Published by Avanti Publishers

International Journal of Architectural Engineering Technology

ISSN (online): 2409-9821

Examining Space Efficiency in Supertall Towers through an Analysis of 135 Case Studies

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ARTICLE INFO

Article Type: Research Article

Guest Editor: Mariangela De Vita

Keywords:
Core typology
Supertall tower
Space efficiency
Structural system
Structural material

Timeline:
Received: October 31, 2023
Accepted: December 11, 2023
Published: December 27, 2023

Citation: Ilgın HE. Examining space efficiency in supertall towers through an analysis of 135 case studies. Int J Archit Eng Technol. 2023; 10: 140-157.

DOI: https://doi.org/10.15377/2409-9821.2023.10.10

ABSTRACT

This study addresses the critical need for a comprehensive exploration of space efficiency in supertall buildings, a crucial aspect of skyscraper architecture with profound implications for sustainability. Despite the paramount importance of spatial utilization, the existing literature lacks a thorough investigation into this domain. This research aims to fill this significant gap by conducting an exhaustive analysis based on data from 135 case studies. The proposed model for evaluating space efficiency yielded compelling technical insights. The key metrics employed in this examination include: (1) average space efficiency: the findings revealed an average space efficiency of about 72%. This metric provides a quantitative measure of how effectively space is utilized in supertall buildings. (2) core area proportion: on average, the proportion of core area to the gross floor area was around 24%. This metric sheds light on the distribution of core areas within the overall structure, impacting both functionality and spatial optimization. This study also highlighted notable trends and characteristics observed in the examined cases: (3) central core design: the majority of skyscrapers featured a central core design tailored primarily for mixed-use purposes. This architectural choice reflects a strategic approach to maximize functionality and versatility in supertall structures. (4) structural systems: The outriggered frame system emerged as the prevailing structural system, with composite materials commonly used for the structural components. This insight into prevalent structural choices contributes to the understanding of the technical aspects influencing space utilization in skyscraper design. The superiority of the proposed model lies in its ability to offer precise and quantitative measures of space efficiency, providing architects and designers with valuable data-driven guidance. By bridging the research gap, this study aims to empower professionals in the field to make informed decisions that optimize sustainable development in future skyscraper projects.

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1. Introduction

The contemporary urban environment is undergoing a rapid transformation marked by an unprecedented proliferation of vertical architectural design [1, 2]. Skyscrapers, often emblematic of modernity and progress, hold a central role in shaping the cityscapes worldwide [3, 4]. The escalating demand for vertical living and working environments intensifies the significance of the architectural framework of skyscrapers, particularly within the contexts of sustainability and the effective utilization of space [5]. The evolution of supertall buildings presents a challenge to conventional design paradigms and necessitates the development of innovative approaches geared toward the optimization of spatial efficiency [6]. This evolution reflects a complex interplay of architectural, engineering, and environmental factors that must be addressed to meet the demands of modern urban living [7].

In the context of supertall structures, the notion of space efficiency exhibits a complicated nature, encompassing the intricate optimization of several key facets, including the effective utilization of available floor area, the strategic allocation of service core space, and the judicious selection of structural systems and materials [8]. These elements assume a critical role, not merely in the pursuit of economic benefits but also in the broader context of elevating the overall well-being of building occupants and cultivating the environmental sustainability of vertical urban environments. The intricate interplay of these factors demands rigorous analysis and strategic decision-making to achieve the multifaceted goals of supertall building design and construction [9].

Consequently, the assessment of space efficiency in skyscrapers holds critical significance for several reasons, as delineated below:

a. Scarce land resources [10, 11]: The importance of space efficiency becomes pronounced in urban settings grappling with limited available land for expansion. Supertall towers offer a vertical expansion solution, thereby conserving valuable land resources. This approach optimizes land utilization, curbing urban sprawl, and contributing to environmental preservation and the maintenance of green areas.

b. Infrastructure streamlining [12]: Tall structures facilitate the judicious use of vital infrastructure, including water supply, sewage systems, and transportation networks. Concentrating people and activities within a smaller footprint diminishes the per capita strain on these systems and minimizes resource consumption, resulting in cost savings and environmental benefits.

c. Energy conservation [13, 14]: Thoughtful spatial design in tall buildings can yield substantial energy savings. For example, compact designs mitigate heat loss and heat gain, crucial for temperature control and energy efficiency. Well-designed supertall buildings can exhibit lower per capita energy consumption compared to sprawling, low-rise alternatives.

d. Sustainable building practices [15, 16]: Space efficiency in tall buildings often aligns with sustainable design principles. This entails integrating green building technologies, sustainable materials, and energy-efficient systems, which are empirically proven to reduce environmental impacts and contribute to a sustainable urban environment.

e. Economic considerations [17, 18]: Effective space utilization in tall buildings can result in increased property values, rental returns, and a more favorable return on investment. This is substantiated by economic analyses and research demonstrating the economic benefits of space-efficient designs, thus attracting developers and investors.

Despite the interest and swift expansion of skyscraper construction, a notable lacuna emerges within the existing body of literature when it comes to comprehensive inquiries into the domain of space efficiency within supertall buildings. Space efficiency, a multifaceted concept, encompasses a thorough examination of how space is utilized within skyscrapers. It wields a profound influence not solely on the operational and aesthetic dimensions of these towering edifices but also on their environmental repercussions and sustainability implications. This research gap assumes a conspicuous significance, particularly in light of the escalating global concerns that pertain to urbanization dynamics, resource conservation imperatives, and the overarching goals of sustainable development in the contemporary urban milieu. Addressing this gap is essential to advancing our understanding of how to create more sustainable and functional supertall structures within the context of rapidly evolving urban environments.

To address this critical gap in knowledge, this study aims to conduct an exhaustive examination of space efficiency in supertall buildings. The research draws from 135 case studies, as delineated in Appendices A-C. Through a systematic analysis of these cases, it was aimed to shed light on the space efficiency trends and design choices that underpin the construction of supertall buildings. This examination paid attention to their design, functional characteristics, structural systems, and material selections. It is important to note that sustainable planning elements, such as energy consumption, were not incorporated into the analysis due to insufficient data availability for all the towers. The primary emphasis of this research remains centered on the assessment of space efficiency.

The central objectives of this study are as follows: (1) to determine the average space efficiency in supertall buildings and explore the variations within this metric, (2) to investigate the proportion of core area relative to the GFA in supertall structures, (3) to identify prevalent design strategies employed by architects and engineers in optimizing spatial utilization, and (4) to assess the predominant structural systems and materials used in the construction of supertall buildings. Notably, the aftermath of the tragic events associated with the World Trade Center incident on September 11, 2001, in the United States significantly impeded data acquisition efforts due to heightened security measures in skyscraper-related research.

