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Examination of spatial efficiency in super-tall towers within the Middle Eastern context

Hüseyin Emre Ilgın
Tampere University, Tampere, Finland

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Abstract

Purpose – Super-tall towers have surfaced as a pragmatic remedy to meet the escalating requisites for both residential and commercial areas and to stimulate economic growth in the Middle East. In this unique regional context, optimizing spatial usage stands as a paramount consideration in the architectural design of skyscrapers. Despite the proliferation of super-tall towers, there exists a conspicuous dearth of comprehensive research pertaining to space efficiency in Middle Eastern skyscrapers. This study endeavors to bridge this substantial gap in the literature.

Design/methodology/approach – The research methodology utilized in this paper adopts a case study approach to accumulate data regarding super-tall towers in the Middle East, with a specific focus on investigating space efficiency. A total of 27 super-tall tower cases from the Middle East were encompassed within the analytical framework.

Findings – Key findings can be succinctly summarized as follows: (1) average space efficiency was 75.5%, with values fluctuating between a minimum of 63% and a maximum of 84%; (2) average ratio of the core area to the gross floor area (GFA) registered 21.3%, encompassing a spectrum ranging from 11% to 36%; (3) predominantly, Middle Eastern skyscrapers exhibited a prismatic architectural form coupled with a central core typology. This architectural configuration mostly catered to residential and mixed-use functions; (4) the combination of concrete and outrigger frame systems was the most frequently utilized; (5) as the height of the tower increased, space efficiency tended to experience a gradual decline and (6) no significant discernible disparities were detected in the impact of diverse load-bearing systems and architectural forms on space efficiency.

Originality/value – Despite the proliferation of super-tall towers, there exists a conspicuous dearth of comprehensive research pertaining to space efficiency in Middle Eastern skyscrapers. This study endeavors to bridge this substantial gap in the literature.

Keywords Space efficiency, Middle east, Super-tall tower, Architectural and structural design considerations

Paper type Research paper

1. Introduction

In contemporary times, the predominance of skyscrapers has emerged as the prevalent architectural trend in Middle Eastern nations, driven by rapid economic advancements (Ilgın, 2022a). Moreover, there has been a notable surge in the height of skyscrapers in recent decades, giving rise to a novel classification referred to as super-tall buildings (300m+) (Ilgın, 2023a). The progression of this development persists vigorously, especially within the Middle East, on an unparalleled scale, establishing the region as one of the most active centers for skyscraper construction (Moon, 2015).

The development of skyscrapers in the Middle East is a complex and multifaceted process driven by various factors, including economic growth, urbanization, architectural innovation and regional aspirations. Scientifically, this development can be understood through the lens of urbanization dynamics, economic expansion and architectural advancements. Here's a breakdown of these key factors:

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(1) Economic growth: Many Middle Eastern countries, particularly those in the Gulf region, have experienced significant economic growth due to factors such as oil wealth, diversification of economies and strategic investments. This economic prosperity has fueled the demand for modern infrastructure, including high-rise buildings, to support growing industries, commerce and a rising population.

(2) Urbanization: As people move from rural areas to cities in search of better opportunities, cities in the Middle East have expanded rapidly. Urbanization drives the need for high-density housing, commercial space and infrastructure. Skyscrapers provide an efficient solution to accommodate a large population in relatively small urban footprints.

(3) Architectural innovation: Middle Eastern cities have become global hubs for architectural experimentation, with architects and designers creating iconic skyscrapers that push the boundaries of design and engineering. Scientific advancements in materials, construction techniques and sustainable building practices have enabled the realization of ambitious architectural visions.

(4) Cultural and symbolic significance: In the Middle East, skyscrapers are seen as symbols of modernity, progress and regional identity. These structures are used to showcase a nation's economic prowess and its commitment to innovation. The Burj Khalifa in Dubai, for example, is not just a tall building but a symbol of the city's transformation into a global business and tourism hub.

(5) Sustainable development: Middle Eastern countries are recognizing the need to balance economic growth with environmental responsibility. Many modern skyscrapers in the region incorporate sustainable features, such as energy-efficient designs, renewable energy sources and green building materials, which align with global efforts to combat climate change.

(6) Global connectivity: The Middle East's strategic location as a crossroads between continents has contributed to its skyscraper development. The region's major cities, like Dubai and Doha, have positioned themselves as global business and transportation hubs. This connectivity fosters international investment and the construction of world-class infrastructure, including tall buildings.

(7) Government policies and investments: Government policies and investments play a pivotal role in shaping the skyline of Middle Eastern cities. Many governments in the region have actively promoted urban development and infrastructure projects, including skyscrapers, to diversify their economies and enhance their global competitiveness.

In summary, the development of skyscrapers in the Middle East is a result of a complex interplay of economic, urbanization, architectural, cultural and policy-related factors. It reflects the region's aspiration for economic prosperity, urban modernization and its desire to make a global impact through iconic and innovative architecture. Scientific analysis helps us understand how these factors interact and influence the growth of tall buildings in the Middle East.

The Middle East faces ongoing challenges in meeting the demand for residential and commercial spaces, driven by the need to establish iconic symbols of power, wealth and prestige, along with substantial economic growth. Unless innovative alternatives are identified for the establishment of effective architectural spaces, the construction of skyscrapers seems to be the inevitable resolution for the future development of this geographical area (Al-Kodmany and Ali, 2012). The matter of spatial efficiency becomes pivotal, especially concerning super-tall structures in the Middle East, as they aim to respond to socioeconomic transformations and offer viable architectural and engineering answers.

Spatial efficiency assumes a significant role in fulfilling the worth and expenditure cost of skyscrapers (Kim and Elnimeiri, 2004).

The investigation into the efficiency of space in super-tall towers in the Middle East has been notably absent in existing literature. This study aims to fill this gap by conducting a comprehensive analysis of 27 case studies. The primary objective is to scrutinize key architectural and structural design factors pertaining to space efficiency. The paper offers in-depth assessments, covering aspects such as the building's function, form, core type, load-bearing system and materials and their interconnectedness with space efficiency. While sustainable planning considerations (Karjalainen *et al.*, 2022; Ilgın and Karjalainen, 2021) like energy consumption were not included due to insufficient data for all towers, the research is primarily centered on space efficiency. The results of this research are anticipated to offer insights that will steer the sustainable advancement of skyscrapers in the Middle East, especially in the realms of architectural and structural design.

According to data from the Council on Tall Buildings and Urban Habitat (CTBUH) database (CTBUH, 2023), this study classifies structures with a height of 14 stories or 50 meters as "tall buildings". Meanwhile, those surpassing the 300-meter and 600-meter marks in height are designated as "super-tall buildings" or "skyscrapers" and "megatall buildings", respectively.

