 91 %. Consequently, there is a 4 % variation in average spatial efficiency between the predominantly utilized load-bearing systems.

3.3.4. Interrelation of space efficiency and structural material

Fig. 11 presents data regarding the analyzed buildings, with specific attention to their load-bearing materials. The diagram showcases bars on the right-hand side, illustrating the total number of cases classified by their structural materials. Furthermore, green dots are employed to represent the spatial efficiency of these structures for each respective structural material. Additionally, a gray bar is integrated into the graph to visually represent the frequency of cases that share the same load-bearing material.

In timber office towers, the primary structural materials employed are pure timber and composite materials. Spatial efficiency levels for timber and composite materials have been observed to range from 79 % to 95 % and 75 %–95 %, respectively, with average efficiencies of 90 % and 87 %. Consequently, there is only a 3 % variation in average spatial efficiency between the predominantly used structural materials in our case studies.

3.3.5. Interrelation of space efficiency and composite structural material combinations

Fig. 12 gives data connected to the analyzed towers, with a specific focus on their composite structural material combinations. The diagram demonstrates bars on the right-hand side, indicating the total count of composite structures categorized by their material combinations. Moreover, green dots are utilized to denote space efficiency of these cases for each respective composite material combination. Additionally, a gray bar is integrated into the graph to visually represent the occurrence frequency of buildings within the sample set sharing identical combinations.

In the analyzed sample, composite structural materials predominantly consist of timber and concrete, with 18 cases out of 24 reflecting this combination as the primary choice. Following closely is the integration of timber, concrete, and steel composite. Spatial efficiency levels of timber and concrete hybrids range from 75 % to 95 %, averaging at 87 %, while those of timber, concrete, and steel combinations range from 81 % to 93 %, averaging at 88 %. Thus, there is minimal disparity in average spatial efficiency between these composite configurations.

4. Discussion

This article seeks to methodically gather and combine comprehensive data on 33 contemporary timber office buildings. The focus of this research is to analyze the spatial efficiency regarding both architectural and structural aspects of these eco-friendly structures, with the goal of enhancing our comprehension of the complexities in planning and erecting such structures.

The findings presented in our research show similarities and dissimilarities compared to earlier studies, as illustrated by the study conducted by (e.g. Ref. [17]). In summary, our primary findings can be encapsulated as follows.

- (i) Central cores stood out as the prevailing core layouts, while peripheral arrangements were noted as alternative preferences. Prismatic shapes emerged as the most favored options.
- (ii) Timber was extensively used as a primary building material, closely followed by combinations of timber and concrete. Load-bearing systems mainly relied on shear walled frames and configurations.
- (iii) Average space utilization across examined cases was 88 %, with variances ranging from 75 % to 95 % among different instances.
- (iv) Average ratio of core area to GFA was 10 %, showing variations between 4 % and 19 % across various scenarios.

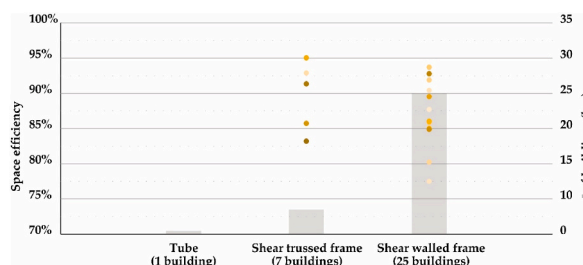


Fig. 10. Interrelation between space efficiency and structural system (figure by authors).

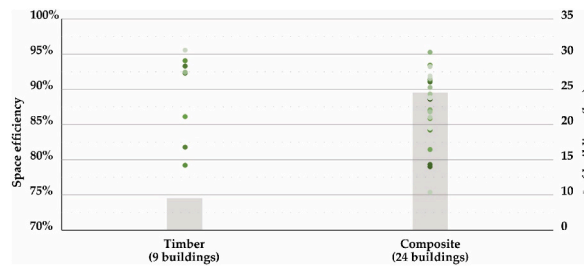


Fig. 11. Interrelation between space efficiency and structural material (figure by authors).