By presenting a comprehensive analysis of these key facets, this research aims to contribute significantly to the body of knowledge concerning skyscraper architecture and sustainable urban development. The insights gleaned from this study are expected to offer valuable direction, particularly to architectural designers, as they strive to meet the challenges of optimizing space within supertall structures while upholding principles of sustainability. In an era characterized by the relentless expansion of urban landscapes, understanding and enhancing spatial utilization in skyscrapers holds the promise of shaping more efficient, sustainable, and visually striking cities of the future.

The contribution of this research can be summarized:

1. Filling research gap: Addresses the existing lack of comprehensive research on space efficiency in supertall buildings, contributing to a more holistic understanding of spatial utilization in skyscraper architecture.
2. Quantitative insights: Provides precise quantitative measures of space efficiency, offering a nuanced perspective on how effectively space is utilized in the examined supertall buildings.
3. Data-driven analysis: Conducts an exhaustive examination based on a curated pool of 135 case studies, ensuring a robust and data-driven analysis of space efficiency trends in skyscraper design.
4. Key metrics identified: Introduces key metrics, such as average space efficiency (72.1%) and the proportion of core area to gross floor area (GFA) (24.4%), providing architects with specific benchmarks for evaluating and optimizing spatial utilization.
5. Architectural trends highlighted: Identifies prevalent architectural trends, including the widespread use of a central core design for mixed-use purposes, offering valuable insights into design preferences and functionality considerations in skyscraper projects.
6. Structural system analysis: Highlights the outriggered frame system as the prevailing structural choice, with the common use of composite materials for structural components, contributing to a deeper understanding of the technical aspects influencing space efficiency in supertall buildings.

The motivation for this research can be summarized:

1. Importance of spatial utilization: Acknowledges the paramount importance of spatial utilization in the architectural blueprint of skyscrapers, recognizing its profound implications for sustainability and the overall success of these monumental structures.
2. Research gap recognition: Identifies a notable research lacuna in the existing literature, emphasizing the need for a comprehensive exploration of space efficiency in supertall buildings to inform and guide architectural design practices.

3. Anticipation of practical impact: Expresses the anticipation that the insights gained from the research will offer valuable direction, especially for architectural designers, in their efforts to optimize sustainable development in future skyscraper projects.
4. Contributing to sustainable practices: Reflects a broader motivation to contribute to sustainable practices in skyscraper construction by providing architects with data-driven guidance and benchmarks for enhancing spatial efficiency.

The subsequent sections were organized in the following order. Initially, a comprehensive examination of the prevailing scholarly literature in the field was conducted. Subsequently, the study's research methodology was clarified, and the ensuing results were delineated. This was followed by an exploration of 135 case studies, yielding relevant insights into the notable examples' key attributes and considerations regarding space efficiency. Lastly, a conclusion was formulated, along with potential directions for future research and the acknowledged limitations of this study.

2. Literature Survey

The existing body of scientific literature lacks comprehensive research endeavors aimed at achieving a full understanding of the complexities related to space utilization in tall buildings. Previous studies in this field have been limited in their focus, typically centering on a narrow subset of tall structures.

Okbaz *et al*. [19] developed a spatial efficiency model for 11 high-rise office buildings with freeform designs. The investigation involved analyzing different design factors including the service core and structural elements. The results indicated that (i) building form strongly influences spatial efficiency, with floor-to-floor height having minimal impact; and (ii) tapered forms yield the highest efficiency ratio, whereas freeform designs yield the lowest ratio.

Tuure *et al*. [20] investigated the space efficiency of 55 mid-rise wooden apartments in Finland. Their findings revealed that (a) space efficiency ranged between 78% and 88% on average, with a mean of 83%, and (b) no discernible scientific correlation was identified between the number of stories and space efficiency.

Ibrahimy *et al*. [21] conducted an assessment of the effectiveness of space utilization in residential dwellings within Kabul City. The results demonstrated that a majority of residential structures do not adhere to space utilization regulations and prescribed standards, largely due to a lack of consideration for the interior design process and governmental construction guidelines.

Goessler *et al*. [22] examined the influence of smart technologies on compact urban residences, aiming to make them more versatile, adaptable, and customized to individual needs. The research was based on the idea that integrating adaptive housing design with smart technology could significantly improve efficiency and space utilization, showing a potential two to threefold enhancement compared to traditional apartment layouts. The results revealed that incorporating smart and adaptable technology can increase space efficiency by reducing the need for distinct physical areas assigned to different activities.

Ilgin [23] delved into an analysis of core design and spatial optimization in contemporary supertall office edifices. The study gleaned insights from a carefully curated group of ten case study towers, aiming to investigate the pivotal factors influencing service core design. The author duly recognizes the continual evolution of contemporary trends in service core design, and the chapter elucidates essential design principles that incorporate these dynamic trends.

Hamid *et al*. [24] performed interviews with architectural firms to investigate the spatial efficiency of 60 single-family homes in Sudan. The findings revealed that (i) optimal land utilization occurs when the house is positioned at a corner, and (ii) parcels with greater width relative to depth exhibit the highest levels of space efficiency.

In a study by Suga [25], an examination of space efficiency within hotels was carried out. The results indicated that (a) strategies emphasizing space efficiency yield favorable outcomes, and (b) the significance of space efficiency amplifies particularly in larger spatial contexts.

Ilgın [26] conducted a study on optimizing spatial usage in office structures by considering key architectural and structural design principles. Concurrently, Ilgın [27] explored spatial efficiency in residential skyscrapers, also incorporating these identical design principles. Furthermore, Ilgın [28] directed attention towards optimizing spatial utilization in mixed-use towers, analyzing 64 case study edifices. In all instances, it was demonstrated that (i) the central core configuration emerged as the predominant choice; (ii) the outriggered frame system was the prevalent choice for load-bearing; and (iii) an inverse correlation was observed between building height and space efficiency.

Arslan [29] researched the factors influencing the service core and load-bearing system in prismatic towers. The findings revealed that (a) with the elevation of the building, there is a proportional augmentation in the space designated for the core and load-bearing system; and (b) no discernible scientific correlation exists between construction material and space efficiency.

Von Both [30] proposed a method tailored for the early phases of planning, centered around stakeholder analysis. This method assists in outlining user functions related to processes and establishing clear functional interconnections. It encourages planners to consider potential improvements in terms of area and space efficiency. An illustrative prototype of this approach was presented as a web-based tool, facilitating a participatory planning process that involves both users and stakeholders.