The following sections were organized in the subsequent manner: Firstly, an in-depth literature review was conducted. Afterward, the research methodology was delineated, and the acquired results were exhibited. Subsequent to this, a discussion section was furnished, expounding on the analysis and elucidation of the findings. Lastly, a conclusion was drawn, encompassing the practical ramifications, future research areas and constraints of the study.

2. Literature survey

There is a paucity of research in the existing body of literature that delves into the notion of space efficiency in both tall and super-tall buildings. Prior investigations have predominantly concentrated on scrutinizing a limited set of tall buildings, with the notable exception of Ilgın's extensive studies (2021a; 2021b; 2023a).

Kim and Elnimeiri (2004) conducted an analysis of space efficiency within a set of 10 mixed-use tall structures. They underscored its critical relevance in tandem with structural and energy efficiency. Elevator optimization and strategic functional distribution were identified as crucial factors in augmenting space efficiency. Furthermore, they stressed that the design of the building's form and load-bearing systems plays a pivotal role in enhancing space efficiency.

Saari *et al.* (2006) scrutinized the correlation between space efficiency and the overall cost of construction in tall office edifices. Their investigation revealed a noteworthy association, highlighting that heightened space efficiency played a substantial role in attaining the desired indoor climate comfort.

Sev and Özgen (2009) conducted an inquiry into spatial efficiency across ten tall office skyscrapers, taking into account factors such as structural material, load-bearing system and lease span. The outcomes underscored the significance of core arrangement and load-bearing systems in determining space efficiency. Core planning exhibited considerable variation contingent on occupant requirements, with the central core typology being the most commonly preferred approach.

Nam and Shim (2016) carried out a study focusing on the impact of high-rise corner forms and lease spans on space efficiency. Their research revealed that square-cut corner forms had the most adverse effect on space efficiency, while lease span significantly influenced space efficiency.

Arslan Kılınç (2019) employed regression analysis to scrutinize the factors impacting service core and load-bearing systems in prismatic tall buildings. The investigation uncovered that taller office towers tended to allocate more substantial areas to the structural system and service core. Nevertheless, no discernible scientific correlation was observed between space efficiency and construction material.

Suga (2021) concentrated on the aspect of space efficiency in hotel structures. The research identified that designs that emphasized space efficiency had a beneficial effect on hotel projects. Of particular significance was the efficient layout of common areas concerning the size of guest rooms.

Ilgın (2022b) conducted an investigation into the core design and spatial efficiency of contemporary super-tall office buildings. The study drew insights from a set of ten case study towers to analyze key factors influencing the impact of service core design. The author recognized the ongoing evolution of trends in contemporary service core design and presented essential design principles that consider these dynamic trends.

Hamid *et al.* (2022) conducted a study involving interviews with architectural firms to explore space efficiency in 60 single-family residences in Sudan. The research considered factors like the placement of courtyards, plot orientation and vertical circulation elements. The results indicated that placing buildings at corners optimized land utilization, while the most efficient placement for vertical circulation elements was along the middle of building edges. Additionally, the study observed that the highest space efficiency ratio was attained when the plot had greater width than depth.

Okbaz and Sev (2023) formulated a model to comprehend the concept of space efficiency within the context of 11 office towers featuring free-form designs. Their investigation encompassed design factors including the service core and load-bearing components. The outcomes of their study demonstrated that free-form architectural designs yielded lower space efficiency in contrast to conical forms, with the floor-to-floor height having a minimal impact.

Ilgın (2021a) delved into the exploration of space efficiency within the context of 44 office skyscrapers, taking into account significant architectural and structural design elements. In parallel, Ilgın (2021b) conducted an analysis of space efficiency within 27 residential skyscrapers, with a focus on similar design parameters. Furthermore, Ilgın (2023b) ventured into an investigation of space efficiency in 64 towers featuring mixed-use functionalities. The combined findings derived from Ilgın's studies indicated a prevalent preference for a central core typology, common adoption of outrigger frame systems as load-bearing elements and an inversely proportional relationship between space efficiency and building height.

Tuure and Ilgın (2023) conducted an analysis of data derived from 55 Finnish mid-rise wooden residential structures to enhance our comprehension of the considerations and planning criteria that impact the space efficiency of these buildings. The principal results of this investigation showed the following: (1) within the pool of case study samples, space efficiency spanned from approximately 78%–88%, with an average of 83%; (2) neither construction systems nor materials of shear walls yielded noteworthy variations in terms of space efficiency. Furthermore, there was no scientifically discernible connection between the number of floors and space efficiency; (3) the highest average space efficiency was reached when employing a central core typology.

Ilgın (2023c) conducted a comprehensive examination of spatial efficiency in 75 super-tall towers located in Asia. The primary outcomes of the study can be succinctly outlined as follows: (1) The mean spatial efficiency across these towers was 67.5%, displaying a variation from a minimum of 55% to a maximum of 82%; (2) The average ratio of the core area to the gross floor area (GFA) was 29.5%, with values ranging between 14 and 38%. Additionally, Ilgın (2023d) directed attention to the spatial efficiency in 40 tapered super-tall towers, revealing the following key findings: (1) The average spatial efficiency was approximately 72%, exhibiting fluctuations within a range from 55% to 84%; (2) The average ratio of the core area to GFA was approximately 26%, encompassing a spectrum from 11% to 38%.

As demonstrated through the comprehensive literature review presented earlier, the body of research dedicated to the examination of space efficiency within tall and super-tall buildings is rather scant. Moreover, the existing studies frequently concentrate on specific functions or architectural forms. However, a conspicuous deficiency emerges with respect to a comprehensive inquiry into space efficiency within skyscrapers situated in the Middle East region, which boasts the highest quantity and tallest skyscrapers globally. This research initiative is distinctly poised to rectify this noteworthy void in the current scientific literature.

3. Research method

The research methodology utilized in this paper adopts a case study approach to accumulate data regarding super-tall towers in the Middle East, with a specific focus on investigating space efficiency, as seen in Figure 1. The utilization of this approach is a common practice in the evaluation of projects within the built environment, enabling the collection of both quantitative and qualitative data (Karjalainen and Ilgın, 2021; Tulonen *et al.*, 2021; Saarinen *et al.*, 2022; Rinne *et al.*, 2022; Ilgın and Karjalainen, 2023). A total of 27 super-tall tower cases from the Middle East were encompassed within the analytical framework. In-depth information pertaining to each case can be found in the Appendix section.