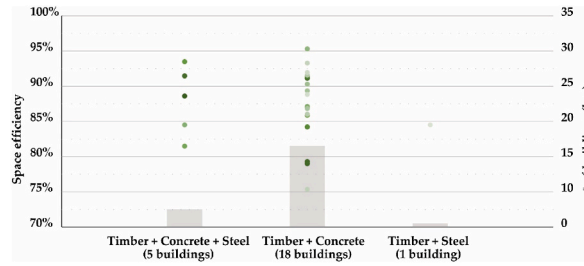


Fig. 12. Interrelation between space efficiency and composite structural material combinations (figure by authors).

- (v) There were no substantial variations noted in the effect of different core planning strategies on spatial efficiency. Similar conclusions were drawn regarding building forms and structural materials.

In the analyzed instances, the central core emerged as the predominant choice for core configuration, evident across diverse contemporary high-rise structures and mid-rise timber apartments in Finland [17,22]. This preference for central cores stems from their ability to accommodate a greater number of residences along the perimeter, thereby augmenting access to natural light and panoramic vistas. Moreover, central cores facilitate safer evacuation procedures, which are paramount for compliance with fire safety standards. The proximity of apartments to the core streamlines evacuation processes, thus bolstering its widespread adoption. Furthermore, central cores afford architectural versatility, unlike exterior core layouts, sidestepping any interference with the building's outward appearance.

This study showed that our examined structures predominantly are characterized by a prismatic configuration within the sample population. Previous research findings [17,18] underscore a widespread adoption of such configurations, primarily due to their inherent simplicity relative to more intricate geometries. Prismatic structures harmonize effectively with conventional construction techniques, thereby streamlining project execution. Their rectangular floor plans afford benefits in spatial use and functional efficiency. The uniformity of internal areas simplifies the organization of room layouts, thereby enhancing convenience for occupants. Furthermore, their modular characteristics optimize the utilization of construction materials and resources.

In the realm of timber office construction, there has been a notable transition towards utilizing timber as a primary construction material, followed by a shift towards incorporating a combination of timber and concrete. This transformation holds significant implications for the construction industry. Among various hybrid materials utilized, fusion of timber and concrete has emerged as the preferred selection. This preference is attributed to the exceptional flexibility and numerous advantages offered by the amalgamation of these materials in modern construction practices [42]. By integrating timber and concrete, the construction process harmonizes the warmth and aesthetic appeal of wood [43] with the robustness, longevity, and adaptability of concrete. This synergy results in a construction methodology that exploits the finest attributes of both materials.

A distinct hierarchy has become apparent in the structural systems employed, with the building's height being a determining factor in the realm of timber construction. The preferred structural approach often centers on shear walled frame and shear wall systems. These structures effectively distribute horizontal forces and offer stability, making them the top choices for tall wooden buildings. Their selection is supported by their proven ability to tackle challenges like wind loads, thereby ensuring the integrity of the structure. As for mid-rise timber buildings, which are not as tall, there is a rising tendency to adopt shear wall systems.

A suggested standard for space utilization in skyscrapers, backed by one source, targets 75 %. Studies on high-rise office, residential, and multi-use buildings construct-ed from materials other than timber has revealed varying levels of space efficiency, with averages ranging between 71 % and 76 %. The ratio of core area to GFA also fluctuates, averaging between 19 % and 26 %. Minimum and maximum values for space efficiency and core area to GFA ratio were documented across these studies. For example, in office skyscrapers, the lowest space efficiency recorded was 63 %, while the highest was 82 %. Similarly, the minimum core area to GFA ratio was 15 %, and the maximum was 36 %. Comparable ranges were observed in residential and mixed-use supertall buildings. Moreover, among 55 mid-rise timber housing units in Finland, space efficiency varied from around 78 %–88 %, with an average efficiency of 83 %. In our study, based on an analysis of 33 cases, average space efficiency and core to GFA ratio were approximately 88 % and 10 %,

respectively. Measurements bridged from a lowest of 75 % and 4 % to a highest of 95 % and 19 %.