Höjer *et al*. [31] discussed the influence of digitalization on the dynamics of interior space demand and supply within existing structures. Utilizing concepts that promote the flexible use of digitally enabled building spaces and innovative measurement techniques, a four-stage construction guideline is proposed. The initial phase involves reducing space requirements, followed by optimizing the use of existing space in the subsequent step. The third stage focuses on renovating and adapting existing structures to meet contemporary needs, and the final phase centers on the construction of new buildings.

Nam *et al*. [32] conducted a study on the impact of lease span and high-rise corner configurations on spatial efficiency. The study emphasized that (i) the square-cut corner configuration exhibited the highest degree of disadvantage; and (ii) corner cuts had minimal influence on spatial efficiency, whereas lease span demonstrated a significant effect.

Zhang *et al*. [33] proposed a methodology for designing a free-form structure in the cold regions of China to improve solar radiation absorption. The findings showed that, compared to a reference building with a cube-shaped design, the optimized free-form structure demonstrates a significant increase in total solar radiation gain, ranging from 30% to 53%. Concurrently, the shape coefficient value decreases by 15% to 20%, while the reduction in space efficiency values remains below 5%.

Sev *et al*. [34] investigated the space efficiency of 10 office towers, analyzing diverse design elements like core type and load-bearing system. The results indicated that (a) structural system and core typology have significant importance, and (b) the most favored configurations are outriggered frame systems and the central core arrangement.

Saari *et al*. [35] focused on variances in overall building expenditure through the enhancement of space efficiency within office towers. The outcomes revealed that as space efficiency experiences substantial improvement, it becomes imperative to implement measures to maintain a desirable indoor climate.

Kim *et al*. [36] scrutinized the space efficiency of ten mixed-use towers. The findings indicated that (i) beyond space efficiency, one must consider structural and energy efficiency; and (ii) essential factors encompass functional allocation and determining the optimal number of elevators.

Based on the literature review provided earlier, it's evident that there's a lack of research investigating space utilization in tall and supertall structures. The current body of research primarily centers on functional aspects such as [34] and architectural design such as [32] of these towering structures.

A significant research gap exists concerning a thorough exploration of space efficiency within skyscrapers, encompassing extensive case studies and a diverse range of global locations. The primary aim of this research endeavor is to address and bridge this notable gap in the existing academic literature.

3. Methods

To investigate the concept of space efficiency in skyscrapers, a case study approach was adopted, utilizing established evaluation methodologies commonly employed in assessing built environment projects. The chosen methodology, well-recognized and endorsed within the scientific community, allows for the gathering of both quantitative and qualitative data. This comprehensive data collection approach facilitates a thorough analysis of the subject matter [37-39]. A meticulous selection process was carried out to identify and include a total of 135 supertall towers, each of which underwent a rigorous examination.

The sample of 135 cases for this study demonstrated a significant and diverse array of geographical distributions, spanning various regions. Among these, 77 towers were situated in Asia, with a predominant concentration of 57 towers in China. Additionally, there were 27 towers in the Middle East, 19 towers in the United States, 7 towers in Russia, and 2 towers in Australia. Furthermore, one tower each was located in Canada, Chile, and the UK, as specified in Appendix **A**. A meticulous documentation process captured detailed information for each case, and this comprehensive dataset is available for reference in Appendix **B**. It is crucial to highlight that, during the case study selection process, intentional measures were taken to exclude supertall buildings that lacked adequate and readily accessible data concerning space efficiency or floor layouts. This rigorous approach was implemented to safeguard the integrity and reliability of the dataset, thereby enabling a focused and meaningful analysis of the 135 chosen cases.

In a thorough endeavor, the researcher conducted a rigorous examination of the floor configurations across a diverse set of supertall cases, including ground, low-rise, and typical floors. This meticulous methodology ensured the collection of reliable and precise information, laying a robust groundwork for evaluating space utilization within the studied cohort. Furthermore, in alignment with prior academic works [40-43], the author applied the all-encompassing classification system introduced by [28] to essential elements in architectural and structural design. This selection was motivated by the attributes of these groupings, as clearly outlined in Table **1**.

In structural systems, it is worth noting that the diagrid-framed-tube system represents a modification of the framed-tube system, featuring diagonals instead of vertical components. In comparison to the traditional framed-tube system, this variant demonstrates enhanced efficacy in mitigating lateral loads. The strategic arrangement of elements in a closely spaced diagrid pattern imparts substantial resistance to both vertical and lateral forces [44-46].

Table 1: Core, structural system, and structural material classifications.

<table>
<tr><th>Core</th><th>Structural System</th></tr>
<tr><td>Central core
• Central
• Central split</td><td>Shear-frame system
• shear trussed frame
• Shear walled frame</td></tr>
<tr><td rowspan="3">Atrium core
• Atrium
• Atrium split</td><td>Mega core system</td></tr>
<tr><td>Mega column system</td></tr>
<tr><td>Outriggered frame system</td></tr>
<tr><td rowspan="2">External core
• Attached
• Detached
• Partial split
• Full split</td><td>Tube system
• Framed-tube
• Trussed-tume
• Bundled-tube</td></tr>
<tr><td>Buttressed core system</td></tr>
<tr><td rowspan="4">Peripheral core
• Partial peripheral
• Full peripheral
• Partial split
• Full split</td><td>Structural material</td></tr>
<tr><td>Steel</td></tr>
<tr><td>Reinforced concrete</td></tr>
<tr><td>Composite</td></tr>
</table>

Considering its broad scope, this study included diverse building form arrangements, as depicted in Fig. (**1**) [47].

(a) *Prismatic forms* refer to structures characterized by symmetrical and parallel shapes on both ends, exhibiting identical sides and vertical axes that are precisely aligned perpendicular to the ground. This arrangement guarantees the maintenance of uniform geometric proportions across the entire building.

(b) *Leaning/tilted forms* delineate buildings characterized by a tilted arrangement. These structures deviate from the typical vertical orientation and intentionally integrate an angle into their design.

(c) *Tapered forms* delineate structures that display a gradual decrease in their floor layouts and surface areas as they rise vertically. This occurrence yields either linear or non-linear profiles, marked by diminishing dimensions and ratios as one progresses toward the upper levels.

(d) *Setback forms* pertain to buildings that incorporate horizontally recessed segments positioned at different elevations along the vertical axis of the structure. These recessed portions generate distinct terraces within the edifice, leading to a layered or cascading visual effect.