The author conducted an exhaustive examination of the floor plans of super-tall towers in the Middle East, encompassing typical, low-rise and ground floors. This rigorous approach facilitated the acquisition of dependable data for the assessment of space efficiency across 27 super-tall towers. Additionally, the author made a conscious choice to employ Ilgın's (2023b) comprehensive categories for key architectural and structural design considerations, drawing from the existing body of literature (e.g. Ilgın, 2006; Gunel and Ilgın, 2007; Taranath,

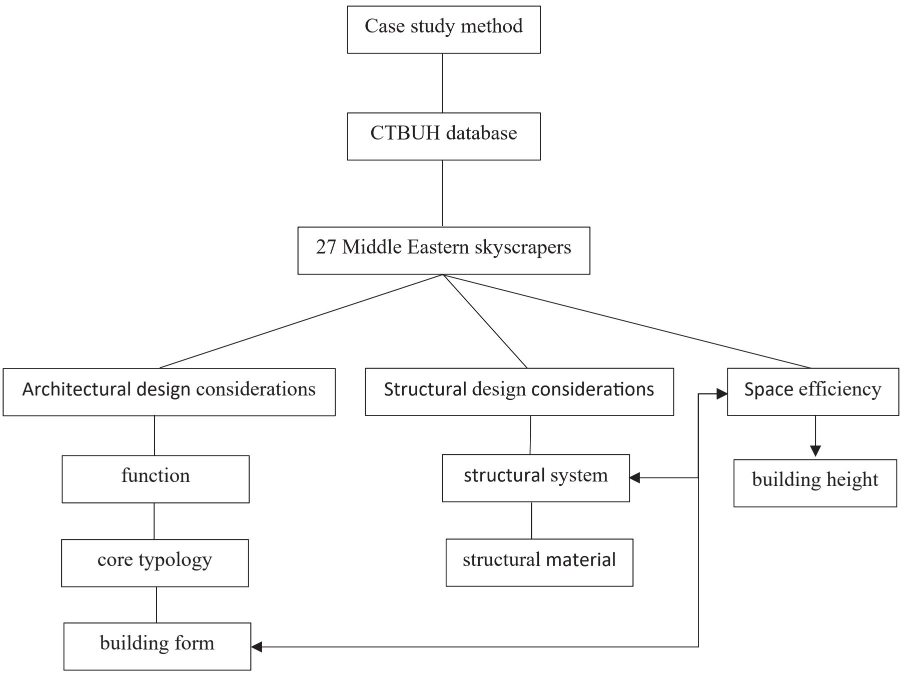

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Figure 1. Flowchart of the methodology and process

2016; Ali and Moon, 2018; Ali and Al-Kodmany, 2022). This decision was rooted in the categories' comprehensive nature, as exemplified in Table 1.

Space efficiency is a critical metric denoting the proportion of net floor area (NFA) relative to the GFA. This parameter holds paramount importance for investors as it revolves around optimizing the utilizable space within floor layouts to yield the highest possible returns on investment. The degree of space efficiency primarily hinges on various factors, including the load-bearing system, architectural form and the arrangement of floor slabs (Ilgın, 2023d). Furthermore, the concept of space efficiency plays a pivotal role in determining the lease span. The lease span denotes the measurement between fixed internal components, such as service core walls and the building's exterior envelope, encompassing features like windows (Ilgın *et al.*, 2023).

4. Findings

4.1 Main architectural design considerations: function, core typology and building form

Regarding building function, the case study sample mostly consisted of residential developments, comprising over 44% (12 instances) of the total. Mixed-use followed closely, representing 33% (9 instances) of the sample, as indicated in Figure 2. The dominance of

Table 1. Core, structural system, and material classifications

Core	Structural system
Central core	Shear-frame system
• central	• shear trussed frame
• central split	• shear walled frame
Atrium core	Mega core system
• atrium	Mega column system
• atrium split	Outrigger frame system
External core	Tube system
• attached	• framed-tube
• detached	• trussed-tube
• partial split	• bundled-tube
• full split	Buttressed core system
Peripheral core	*Structural material*
• partial peripheral	• steel
• full peripheral	• reinforced concrete
• partial split	• composite
• full split	

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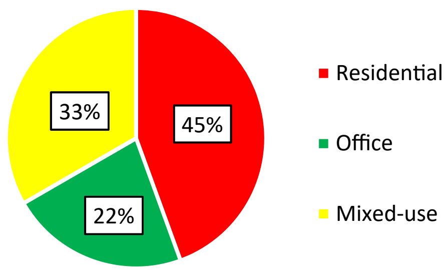

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Figure 2. Middle Eastern super-tall towers by function

residential skyscrapers in the Middle East can be explained through a combination population density, land scarcity, economic factors, cultural preferences, real estate investment dynamics and government policies (Alani and Kahera, 2023). The presence of mixed-use towers can be attributed to the adoption of vertical community principles, offering solutions to address population growth while curbing urban sprawl. The inclination towards mixed-use functionality has further surged, especially during market fluctuations, owing to its potential for increased rental returns and diversification of the customer base (Ilgın, 2023e).

Except for Abu Dhabi National Oil Company (ADNOC) Headquarters, characterized by an external core, the predominant approach in Middle Eastern super-tall towers is the adoption of a central core strategy. This inclination towards central cores can be rationalized by various factors, including their streamlined design, significant role in enhancing the overall structural integrity and their facilitation of effective fire evacuation procedures (Ilgın *et al.*, 2021). Conversely, the relatively limited prevalence of external cores might be attributed to the elongation of circulation distances they entail, subsequently leading to extended fire evacuation routes (Ilgın, 2018).

As illustrated in Figure 3, prismatic designs emerged as the predominant architectural approach within the 27 examined skyscrapers, constituting 44% (12 instances) of the cases. Free-form designs closely trailed behind, representing 37% (10 instances) of the sampled towers.

The prevalence of prismatic forms may be attributed to several factors that render them advantageous in the context of skyscraper construction. One key factor is the relative simplicity and ease of construction associated with prismatic designs when compared to the intricate and less structured free forms. Prismatic forms typically involve more regular shapes, such as rectangles, which are inherently easier to work with in terms of construction logistics and material usage (Goncikowski, 2022). Additionally, prismatic forms facilitate efficient utilization of interior space, especially in the case of buildings with rectangular floor plans. The preference for free-form architectural designs, exemplified by projects like Al Hamra Tower in the context of Middle Eastern skyscrapers, can be scientifically explained by the favorable aerodynamic properties associated with such designs. This preference is rooted in a thorough consideration of the significant impact of wind-induced lateral loads, a critical structural design factor in skyscrapers, as established by research conducted by Gunel and Ilgın (2014a). Free-form architectural designs, characterized by non-rectilinear or irregular shapes, often exhibit improved aerodynamic characteristics compared to more traditional, rectilinear designs. Scientifically, this can be explained by the way these designs interact with wind patterns. Irregular shapes can disrupt and diffuse wind currents, reducing the intensity of wind forces acting on the structure (Gunel and Ilgın, 2014b).