## 5. Conclusions

This research introduces a novel focus on space efficiency in modern timber office buildings, filling a gap in existing studies. By analyzing data from 33 buildings through literature reviews and case studies, the research explores key factors like core layouts, building shapes, structural materials, and load-bearing systems. The practical implementation of this research's outcomes in timber office buildings includes several key elements. First, central core layouts are most common, with peripheral cores as an alternative, guiding architects toward designs that optimize space and accessibility while reducing construction complexity. Prismatic building shapes and shear-walled frames or configurations are favored for load-bearing, indicating an approach that supports structural stability and space efficiency. The extensive use of timber, with some concrete combinations, suggests a material strategy balancing sustainability and strength. With an average space utilization of 88 % and a core area to GFA ratio of 10 %, building designers have benchmarks for optimizing rentable space and achieving efficient office layouts. By following these insights, architectural designers can create more effective, sustainable, and profitable timber office buildings. By striking this delicate balance, they can create distinctive, environmentally conscious timber office buildings that embody modern design principles and ecological mindfulness.

Future studies of timber office buildings can expand upon this research by collecting data from a wider range of buildings across various regions to understand how geography, climate, and culture impact space efficiency. A longitudinal analysis could reveal how space efficiency evolves as these structures age, while examining occupant experience might highlight the relationship between space efficiency and productivity, comfort, and health. Life cycle analyses could further assess the environmental footprint of different design choices, while technological advancements, such as modular construction and prefabrication, may offer new insights into enhancing efficiency. Investigating the financial implications through cost-benefit analyses, alongside exploring the influence of building codes and regulations, could shape the future design of timber offices. Additionally, studies should consider cross-disciplinary collaboration, integrating sustainability practices, and examining a broader range of core designs to understand their effects on space efficiency. These diverse research avenues can foster sustainable, efficient, and user-friendly timber office building designs.

Due to limitations in data availability, our research did not delve into sustainable planning aspects. Certain factors such as circulation flow, space flexibility, and adaptability were intentionally excluded as they require separate research efforts. Moreover, this study concentrated on proportional assessments of crucial building zones, such as the core, while overlooking considerations like floor area dimensions and structural elements such as columns and pillars.

## CRedit authorship contribution statement

**Özlem Nur Aslantamer:** Writing – review & editing, Supervision, Software, Methodology, Investigation, Formal analysis, Conceptualization. **Hüseyin Emre Ilgin:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

No data was used for the research described in the article.

## Appendix A. Timber Office Buildings

#	Building name	Country	City	Height (meters)	# of stories	Completion date
1	Metropolitan Park Building 7/8	USA	Arlington	99	23	2023
2	TRAE	Denmark	Aarhus	82	20	UC
3	Abro	Switzerland	Risch-Rotkreuz	60	15	2019
4	Sub Station No. 164	Australia	Sydney	57	14	2021
5	Ngytan Koriayo	Australia	Greater Geelong	52	12	UC
6	503 on Tenth	USA	Portland	50	10	2023
7	25 King	Australia	Brisbane	47	10	2018
8	2150 Keith Drive	Canada	Vancouver	45	10	UC
9	Obayashi Training Facility	Japan	Yokohama	44	11	2022
10	Palazzo Nice Meridia	France	Nice	44	10	2019
11	T3 Bayside	Canada	Toronto	42	10	2023
12	Spor X	Norway	Drammen	41	10	2021
13	T3 Sterling Road Building 5 A	Canada	Toronto	40	8	UC
14	77 Wade	Canada	Toronto	38	8	2020
15	Suurstoffi 22	Switzerland	Risch-Rotkreuz	36	10	2018
16	Punggol Digital District	Singapore	Singapore	36	7	2024

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(continued)