(e) *Twisted forms* pertain to buildings that experience a gradual rotational or torsional shift of their floors or facades as they ascend in proximity to a central axis. This rotational alteration takes place in a stepwise manner, resulting in a twisting or spiraling visual effect that imparts a sense of dynamism and aesthetic fascination to the edifice.

(f) *Free forms* emerge through the implementation of transformative processes applied to geometrically fundamental elements, including lines or volumes. These processes involve a sequence of manipulations and alterations orchestrated by the architect, ultimately resulting in a definitive form that diverges from the established categories previously discussed.

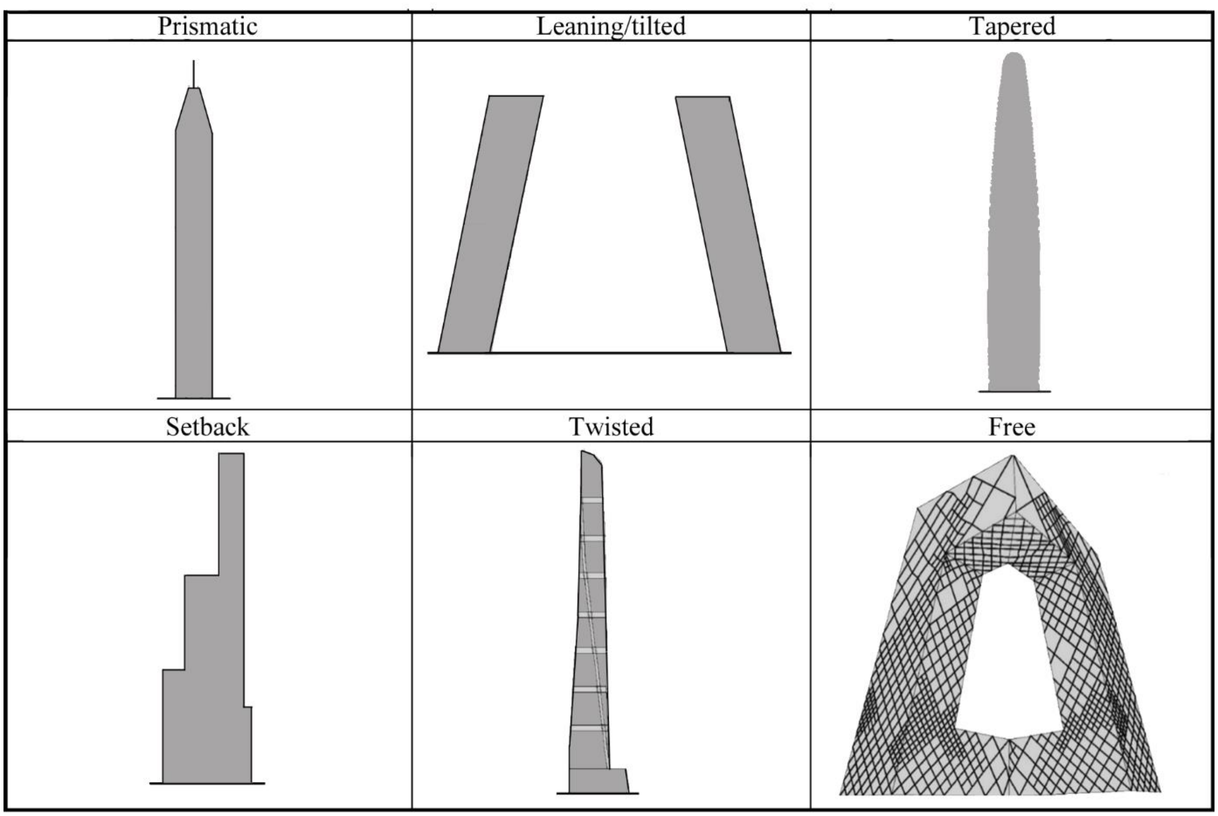


Figure 1: Supertall building forms.

The establishment of a definitive criterion for delineating the exact number of stories or elevations that classify a building as a supertall tower remains a topic of debate within the scientific community, given the absence of a universally agreed-upon definition in this context. However, within the context of this research, the classification of a building as a supertall tower conforms to the criteria set forth by the CTBUH database, which defines a supertall structure as one that surpasses a height of 300 meters [48].

Space efficiency pertains to the correlation between the net floor area (NFA) and GFA. It carries significance, especially for investors, as it involves the efficient utilization of floor plan spaces to achieve the highest possible return on investment. The level of space efficiency is predominantly shaped by a range of factors, including the selection of load-bearing systems and construction materials, architectural design, and the layout of floor slabs.

Furthermore, the concept of space efficiency plays a pivotal role in defining lease span, representing the measurement of the distance between stationary internal elements such as service core walls and external elements like windows [49]. This factor directly impacts the efficient utilization of space within a particular building.

4. Findings

4.1. Main Architectural Design Considerations: Function, Form, and Core Typology

Concerning the intended functions of high-rise buildings, the examined collection of case studies primarily comprised mixed-use developments, representing more than 47% of the total sample. Office usage accounted for 33% of the overall utilization, while residential occupancy constituted 20%, as illustrated in Fig. (**2**). The prevalence of multifunctional buildings can be elucidated by the adoption of the 'vertical communities' concept. This approach arises from the acknowledgment that hybrid functions effectively accommodate a growing population and the swift urbanization experienced, especially in developing nations. From a financial perspective, multi-functional developments have gained favor due to their ability to optimize leasing opportunities, particularly during market fluctuations [50, 51]. They achieve this by offering round-the-clock visitor potential and by sustaining a diverse customer base.

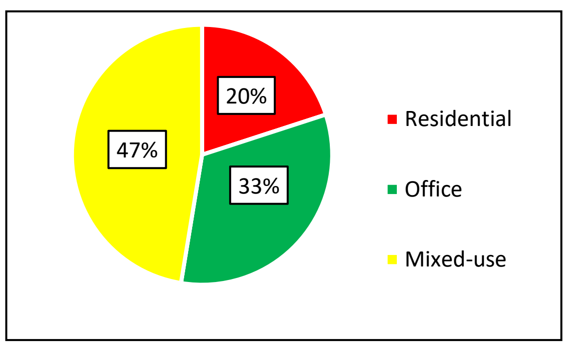


Figure 2: Supertall towers by function.