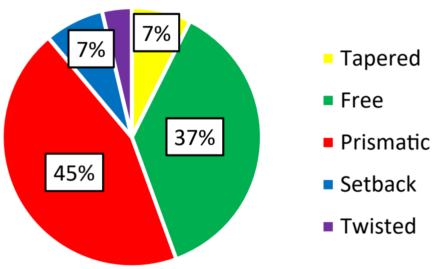

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Figure 3. Middle Eastern super-tall towers by form

4.2 Main structural design considerations: structural system and structural material

Figure 4 presents a visual representation of the prevalence of different structural systems in Middle Eastern skyscrapers. It reveals that outrigger frame systems were the most commonly adopted structural approach, constituting more than 40% (12 instances) of the cases. Tube systems emerged as the second most widely employed method, encompassing 26% (7 instances) of the sampled skyscrapers.

The preference for outrigger frame system in the context of skyscraper construction can be attributed to its capacity to provide a certain degree of flexibility in positioning the outer columns. This attribute affords architects greater latitude in shaping the building envelope according to design specifications. Furthermore, the system's compatibility with achieving substantial heights in skyscraper construction contributes significantly to its widespread utilization. This popularity aligns with its suitability for addressing the vertical demands of super-tall buildings, as highlighted in the literature (Ilgın, 2023f).

Figure 5 illustrates that the predominant selection among the case studies was reinforced concrete construction, representing the choice in 70% (19 instances) of the sample. Following closely, composite construction accounted for 30% (8 instances) of the cases in the analysis.

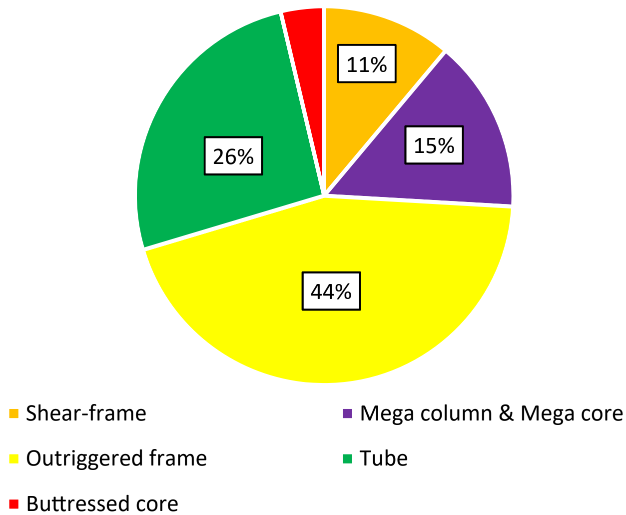

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Figure 4. Middle Eastern super-tall towers by structural system

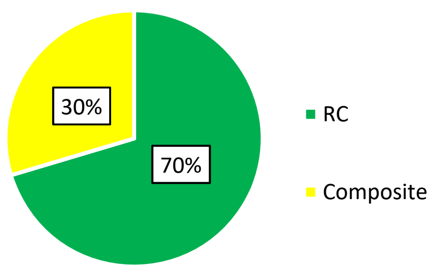

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Figure 5. Middle Eastern super-tall towers by structural material

The dominance of concrete in Middle Eastern skyscrapers can be justified by its combination of strength, durability, fire resistance, local availability, architectural versatility, cost efficiency, regulatory compliance and energy efficiency. The convergence of these elements collectively establishes concrete as the favored and pragmatic option for erecting tall structures within the area (Ziyatov *et al.*, 2022).

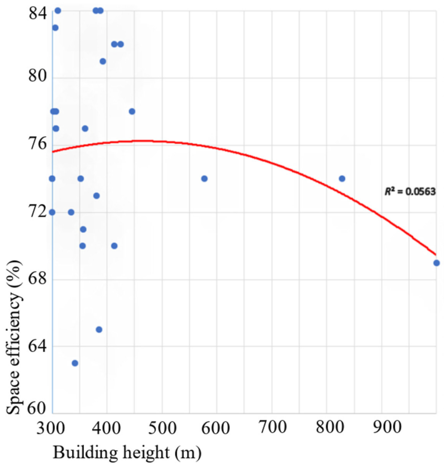
4.3 Space efficiency and interrelations with main design criteria

The benchmark for space efficiency in tall towers can be established at approximately 75% (Yeang, 2000). In Ilgın's (2021a) examination of tall office structures, the average space efficiency and core-to-GFA ratio were calculated at 71 and 26%, respectively. The lowest recorded figures were 63% for space efficiency and 15% for the core-to-GFA ratio, while the highest values reached 82 and 36%, correspondingly. In Ilgın's (2021b) study on residential towers, the average space efficiency and core-to-GFA ratio were 76 and 19%, respectively. The lowest recorded numbers were 56% for space efficiency and 11% for the core-to-GFA ratio, while the highest values were 84 and 36%, respectively. In Ilgın's (2023b) research focusing on contemporary mixed-use super-tall buildings, the typical space efficiency and core-to-GFA ratio were determined as 71 and 26%, respectively. The minimum recorded figures were 55% for space efficiency and 16% for the core-to-GFA ratio, while the maximum values were 84 and 38%, respectively. In this current article, based on the analysis of 27 super-tall towers in Middle East, the average space efficiency and core-to-GFA ratio were established at 75.5 and 21.3%, respectively. The lowest recorded values were 63% for space efficiency and 11% for the core-to-GFA ratio, while the highest figures reached 84 and 36%, respectively (please refer to the Appendix for more comprehensive details).

4.3.1 Interrelation of space efficiency and the height of the building. Figures 6a and 6b depict the correlation between space efficiency and the height of skyscrapers in the Middle East. The data points on these figures represent the Middle Eastern skyscrapers examined in the case study. To address correlations in the data, a polynomial regression approach was utilized, chosen for its ability to yield a more precise R-square correlation coefficient when compared to linear or exponential approaches. Of significance was the observation that the Public Investment Fund (PIF) Tower and ADNOC Headquarters stand out as exceptional cases, displaying space efficiencies of 65 and 63%, along with core-to-GFA ratios of 33 and 36%, respectively. The impact of outliers on the regression line can be visualized in Figure 6b. As illustrated by the trendline in Figure 6a, there is an inclination for space efficiency to diminish as building height increases. Additionally, upon the exclusion of outliers, the diminishing pattern becomes more conspicuous, as shown in Figure 6b. This decline can be ascribed to the phenomenon that as tall buildings ascend, the dimensions of the central core and load-bearing components enlarge, rendering the attainment of elevated space efficiency ratios more arduous. This has been emphasized in prior works by Ilgın (2021a, 2023b).

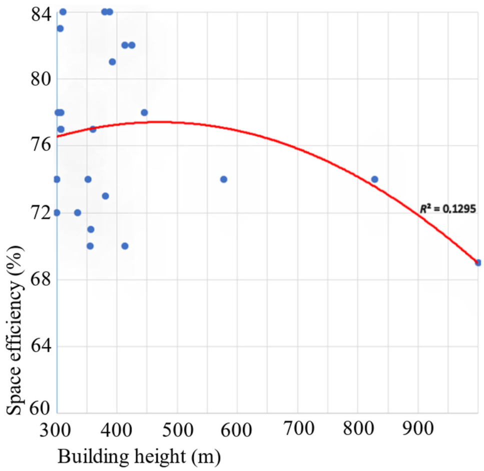
Figures 7a and 7b offer additional illumination regarding the core-to-GFA ratio concerning tower height. This augments our earlier observation regarding the escalating demand for larger service cores as tower height extends, consistent with the findings reported by Ilgın (2021b). Much like the situation in Figure 6b, the elimination of outliers accentuates an even more noticeable upward trend, as illustrated in Figure 7b.