#	Building name	Country	City	Height (meters)	# of stories	Completion date
17	Wood and Innovation Design Centre	Canada	Prince George	35	8	2014
18	Opalia	France	Saint-Ouen-sur-Seine	35	8	2017
19	Green Office ENJOY	France	Paris	35	8	2018
20	Pont de Flandres Batiment 007	France	Paris	35	8	2019
21	Apex Plaza	USA	Charlottesville	35	8	2022
22	T3 Sterling Road Building 3 A	Canada	Toronto	32	6	UC
23	Timber Pioneer	Germany	Frankfurt am Main	30	8	UC
24	Haus C	Switzerland	Risch-Rotkreuz	30	7	2020
25	International House South	Australia	Sidney	30	7	2017
26	Daramu House	Australia	Sidney	30	7	2020
27	EDGE Suedkreuz	Germany	Berlin	29	8	2022
28	LCT One	Australia	Dunrobin	27	8	2012
29	T3	USA	Minneapolis	26	7	2016
30	T3 West Midtown	USA	Atlanta	26	7	2019
31	The Cradle	Germany	Düsseldorf	26	7	UC
32	PAE Living Building	USA	Portland	23	5	2021
33	6 Orsman Road	UK	London	21	6	2020

**Note on abbreviations:** 'UC' indicates Under construction.

## Appendix B. Timber Office Buildings by Building form, Core Type, Structural System, and Structural Material

#	Building Name	Building form	Core type	Structural system	Structural material
1	Metropolitan Park Building 7/8	Prismatic	Central	Shear walled frame	Composite (T + C + S)
2	TRAE	Prismatic	Central	Shear walled frame	Composite (T + C)
3	Abro	Prismatic	Central	Shear walled frame	Composite (T + C)
4	Sub Station No. 164	Free	Peripheral	Shear walled frame	Composite (T + C + S)
5	Ngytan Koriayo	Prismatic	External	Shear walled frame	Composite (T + C)
6	503 on Tenth	Prismatic	Central	Shear walled frame	Timber
7	25 King	Prismatic	External	Shear walled frame	Timber
8	2150 Keith Drive	Free	Peripheral	Tube	Composite (T + C)
9	Obayashi Training Facility	Prismatic	Peripheral	Shear walled frame	Timber
10	Palazzo Nice Meridia	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
11	T3 Bayside	Prismatic	Central	Shear walled frame	Timber
12	Spor X	Prismatic	Central	Shear walled frame	Timber
13	T3 Sterling Road Building 5 A	Prismatic	Central	Shear walled frame	Timber
14	77 Wade	Prismatic	Central	Shear walled frame	Composite (T + C + S)
15	Suurstoffi 22	Prismatic	Central	Shear walled frame	Composite (T + C)
16	Punggol Digital District	Prismatic	Central	Shear walled frame	Composite (T + C)
17	Wood and Innovation Design Centre	Prismatic	Central	Shear walled frame	Timber
18	Opalia	Prismatic	Peripheral	Shear walled frame	Composite (T + C + S)
19	Green Office ENJOY	Prismatic	Central	Shear walled frame	Composite (T + C)
20	Pont de Flandres Batiment 007	Free	Central	Shear walled frame	Composite (T + C + S)
21	Apex Plaza	Prismatic	Central	Shear trussed frame	Composite (T + C)
22	T3 Sterling Road Building 3 A	Prismatic	Central	Shear trussed frame	Timber
23	Timber Pioneer	Prismatic	Peripheral	Shear walled frame	Composite (T + C)
24	Haus C	Prismatic	Central	Shear walled frame	Composite (T + C)
25	International House South	Prismatic	Peripheral	Shear trussed frame	Composite (T + C)
26	Daramu House	Prismatic	Peripheral	Shear trussed frame	Composite (T + C)
27	EDGE Suedkreuz	Prismatic	Central	Shear walled frame	Composite (T + C)
28	LCT One	Prismatic	Central	Shear walled frame	Composite (T + C)
29	T3	Prismatic	Central	Shear walled frame	Composite (T + C)
30	T3 West Midtown	Prismatic	Central	Shear walled frame	Timber
31	The Cradle	Prismatic	Central	Shear trussed frame	Composite (T + C)
32	PAE Living Building	Prismatic	Central	Shear walled frame	Composite (T + C)
33	6 Orsman Road	Prismatic	Peripheral	Shear trussed frame	Composite (T + S)

**Note on abbreviations:** '(T + C + S)' indicates composite/hybrid structures combining timber and concrete and steel; '(T + C)' indicates composite/hybrid structures combining timber and concrete; '(T + S)' indicates composite/hybrid structures combining timber and steel.