Tapered configuration, with a ratio of 30%, emerges as the most frequently employed form (Fig. **3**). The rationale behind this prevalent choice could be attributed to the structural and aerodynamic advantages associated with tapered shapes in the context of supertall buildings [52, 53]. Furthermore, the versatility of tapered forms in accommodating a variety of functions with differing lease spans may enhance their architectural desirability within the context of mixed-use supertall buildings. The second most common type of supertall buildings was characterized by freeform and prismatic designs, with such structures accounting for 26% each. This relatively high prevalence of freeform designs may be attributed to architects' keen interest in exploring distinctive and innovative building shapes [54, 55]. The common occurrence of prismatic shapes in skyscraper design can be explained by several factors that make them advantageous in this context. One significant factor is the inherent simplicity and construction convenience associated with prismatic designs, especially when contrasted with the more complicated designs. Prismatic shapes often involve more regular forms, such as rectangles, which are intrinsically more straightforward to handle in terms of construction logistics and efficient material utilization. On the other hand, the adoption of freeform designs might have become prevalent because of their superior aerodynamic properties and the inclination of skyscraper architects to craft iconic and distinctive structures.

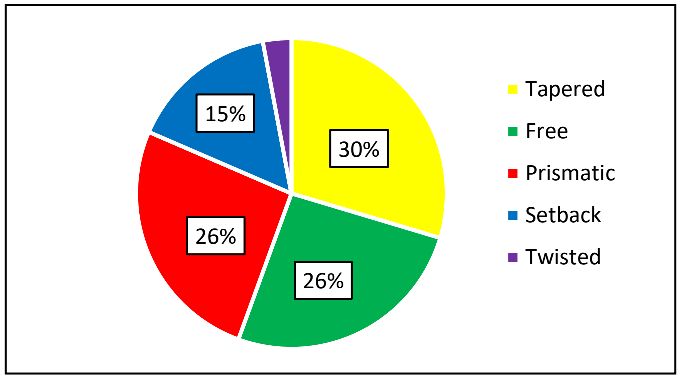


Figure 3: Supertall towers by form.

Among the various design options evaluated for these buildings, the dominant selection for supertall towers was the adoption of the central core strategy. The widespread use of the central core approach can be ascribed to its streamlined and effective structural configuration. This design provides substantial advantages in terms of bolstering overall structural integrity and streamlining fire evacuation protocols, as detailed by [56]. On the flip side, the rare utilization of external and peripheral cores can be attributed to the elongated circulation paths they create, resulting in longer pathways for fire escape, as explained by [57, 58].

4.2. Main Structural Design Considerations: Structural System and Structural Material

In Fig. (**4**), it is evident that outriggered frame systems have emerged as the predominant choice, being selected in 68% of cases. In contrast, tube systems make up a smaller proportion, totaling 20%. The prevailing preference for outriggered frame systems can be attributed to their inherent ability to provide some flexibility in the placement of exterior columns [59-61]. As a result, architects have greater latitude to exercise their creative imagination when it comes to molding the building's exterior appearance, especially in the pursuit of unobstructed external views. This expanded spectrum of design options, in a reciprocal manner, promotes the investigation of taller building heights, rendering the outrigger frame system an appealing option for erecting skyscrapers.

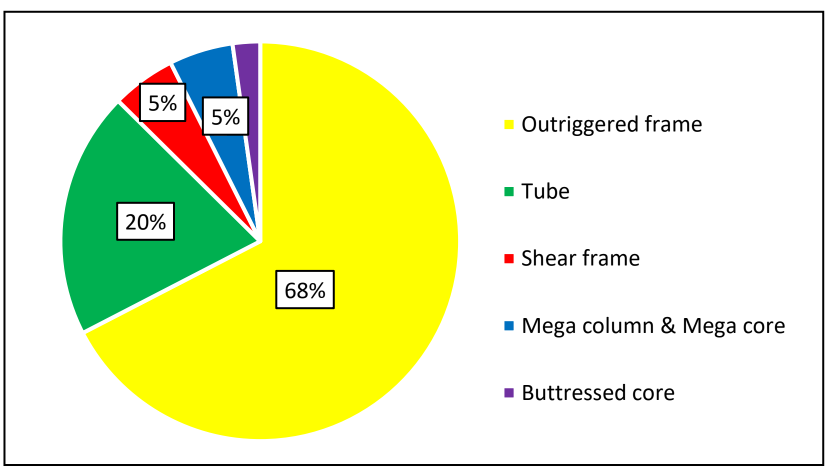


Figure 4: Supertall towers by the structural system.

Fig. (**5**) illustrates that the most common selection among the investigated case studies was composite construction, representing more than 60% of the sample. In the subsequent position, reinforced concrete construction was observed in over 36% of the analyzed cases. The widespread adoption of composite construction can primarily be credited to the synergistic benefits derived from the combination of two materials [62-64]: the high strength of steel, along with the exceptional fire resistance (particularly in the case of concrete-encased sections) and structural rigidity (stemming from the inherent attributes of stiffness and damping) of reinforced concrete segments. Consequently, it should come as no surprise that 61% of supertall buildings fall under the 'composite' category (Fig. **5**). Within the realm of composite construction, structural configurations based on cross-sections account for more than 70% of the sample, encompassing elements such as concrete-filled steel and/or steel-encased concrete.

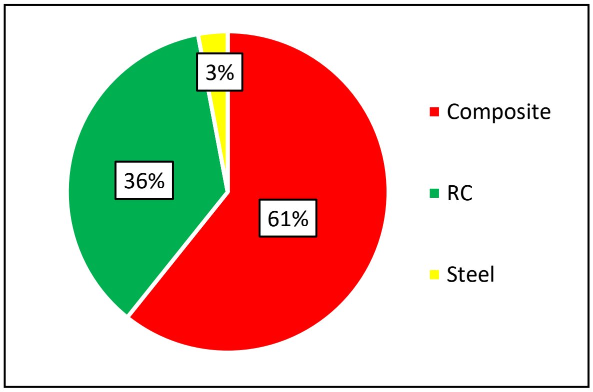


Figure 5: Supertall towers by the structural material.

4.3. Space Efficiency in Tall and Supertall Towers

The suggested standard for assessing space efficiency in tall skyscrapers, as proposed by [65], could potentially be set at 75%. In research conducted by [26] regarding tall office buildings, it was found that the typical space efficiency, as well as the proportion of core area to total floor area, stood at 71% and 26%, respectively. The range of values spanned from a minimum of 63% and 15% to a maximum of 82% and 36%, respectively.

Likewise, in the paper of [27], which centered on residential high-rise buildings, it was determined that the mean space efficiency and the core area to GFA ratio were 76% and 19%, respectively. The spectrum of values ranged from a minimum of 56% and 11% to a maximum of 84% and 36%, respectively.