4.3.2 Interrelation of space efficiency and building form. Figure 8 portrays the distribution of Middle Eastern super-tall structures based on their architectural forms, with the total count of buildings being depicted as bars on the right axis. The chart showcases the space efficiency of buildings for each specific architectural form, represented by blue dots. Meanwhile, the red dots on the graph correspond to the tallest Middle Eastern skyscraper following the same architectural form. The black bar on the chart provides a visual representation of the quantity of super-tall buildings in the sample set that utilize the same architectural form.



Including outliers

(a)



Excluding outliers

(b)

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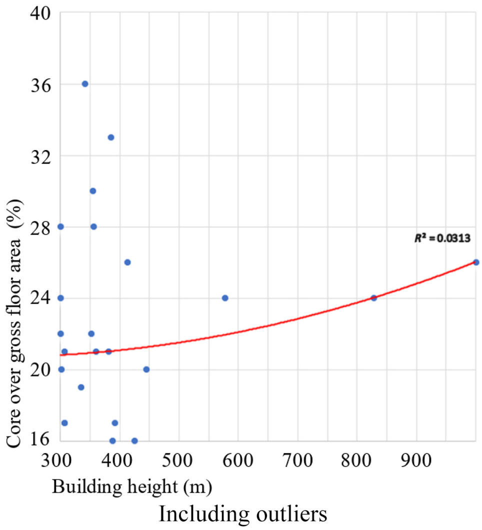
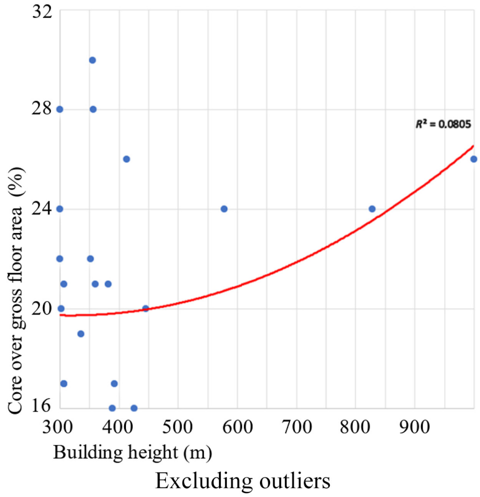
Figure 6.
The interrelationship between space efficiency and height

Prismatic Middle Eastern towers exhibited space efficiency within the range of 63%–84%, averaging at 76%. In comparison, free-form Middle Eastern towers demonstrated space efficiency ranging from 69% to 84%, with an average of 76%. Notably, one instance of a tower featuring a twisted architectural design achieved an exceptional space efficiency exceeding 83%. Consequently, when considering these values above the mean, it becomes evident that there exists no substantial disparity in the influence of different architectural forms on the space efficiency of Middle Eastern skyscrapers. Due to the limited occurrence of buildings with tapered, setback and twisted designs, it appears improbable to establish a scientifically meaningful correlation between these architectural forms and the space efficiency of these towers.



(a)



(b)

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Figure 7. The interrelationship between core over GFA and height

4.3.3 Interrelation of space efficiency and structural system. Figure 9 exhibits the cumulative count of Middle Eastern skyscrapers, with these counts depicted as bars on the right axis, categorized according to their respective load-bearing systems. The chart illustrates the space efficiency of these constructions for each distinct load-bearing system, denoted by blue dots. Conversely, the red dots on the graph represent the tallest Middle Eastern skyscraper employing the corresponding structural system. Furthermore, the black bar visually represents the count of super-tall buildings within the sample set that utilize the same structural system.

In the realm of load-bearing systems found in Middle Eastern skyscrapers, outrigger frame systems emerged as the predominant choice, with 12 towers adopting this approach. These towers showcased space efficiency levels spanning from 72% to 84%, averaging at 76%. In contrast, both mega column and mega core systems and shear walled frame systems were comparatively infrequent, each featuring in just two towers. Conversely, the buttressed core system, the least favored among load-bearing systems, was employed in only one tower but achieved a commendable space efficiency rate of 74%. The space efficiency of towers constructed using tube systems, amounting to 7 towers in total, spanned from 65% to 84%, with an average of 76%. In light of these average values, it can be reasonably deduced that the influence of distinct load-bearing systems on space efficiency in Middle Eastern skyscrapers does not exhibit significant divergence. Given the limited occurrence of cases involving shear walled frame systems, mega column and mega core systems and buttressed core systems, it appears improbable to establish a scientifically meaningful correlation between the space efficiency of these towers and their structural systems.

5. Discussion

The results showed both congruities and disparities in relation to prior research, exemplified by studies like Oldfield and Doherty (2019) and Ilgın (2023b). The principal discoveries of this investigation can be succinctly outlined as follows:

(1) Average space efficiency of skyscrapers in the Middle East stood at 75.5%, with a range spanning from a minimum of 63% to a maximum of 84%.

(2) Average core-to-GFA ratio reached 21.3%, encompassing values ranging from a minimum of 11% to a maximum of 36%.

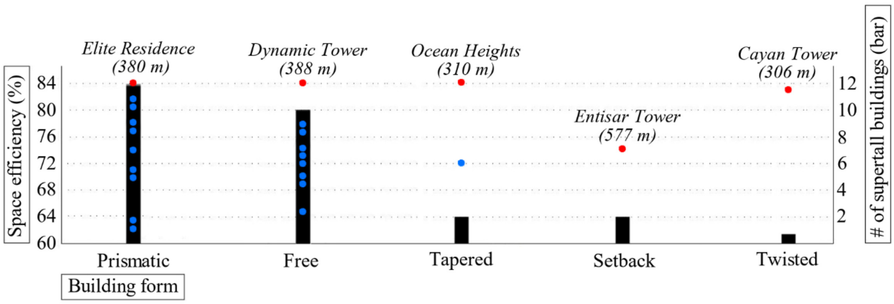

Figure 8. The interrelationship between space efficiency and building form

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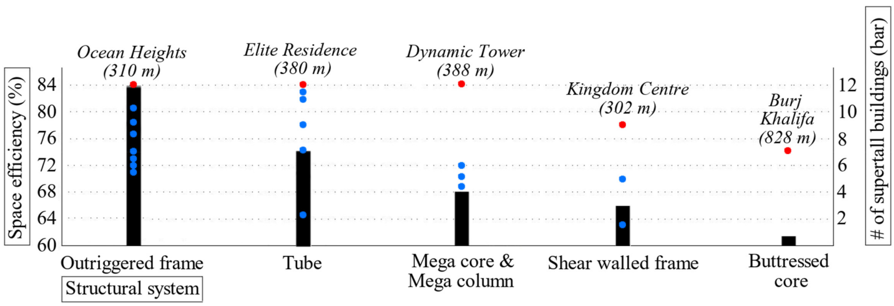

Figure 9. The interrelationship between space efficiency and structural system

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(3) Prismatic configurations were the prevailing choice for Middle Eastern skyscrapers, predominantly featuring a central core design tailored for residential and mixed-use functions.