## Appendix C. Space Efficiency and Core/GFA of Timber Office Buildings

# - Building Name (Buildings are listed from highest to lowest.)								# - 1 to 20
Space Efficiency *				Core/GFA **				
1-Metropolitan Park Building 7/8		2 - TRAE		3 - Abro		4 - Sub Station No. 164		
89%	11%	79%	18%	80%	18%	91%	8%	
				Low-rise floor				
5-Ngytan Koriayo		6-503 on Tenth		7-25 King		8-2150 Keith Drive		
91%	8%	92%	7%	93%	4%	91%	8%	
				Low-rise floor				
9-Obayashi Training Facility		10-Palazzo Nice Meridia		11-T3 Bayside		12-Spor X		
82%	16%	84%	12%	92%	6%	79%	13%	
				Low-rise floor				
13-T3 Sterling Road Building 5A		14-77 Wade		15-Saurstoff 22		16-Punggol Digital District		
94%	4%	93%	6%	87%	11%	86%	13%	
				Low-rise floor				
17-Wood and Innovation Design Centre		18-Opalia		19-Green Office ENJOY				
86%	10%	81%	13%	87%				
20-Pont de Flandres Batiment 007								
84%		14%						
		Low-rise floor						

# - Building Name (Buildings are listed from highest to lowest.)										# - 21 to 30
Space Efficiency *					Core/GFA **					
21-Apex Plaza		22-T3 Sterling Road Building 3A			23-Timber Pioneer		24-Haus C			
95%	4%	92%	7%	90%	8%	89%	10%			
				Low-rise floor						
25-International House South					26-Daramu House					
87%					12%					
Low-rise floor					Low-rise floor					
27-EDGE Suedkreuz			28-LCT One			29-T3				
86%			11%			75%				
Low-rise floor			Low-rise floor			Low-rise floor				
30-T3 West Midtown		31-The Cradle								
95%		4%		92%						
				Low-rise floor						
Low-rise floor		Low-rise floor		Low-rise floor						
32-PAE Living Building		33-6 Orsman Road								
89%		7%				84%				
						Low-rise floor				
Low-rise floor		Low-rise floor				Low-rise floor				

Space Efficiency\* : calculated as the ratio of the net floor area [obtained by subtracting the service core (the gray area on the floor plan) and structural elements from GFA] to GFA.  
 Core / GFA\* : calculated as the ratio of the service core (the gray area on the floor plan) to GFA  
 In the floor plans the gray area corresponds to service core while black area signifies structural elements.