In the study by [28], focusing on mixed-use supertall buildings, it was determined that the mean space efficiency and the core area to GFA ratio were 71% and 26%, respectively. The range of values extended from a minimum of 55% and 16% to a maximum of 84% and 38%, respectively.

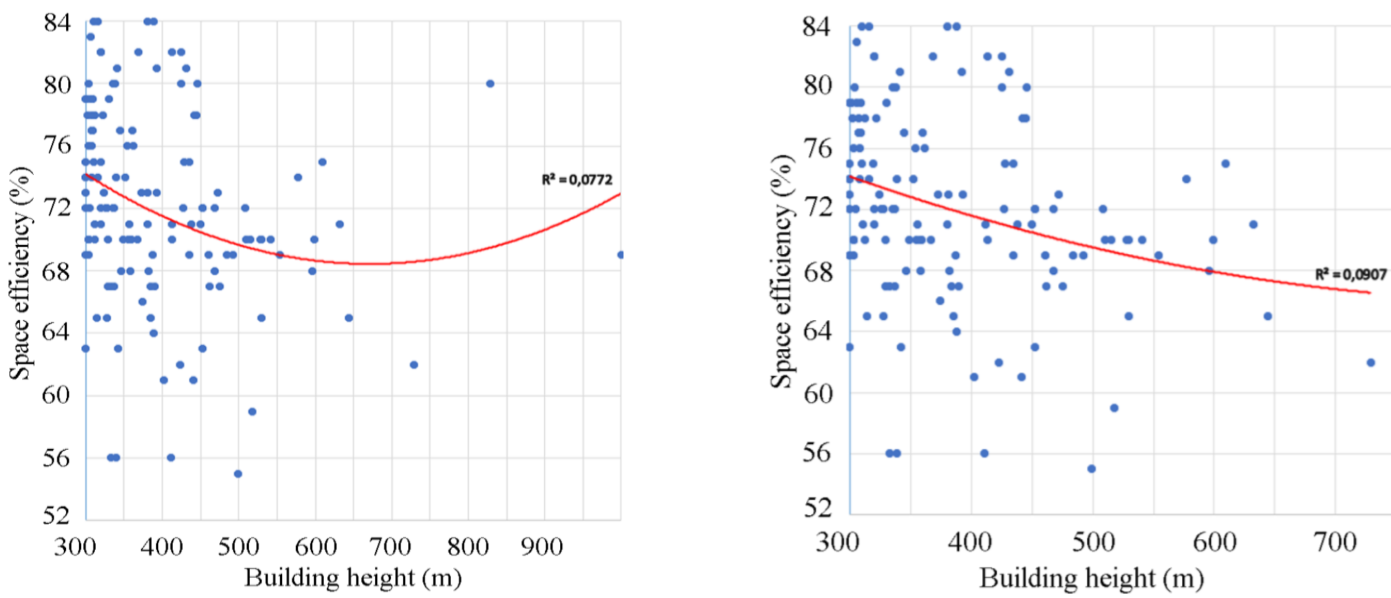
In this paper, through the examination of 135 supertall cases, the mean space efficiency and the core area to GFA ratio were computed to be approximately 72.1% and 24.4%, respectively. The range of values spanned from a minimum of 55% and 11% to a maximum of 84% and 38%, as depicted in Appendix **C**.

4.3.1. Interrelation of Space Efficiency and the Height of the Building

In Fig. (**6a** and **6b**), the connection between the efficiency of space utilization and the height of skyscrapers was illustrated. The data points in these figures correspond to the skyscrapers being studied in this case analysis. To examine the associations within this dataset, a polynomial regression technique was employed. This choice was motivated by its capacity to provide a more accurate R-squared correlation coefficient when compared to linear or exponential regression methodologies. The remarkable point of emphasis is the exceptional efficiency in space utilization observed in Nakheel Tower [66, 67]. They demonstrated efficiency rates of 69% and 80%, respectively, along with core-to-GFA ratios of 26% and 19%, which were particularly noteworthy.

It is worth noting that given the substantially lower count of buildings exceeding 650 meters in height compared to those falling within the 300-650 meters range, a precautionary measure was implemented to mitigate potential bias in the results. To ensure a more impartial analysis, megatall structures (exceeding 600 meters), exemplified by iconic buildings like Burj Khalifa and Nakheel Tower, were deliberately designated as outliers and excluded from the dataset. This strategic approach aims to prevent undue influence on the outcomes, particularly in scenarios where the representation of supertall structures may disproportionately impact statistical analyses or trend identifications in the context of buildings within the specified height range.

The discernible impact of these exceptional data points on the regression line is vividly depicted in the graphical representation presented in Fig. (**6b**). In coherence with the trend observed in Fig. (**6a**), characterized by an R^2 value of 0.07, there is a conspicuous inclination towards decreased spatial efficiency as the height of buildings increases. Furthermore, the deliberate exclusion of data outliers serves to accentuate this diminishing trend, resulting in an R^2 value of 0.09, as elucidated in Fig. (**6b**). This augmentation of the declining trend is intricately linked to the phenomenon where taller skyscrapers undergo an expansion in their core and load-bearing elements, thereby presenting a heightened challenge in achieving higher space efficiency ratios. The meticulous scrutiny of these data points, particularly the outliers, contributes significantly to a more nuanced and accurate understanding of the correlation between building height and spatial efficiency. This nuanced analysis provides valuable insights into the complex interplay of architectural and structural considerations in tall buildings, ultimately enriching this comprehension of the intricate dynamics influencing spatial efficiency trends in supertall structures.