(4) Concrete construction combined with outrigger frame systems emerged as the most frequently employed structural solutions.

(5) A discernible inverse correlation surfaced between a skyscraper's height and its space efficiency.

(6) The study discerned no substantial disparities in how various load-bearing systems and architectural forms influenced space efficiency.

These results offer significant insights into the attributes and patterns observed in Middle Eastern skyscrapers, providing valuable information regarding crucial factors like space utilization, core configuration, architectural design and structural considerations.

According to Yeang's (2000) research, which set a 75% space efficiency criterion for tall towers, Middle Eastern skyscrapers met this criterion with an average of 75.5%. However, the average space efficiency (71%) reported in Ilgın's surveys of office and mixed-use skyscrapers (2021b; 2023b) was below Yeang's predicted threshold. The threshold value of space efficiency of Middle East towers can be largely attributed to the dimensions of the service core area and structural components. Most Middle Eastern super-tall structures displayed a predilection for prismatic forms, consistent with Ilgın's (2021b) observations concerning super-tall residential edifices. Conversely, Ilgın's (2021a; 2023b) examination of super-tall office and mixed-use towers underscored the prevalence of tapered forms. The central core arrangement emerged as the preferred option among the buildings surveyed, aligning with the results of Oldfield and Doherty (2019) and Ilgın (2021a). Outrigger frame systems and reinforced concrete materials were commonly utilized as load-bearing systems and structural materials, as revealed in the study conducted by Ilgın (2021b). Studies by Sev and Özgen (2009) and Arslan Kılınç (2019) have shown that as building height increases, space efficiency tends to decline due to the increased size of the core space area and structural system components at greater heights. The findings concerning the connections between space efficiency and structural systems, as well as space efficiency and building forms, are consistent with the results reported in the studies by Ilgın (2021b, 2023b). These investigations revealed no notable variations in how load-bearing systems affect space efficiency and analogous outcomes were derived for building forms, mirroring the outcomes of this research.

Future studies in the field of super-tall towers design in the Middle East might consider the following research avenues: environmental impact assessment, human-centric design, safety and disaster resilience, socioeconomic impact and cultural and historical context.

This paper possesses certain constraints. The dataset scrutinized within this research was limited to 27 super-tall towers in the Middle East, potentially constraining the applicability of the results. To bolster the validity and facilitate more extensive inferences, prospective research may contemplate broadening the sample size to encompass more extensive case study structures. Furthermore, it is advisable that future investigations encompass skyscrapers falling below the 300-meter threshold and create numerous subcategories to offer a more exhaustive analysis.

6. Conclusion

Analyzing data from 27 case study towers, this research reveals an average space efficiency of 75.5%, varying between 63 and 84% and the core area to GFA ratio averages at around 21%, ranging from 11% to 36%, as seen in the Appendix. Predominantly adopting a prismatic architectural form with a central core typology, Middle Eastern skyscrapers focus on residential and mixed-use functions. The combination of concrete and outrigger frame systems emerges as the most prevalent. As tower height increases, a gradual decline in space efficiency is observed. Notably, no significant differences were found in the impact of diverse load-bearing systems and architectural forms on space efficiency.

In light of this paper revealing a critical gap in the literature on Middle Eastern skyscrapers, construction stakeholders should heed several key recommendations for fostering sustainable development in super-tall towers. (1) First, prioritize innovative core design solutions to strike a balance between functionality and minimal footprint, optimizing the average space efficiency of around 76%. (2) Considering the observed decline in efficiency with increasing tower height, implement height-related design strategies, such as reevaluating floor plans and incorporating modular elements. (3) Encourage diversification in functional use to accommodate regional demands effectively. (4) Explore alternative structural systems beyond the prevalent combination of concrete and outrigger frames to enhance efficiency. (5) Emphasize collaboration between architects and structural designers to ensure a holistic approach and regularly update design standards to incorporate the latest advancements. (6) Additionally, promote the adoption of sustainable construction practices, including environmentally friendly materials and energy-efficient systems. These practical insights will guide stakeholders in shaping architectural designs and optimizing spatial usage, contributing significantly to the sustainable development of Middle Eastern urban landscapes.

References

Al-Kodmany, K. and Ali, M.M. (2012), "Skyscrapers and Placemaking: supporting local culture and identity", *ArchNet-IJAR*, Vol. 6 No. 2, p. 43.

Alani, M. and Kahera, A. (2023), "Contextualized computations: a multi-objective optimization approach for designing contextually responsive building envelopes", *Open House International*, Vol. ahead-of-print No. ahead-of-print, doi: 10.1108/OHI-04-2023-0074.

Ali, M.M. and Moon, K.S. (2018), "Advances in structural systems for tall buildings: emerging developments for contemporary urban giants", *Buildings*, Vol. 8 No. 8, p. 104, doi: 10.3390/buildings8080104.

Ali, M.M. and Al-Kodmany, K. (2022), "Structural systems for tall buildings", *Encyclopedia*, Vol. 2 No. 3, pp. 1260-1286, doi: 10.3390/encyclopedia2030085.

Arslan Kılınç, G. (2019), "Improving a model for determining space efficiency of tall office buildings", Ph.D. dissertation, Mimar Sinan Fine Art University, Department of Architecture, Istanbul, (in Turkish).

CTBUH (2023), *Council on Tall Buildings and Urban Habitat*, Illinois Institute of Technology, S.R. Crown Hall, Chicago, IL, available at: https://www.ctbuh.org (accessed 31 December 2023).

Goncikowski, M. (2022), "Landmarks of the metropolis, the types of forms of varsovian skyscrapers as compared to global precedence", *Buildings*, Vol. 12 No. 10, p. 1507, doi: 10.3390/buildings12101507.

Gunel, M.H. and Ilgın, H.E. (2007), "A proposal for the classification of structural systems of tall buildings", *Building and Environment*, Vol. 42 No. 7, pp. 2667-2675, doi: 10.1016/j.buildenv.2006.07.007.

Gunel, M.H. and Ilgın, H.E. (2014a), *Tall Buildings: Structural Systems and Aerodynamic Form*, Routledge, London.