References

- [1] A. Bahrami, S.P. Rashid, Sustainable development of recent high-rise timber buildings, in: Sustainable Structures and Buildings, Springer International Publishing, Cham, 2024, pp. 1–16.
- [2] N. Chayaamor-Heil, T. Houette, Ö. Demirci, L. Badarnah, The potential of Co-designing with living organisms: towards a new ecological paradigm in architecture, Sustainability 16 (2) (2024) 673.
- [3] R. Toivonen, H. Vihemäki, A. Toppinen, Policy narratives on wooden multi-storey construction and implications for technology innovation system governance, For. Pol. Econ. 125 (2021) 102409.
- [4] V. De Araujo, A. Christoforo, The global cross-laminated timber (CLT) industry: a systematic review and a sectoral survey of its main developers, Sustainability 15 (10) (2023) 7827.
- [5] F. Benedetti, V. Rosales, A. Jélvez, M. Núñez, A. Rebollo, A. Jara-Cisterna, Economic and technical analysis of CLT production facilities: an application to small and emerging markets, European Journal of Wood and Wood Products 80 (5) (2022) 1247–1261.
- [6] C. Howard, C.C. Dymond, V.C. Griess, D. Tolkien-Spurr, G.C. van Kooten, Wood product carbon substitution benefits: a critical review of assumptions, Carbon Bal. Manag. 16 (2021) 1–11.
- [7] A.A. Umoh, A. Adefemi, K.I. Ibewe, E.A. Etukudoh, V.I. Ilojiyana, Z.Q.S. Nwokediegwu, Green architecture and energy efficiency: a review of innovative design and construction techniques, Engineering Science & Technology Journal 5 (1) (2024) 185–200.
- [8] H.E. Ilgin, Core design and space efficiency in contemporary supertall office buildings, in: K. Al-Kodmany, P. Du, M.M. Ali (Eds.), Sustainable High-Rise Buildings: Design, Technology, and Innovation, The Institution of Engineering and Technology, London, UK, 2022.
- [9] M. Caniato, A. Marzi, S.M. da Silva, A. Gasparella, A review of the thermal and acoustic properties of materials for timber building construction, J. Build. Eng. 43 (2021) 103066.
- [10] N. Ahn, A. Dodoo, M. Riggio, L. Muszynski, L. Schimleck, M. Puettmann, Circular economy in mass timber construction: state-of-the-art, gaps and pressing research needs, J. Build. Eng. 53 (2022) 104562.
- [11] M. Solla, M.A. Maté-González, C.S. Blázquez, S. Lagüela-López, I.M. Nieto, Analysis of structural integrity through the combination of non-destructive testing techniques in heritage inspections: the study case of San Segundo's Hermitage (Ávila, Spain), J. Build. Eng. 109295 (2024).
- [12] M. Ghobadi, S.M. Sepasgozar, Circular economy strategies in modern timber construction as a potential response to climate change, J. Build. Eng. (2023) 107229.
- [13] Q. Wang, X. Zhang, C. Guo, H. Zhou, Y. Zhao, B. Lin, Analysis of carbon emission differences between Chinese and Japanese buildings based on qualitative and quantitative comparisons, J. Build. Eng. 109260 (2024).
- [14] M.R. Cabral, P. Blanchet, A state of the art of the overall energy efficiency of wood buildings—an overview and future possibilities, Materials 14 (8) (2021) 1848.