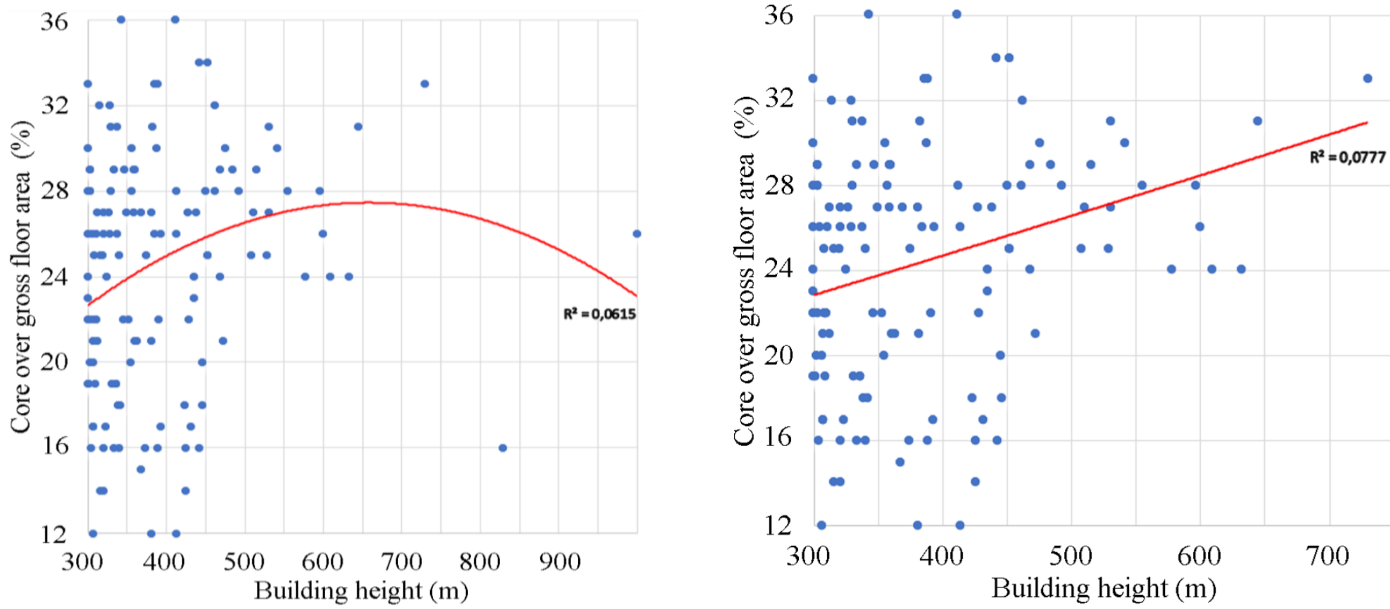
(**a**) (**b**)

Figure 6: The interrelationship between space efficiency and height: (**a**) including outliers, (**b**) excluding outliers.

Fig. (**7a**), characterized by an R^2 value of 0.06, and Fig. (**7b**), featuring an R^2 value of 0.07, contribute additional depth to the exploration of the correlation between the ratio of the core to the GFA and the height of the tower. These figures substantiate the earlier observation that an augmentation in tower height necessitates more substantial and robust service cores. Analogous to the pattern observed in Fig. (**7b**), the deliberate exclusion of anomalies serves to underscore and elucidate a more pronounced upward trend, as portrayed in Fig. (**7b**). The heightened clarity in the ascending trend underscores the critical relationship between building height and the proportion of core area to the total GFA. This refined analysis provides valuable insights into the evolving structural demands associated with taller towers, emphasizing the necessity for reinforced service cores to accommodate the heightened requirements of supertall buildings. The correlation highlighted in Fig. (**7a**), and Fig. (**7b**) contributes significantly to the understanding of the intricate interplay between architectural design, structural considerations, and spatial efficiency in the context of tall and supertall structures.

4.3.2. Interrelation of Space Efficiency and Structural System

Fig. (**8**) offers a graphical depiction illustrating the total number of skyscrapers. These counts are depicted as vertical bars on the right side, grouped based on their respective load-bearing systems. Furthermore, the chart showcases the spatial efficiency of these constructions for each particular load-bearing system, represented by blue dots. Conversely, red dots are utilized in the graph to illustrate the skyscraper that attains the utmost space efficiency within the corresponding structural system. Moreover, the black bar serves as a visual indicator denoting the number of supertall buildings in the analyzed sample employing the same structural system.



(**a**) (**b**)

Figure 7: The interrelationship between core over GFA and height: (**a**) including outliers, (**b**) excluding outliers.

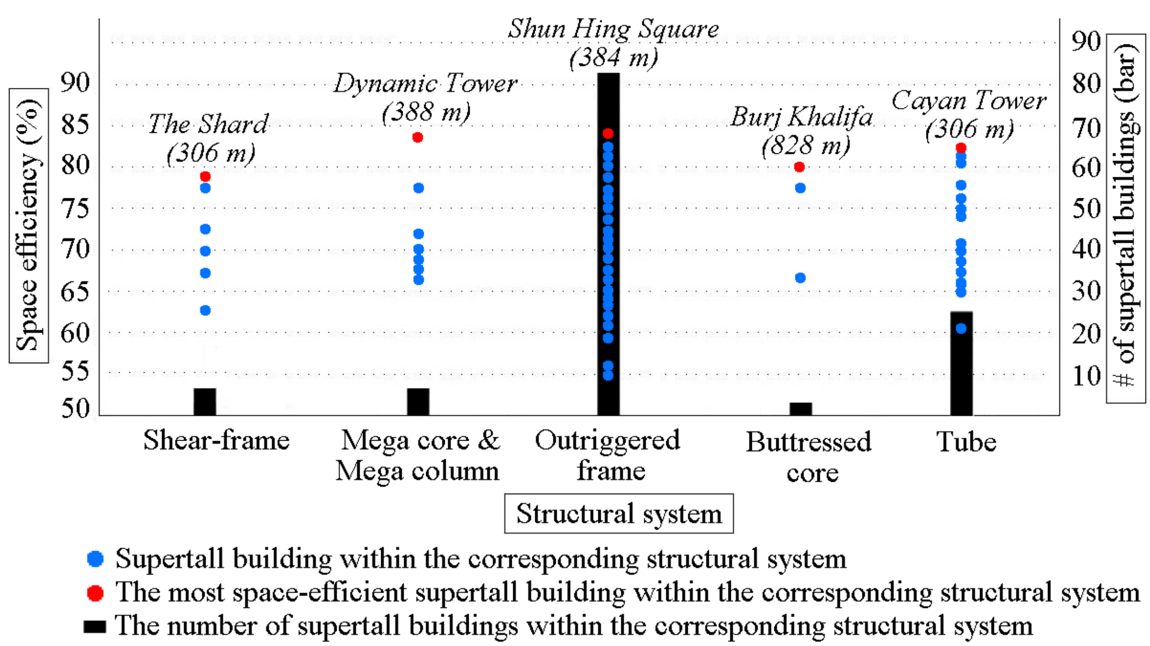


Figure 8: The interrelationship between space efficiency and structural system.

In the realm of structural systems implemented in skyscrapers, outriggered frame systems have emerged as the predominant preference, chosen for 91 towers. These structures demonstrated notable space optimization, ranging from 55% to 84%, with an average of 72.1%. Conversely, shear walled frame systems, buttressed core, mega column & mega core systems were notably less common, utilized in merely four towers. Skyscrapers employing tube systems, numbering nine in total, exhibited spatial efficiency ranging from 61% to 83%, averaging at about 72%.