Gunel, M.H. and Ilgın, H.E. (2014b), *Yüksek Bina: Taşıyıcı Sistem Ve Aerodinamik Form*, METU Faculty of Architecture Press, Ankara, 978-975-429-278-7, (in Turkish).

Hamid, G.M., Elsawi, M. and Yusra, O. (2022), "The impacts of spatial parameters on space efficiency in hybrid villa-apartments in greater khartoum, Sudan", *Journal Architecture and Planning*, Vol. 34 No. 4, pp. 425-440.

Ilgın, H.E. (2006), "A study on tall buildings and aerodynamic modifications against wind excitation", MSc Thesis, Department of Architecture, Middle East Technical University, Ankara.

Ilgın, H.E. (2018), "Potentials and limitations of supertall building structural systems: guiding for architects", Ph.D. Dissertation, Department of Architecture, Middle East Technical University, Ankara.

Ilgın, H.E. (2021a), "Space efficiency in contemporary supertall office buildings", *Journal of Architectural Engineering*, Vol. 27 No. 3, 4021024, doi: 10.1061/(asce)ae.1943-5568.0000486.

Ilgın, H.E. (2021b), "Space efficiency in contemporary supertall residential buildings", *Architecture*, Vol. 1 No. 1, pp. 25-37, doi: 10.3390/architecture1010004.

Ilgın, H.E. (2022a), "Use of aerodynamically favorable tapered form in contemporary supertall buildings", *Journal of Design for Resilience in Architecture and Planning*, Vol. 3 No. 2, pp. 183-196, doi: 10.47818/drarch.2022.v3i2052.

Ilgın, H.E. (2022b), "Core design and space efficiency in contemporary supertall office buildings", in Al-Kodmany, K., Du, P. and Ali, M.M. (Eds), *Sustainable High-Rise Buildings: Design, Technology, and Innovation*, The Institution of Engineering and Technology, London.

Ilgın, H.E. (2023a), "Interrelations of slenderness ratio and main design criteria in supertall buildings", *International Journal of Building Pathology and Adaptation*, Vol. 41 No. 6, pp. 139-161, doi: 10.1108/ijbpa-07-2022-0102.

Ilgın, H.E. (2023b), "A study on space efficiency in contemporary supertall mixed-use buildings", *Journal of Building Engineering*, Vol. 69, 106223, doi: 10.1016/j.jobe.2023.106223.

Ilgın, H.E. (2023c), "An analysis of space efficiency in Asian supertall towers", *International Journal of Building Pathology and Adaptation*, Vol. 41 No. 6, pp. 237-253, doi: 10.1108/ijbpa-06-2023-0082.

Ilgın, H.E. (2023d), "Space efficiency in tapered super-tall towers", *Buildings*, Vol. 13 No. 11, p. 2819, doi: 10.3390/buildings13112819.

Ilgın, H.E. (2023e), "Review on supertall building forms", *Civil Engineering and Architecture*, Vol. 11 No. 3, pp. 1606-1615, doi: 10.13189/cea.2023.110339.

Ilgın, H.E. (2023f), "A study on interrelations of structural systems and main planning considerations in contemporary supertall buildings", *International Journal of Building Pathology and Adaptation*, Vol. 41 No. 6, pp. 1-25, doi: 10.1108/ijbpa-12-2021-0172.

Ilgın, H.E. and Karjalainen, M. (2021), *Perceptions, Attitudes, and Interests of Architects in the Use of Engineered Wood Products for Construction: A Review*, IntechOpen, London.

Ilgın, H.E. and Karjalainen, M. (2023), "Freeform supertall buildings", *Civil Engineering and Architecture*, Vol. 11 No. 2, pp. 999-1009, doi: 10.13189/cea.2023.110233.

Ilgın, H.E., Ay, B.Ö. and Gunel, M.H. (2021), "A study on main architectural and structural design considerations of contemporary supertall buildings", *Architectural Science Review*, Vol. 64 No. 3, pp. 212-224, doi: 10.1080/00038628.2020.1753010.

Ilgın, H.E., Karjalainen, M. and Pelsmakers, S. (2023), "Contemporary tall residential timber buildings: what are the main architectural and structural design considerations?", *International Journal of Building Pathology and Adaptation*, Vol. 41 No. 6, pp. 26-46, doi: 10.1108/ijbpa-10-2021-0142.

Karjalainen, M. and Ilgın, H.E. (2021), "A statistical study on multi-story timber residential buildings (1995-2020) in Finland", *Proceedings of the LIVENARCH VII Livable Environments & Architecture 7th International Congress OTHER ARCHITECT/URE(S)*, 28-30 September, Vol. 1, Trabzon, pp. 82-94.

Karjalainen, M., Ilgın, H.E., Metsäranta, L. and Norvasuo, M. (2022), *Wooden Facade Renovation and Additional Floor Construction for Suburban Development in Finland*, IntechOpen, London.

Kim, H.I. and Elnimeiri, M. (2004), "Space efficiency in multi-use tall building", in *Tall Buildings in Historical Cities-Culture and Technology for Sustainable Cities*, pp. 10-13, available at: https://global.ctbuh.org/resources/papers/download/1342-space-efficiency-in-multi-use-tall-building.pdf

Moon, K.S. (2015), “Supertall asia/Middle East: technological responses and contextual impacts”, *Buildings*, Vol. 5 No. 3, pp. 814-833, doi: 10.3390/buildings5030814.

Nam, H.J. and Shim, J.H. (2016), “An analysis of the change in space efficiency based on various tall building corner shapes and lease spans”, *Journal of the Architectural Institute of Korea Planning and Design*, Vol. 32 No. 8, pp. 13-20, doi: 10.5659/jaik_pd.2016.32.8.13.

Okbaz, F.T. and Sev, A. (2023), “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*, Vol. 38 No. 1, pp. 113-125.

Oldfield, P. and Doherty, B. (2019), “Offset cores: trends, drivers and frequency in tall buildings”, *CTBUH Journal*, No. 2, pp. 40-45.

Rinne, R., Ilgın, H.E. and Karjalainen, M. (2022), “Comparative study on life-cycle assessment and carbon footprint of hybrid, concrete and timber apartment buildings in Finland”, *International Journal of Environmental Research and Public Health*, Vol. 19 No. 2, p. 774, doi: 10.3390/ijerph19020774.

Saari, A., Tissari, T., Valkama, E. and Seppänen, O. (2006), “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”, *Building and Environment*, Vol. 41 No. 12, pp. 1961-1972, doi: 10.1016/j.buildenv.2005.07.012.

Saarinen, S., Ilgın, H.E., Karjalainen, M. and Hirvilammi, T. (2022), “Individually designed house in Finland: perspectives of architectural experts and a design case study”, *Buildings*, Vol. 12 No. 12, p. 2246, doi: 10.3390/buildings12122246.