- [15] F. Meyer, T. Elliot, S. Craig, B.P. Goldstein, The carbon footprint of future engineered wood construction in Montreal, *Environ. Res.: Infrastructure and Sustainability* 4 (1) (2024) 015012.
- [16] A. Ojala, J. Kostensalo, J. Viik, H. Matilainen, I. Wik, L. Virtanen, R. Muilu-Mäkelä, Psychological and physiological effects of a wooden office room on human well-being: results from a randomized controlled trial, *J. Environ. Psychol.* 89 (2023) 102059.
- [17] A. Tuure, H.E. Ilgin, Space efficiency in Finnish mid-rise timber apartment buildings, *Buildings* 13 (8) (2023) 2094.
- [18] H.E. Ilgin, Space efficiency in contemporary supertall residential buildings, *Architecture* 1 (2023) 25–37.
- [19] H.E. Ilgin, A study on space efficiency in contemporary supertall mixed-use buildings, *J. Build. Eng.* 69 (2023) 106223.
- [22] H.E. Ilgin, Examination of spatial efficiency in super-tall towers within the middle eastern context, *Open House Int.* (2024), <https://doi.org/10.1108/OHI-11-2023-0263> (E-pub ahead of print).
- [23] H.E. Ilgin, Efficiency of space utilization in supertall towers with free forms, in: David S-K. Ting, A. Stagner Jacqueline (Eds.), *The Costs of Climate Change Mitigation Innovations: A Pragmatic Outlook*, CRC press Taylor & Francis Group, 2024, <https://doi.org/10.1201/9781003403456-5>. ISBN 9781032516813.
- [24] F.T. Okbaz, A. Sev, A model for determining the space efficiency in non-orthogonal high rise office buildings, *Journal of the Faculty of Engineering and Architecture of Gazi University* 38 (2023) 113–125.
- [25] R. Ibrahimy, M.A. Mohmmad, F.A. Elham, An evaluation of space use efficiency in residential houses, Kabul city, *J. Res. Appl. Sci. Biotechnol.* 2 (2023) 1–6.
- [26] T. Goessler, Y. Kaluarachchi, Smart adaptive homes and their potential to improve space efficiency and personalisation, *Buildings* 13 (5) (2023) 1132.
- [27] G.M. Hamid, M. Elswawi, O. Yusra, The impacts of spatial parameters on space efficiency in hybrid villa-apartments in greater khartoum, Sudan, *J. Archit. Plan.* 34 (2022) 425–440.
- [28] R. Suga, Space Efficiency in Hotel Development. Master's Thesis, Business Administration with a Specialization in Real Estate Management and Development, MODUL University, Vienna, Vienna, Austria, 2021.
- [29] G. Arslan Kılınc, Improving a Model for Determining Space Efficiency of Tall Office Buildings, Ph.D. Thesis, Department of Architecture, Mimar Sinan Fine Art University, Istanbul, Turkey, 2019 (In Turkish).
- [30] P.A. Von Both, stakeholder-and function-based planning method for space-efficient buildings, *IOP Conf. Ser. Earth Environ. Sci.* 323 (2019) 012040.
- [31] M. Höjer, K. Mjörnell, Measures and steps for more efficient use of buildings, *Sustainability* 10 (2018) 1949.
- [32] H.J. Nam, J.H. Shim, An analysis of the change in space efficiency based on various tall building corner shapes and lease spans, *J. Archit. Inst. Korea Plan. Des.* 32 (2016) 13–20.
- [33] L. Zhang, L. Zhang, Y. Wang, Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China, *Sol. Energy* 132 (2016) 38–50.
- [34] A. Sev, A. Özgen, Space efficiency in high-rise office buildings, *METU J. Fac. Archit.* 26 (2009) 69–89.
- [35] A. Saari, T. Tissari, E. Valkama, O. Seppänen, 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.* 41 (2006) 1961–1972.
- [36] H. Kim, M. Elnimeiri, Space efficiency in multi-use tall building, in: *Proceedings of the Tall Buildings in Historical Cities—Culture and Technology for Sustainable Cities*, Seoul, Republic of Korea, October 2004, pp. 10–13.
- [37] A. Opoku, V. Ahmed, J. Akotia, *Research Methodology in the Built Environment, Choosing an Appropriate Research Method*, 2016, pp. 32–49.
- [38] K.B.M. Noor, Case study: a strategic research methodology, *Am. J. Appl. Sci.* 5 (11) (2008) 1602–1604.
- [39] N. Zahiri, Timber high-rises in nordic countries: current trends, *CTBUH J* (2023) 44–50. Available online: <https://www.proquest.com/openview/18bd24c28e7b2ef07815ea4e8423a3b6/1?pq-origsite=gscholar&cbl=6578554>. (Accessed 24 April 2024).
- [40] R. Verhaegh, M. Vola, J. de Jong, Haut-a 21-storey tall timber residential building, *International Journal of High-Rise Buildings* 9 (3) (2020) 213–220.
- [41] P. Oldfield, B. Doherty, Offset cores: trends, drivers and frequency in tall buildings, *CTBUH J* (2019) 40–45. Available online: <https://global.ctbuh.org/resources/papers/download/4186-offset-cores-trends-drivers-and-frequency-in-tall-buildings.pdf>. (Accessed 24 April 2024).
- [42] A.M.P.G. Dias, J. Skinner, K. Crews, T. Tannert, Timber-concrete-composites increasing the use of timber in construction, *Eur. J. Wood Wood Prod.* 74 (2016) 443–451.
- [43] K. Dharanidharan, S. Selvanayaki, K. Divya, R. Ravikumar, S.V. Raj, Exploring household wood preferences among consumers in coimbatore, *Asian J. Agric. Ext. Econ. Sociol.* 41 (2023) 196–203.