Sev, A. and Özgen, A. (2009), “Space efficiency in high-rise office buildings”, *METU Journal of the Faculty of Architecture*, Vol. 26 No. 2, pp. 69-89, doi: 10.4305/metu.jfa.2009.2.4.

Suga, R. (2021), “Space efficiency in hotel development”, MSc Thesis, Business Administration with a Specialization in Real Estate Management and Development, MODUL University Vienna, Vienna.

Taranath, B.S. (2016), *Structural Analysis and Design of Tall Buildings: Steel and Composite Construction*, CRC Press, Taylor and Francis Group, Boca Raton, FL.

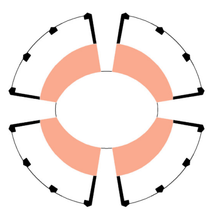
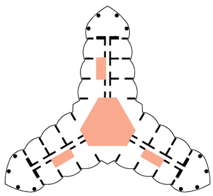
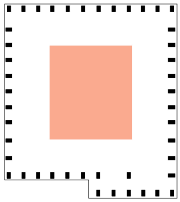
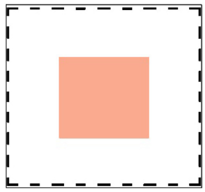
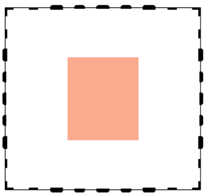
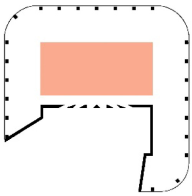
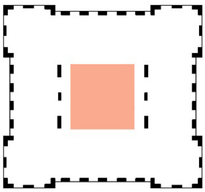
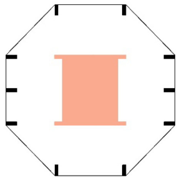
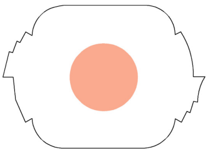
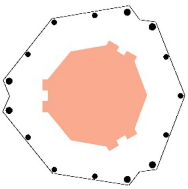
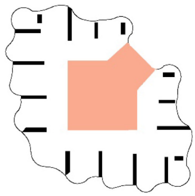
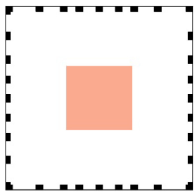
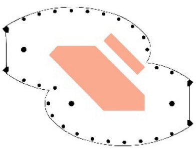
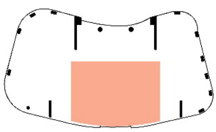
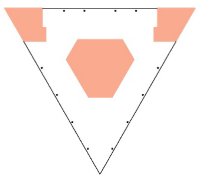
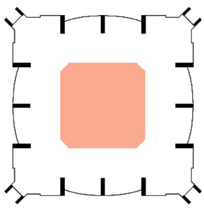
Tulonen, L., Karjalainen, M. and Ilgın, H.E. (2021), *Tall Wooden Residential Buildings in Finland: what Are the Key Factors for Design and Implementation?*, IntechOpen, London.

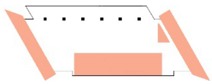
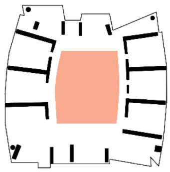
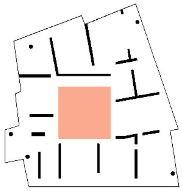
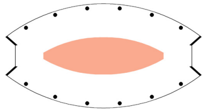
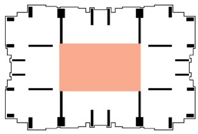
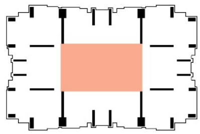
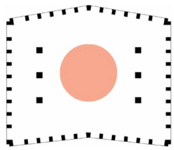
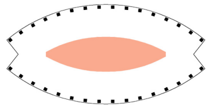
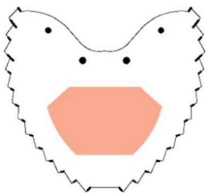
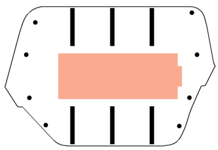
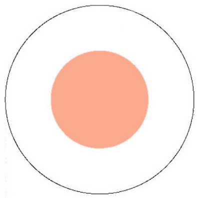
Tuure, A. and Ilgın, H.E. (2023), “Space efficiency in Finnish mid-rise timber apartment buildings”, *Buildings*, Vol. 13 No. 8, 2094, p. 2094, doi: 10.3390/buildings13082094.

Yeang, K. (2000), *Service Cores: Detail in Building*, Wiley-Academy, London.

Ziyatov, F.S.U., Valiev, K.T.U. and Achilov, O.R. (2022), “Specific features in designing and construction of skyscrapers”, *Academic Research in Educational Sciences*, Vol. 3 No. 2, pp. 106-110.

Appendix
Middle Eastern super-tall buildings' floor plan with space efficiency and core/gross floor area ratio

Building name							
Space efficiency*				Core/GFA**			
Nakheel Tower		**Burj Khalifa**		**Entisar Tower**		**Marina 106**	
69%	26%	74%	24%	74%	24%	78%	20%
							
Low-rise floor		Typical floor		Low-rise floor		Typical floor	
Marina 101		**Al Hamra Tower**		**Princess Tower**		**23 Marina**	
82%	16%	70%	26%	82%	12%	81%	17%
							
Typical floor		Low-rise floor		Typical floor		Typical floor	
Dynamic Tower		**PIF Tower**		**Burj Mohammed Bin Rashid**		**Elite Residence**	
84%	16%	65%	33%	73%	21%	84%	12%
							
Low-rise floor		Typical floor		Typical floor		Typical floor	
Almas Tower		**Il Primo Tower 1**		**Emirates Tower One**		**The Torch**	
77%	21%	71%	28%	70%	30%	74%	22%
							
Typical floor		Typical floor		Typical floor		Typical floor	

ADNOC Headquarters		DAMAC Heights		Ocean Heights		Burj Rafal	
63%	36%	72%	19%	84%	11%	78%	21%
							
Low-rise floor		Typical floor		Low-rise floor		Typical floor	
Amna Tower		**Noora Tower**		**Cayan Tower**		**Kingdom Centre**	
77%	17%	77%	17%	83%	12%	78%	20%
							
Typical floor		Typical floor		Typical floor		Typical floor	
NBK Tower		**Al Wasl Tower**		**Aspire Tower**			
74%	24%	74%	22%	72%	28%		
							
Typical floor		Low-rise floor		Low-rise floor			

In the floor plans, the pink areas correspond to the service core, while black areas signify structural elements.
Space efficiency*: calculated as the ratio of the net floor area [obtained by subtracting the service core (the pink area on the floor plan) and structural elements from GFA] to GFA.
Core/GFA**: calculated as the ratio of the service core (the pink area on the floor plan) to GFA.

Source(s): Created by the author

Corresponding author
Hüseyin Emre Ilgın can be contacted at: emre.ilgin@tuni.fi