Using these average measurements, it can be reasonably inferred that different load-bearing systems in skyscrapers don't show substantial differences in spatial efficiency. Given the infrequent use of shear walled frames and mega column & mega core systems, it seems improbable to establish a scientifically significant connection between the spatial efficiency of these towers and their structural systems.

4.3.3. Interrelation of Space Efficiency and Building Form

Fig. (**9**) displays the distribution of supertall structures categorized by their architectural form. The number of buildings for each form is depicted as bars on the right axis. Blue dots represent the space efficiency of these structures for their respective forms, and red dots mark the tallest skyscraper for each form. Additionally, the black bar indicates the count of supertall buildings within the sampled group utilizing the corresponding building form.

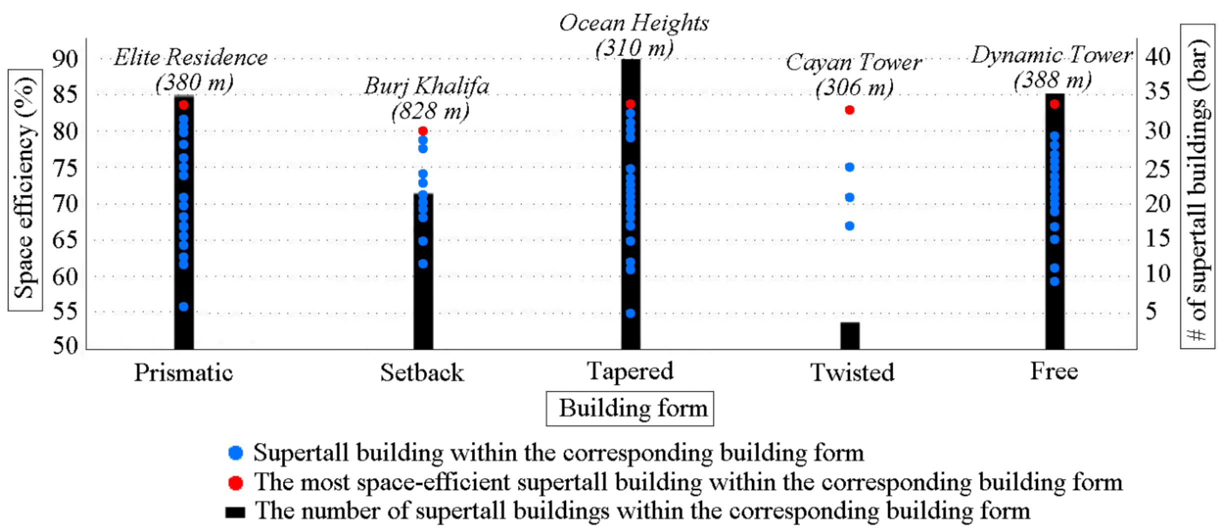


Figure 9: The interrelationship between space efficiency and building form.

Tapered structures, being the favored choice, showcased space efficiency spanning from 55% to 84%, averaging 72% across a sample of 40 towers. Similarly, prismatic and freeform buildings, emerging as the secondary preferred options, designs demonstrated a space efficiency of around 72%. Meanwhile, setback towers also displayed a space efficiency ranging from 68% to 80%, averaging at 72%. Consequently, after assessing the aforementioned values, it was determined that various architectural designs for skyscraper construction did not yield any impact on spatial efficiency.

5. Discussion

The findings revealed in this study provide a deeper understanding of both shared characteristics and distinctive features when compared to prior research, particularly focusing on the significant contributions of [28] as well as [68]. Although certain patterns and results correspond with the studies mentioned earlier, affirming and upholding a sense of validation and uniformity within the field, this research has brought to light new viewpoints and subtle intricacies that enhance the current knowledge base. The primary results obtained from this investigation can be summarized as follows:

(1) average space efficiency was 72.1%, with values ranging from a minimum of 55% to a maximum of 84%;

(2) on average, the proportion of core area to the GFA was 24.4%, with a range extending from 11% to 38%;

(3) most skyscrapers employed a central core design tailored primarily for mixed-use purposes; and

(4) a prevalent structural system identified among the examined cases was the outriggered frame system, with composite materials commonly used for the structural components.

By the findings of reference [65], which established a space efficiency standard of 75% for tall towers, it has become evident that skyscrapers, on the whole, do not quite meet this benchmark. Instead, they exhibit an average space efficiency rating of 72.1%. Furthermore, a closer examination of the most recent studies conducted by [26, 27], with a specific focus on office and mixed-use skyscrapers, has unveiled that these structures tend to achieve an average space efficiency of 71%. These figures, notably falling below the space efficiency target set by Yeang, can primarily be attributed to two key factors: the dimensions of the service core area and the dimensions of the structural components within these towering edifices.

To elaborate further, the discrepancy between the established benchmark and the observed space efficiency ratios is largely due to the sizes and configurations of both the service core area and the structural elements in these tall buildings. The service core, which typically includes elevators, stairwells, mechanical systems, and other essential building utilities, occupies a considerable portion of the building's interior [69]. Its size and layout can have a notable impact on the overall usable space available for occupants.

Similarly, the dimensions of the structural components, such as columns, beams, and load-bearing walls, can limit the flexibility of interior layouts, reducing the efficiency of space utilization [70]. These structural elements are critical for the stability and safety of tall buildings but can encroach on the available floor area.

The primary region of service within a skyscraper, typically containing essential amenities like elevators, staircases, and mechanical systems, tends to occupy a significant portion of the available space. In skyscrapers, including those evaluated by [26, 27], this core area might vary in size or lack optimal organization, thereby diminishing the usable area within the building. Additionally, the structural components of these tall buildings play a pivotal role in space utilization. As skyscrapers grow taller, they necessitate more substantial structural elements to support their weight and withstand external forces like wind and seismic activity. These structural components can occupy a considerable amount of space, impacting the overall efficiency of the floor layouts. When structural systems are not well-designed for space efficiency, it can further contribute to the observed shortcomings.

In the realm of future skyscraper design and construction, tackling these challenges could play a critical role in reaching or even exceeding Yeang's benchmark for space efficiency [65]. This could encompass pioneering strategies for core design, such as creating more condensed and streamlined layouts, along with advancements in structural engineering aimed at minimizing the spatial requirements of load-bearing components. Attaining greater space efficiency in tall buildings not only aligns with objectives related to sustainability and resource optimization but also amplifies the functionality and economic feasibility of these iconic architectural marvels.

Expanding on the discoveries from the research conducted by [26, 27], it becomes clear that the central core strategy has emerged as the favored option among the buildings scrutinized in a range of case studies. This approach entails the placement of a central core within the building, housing critical services like elevators and utilities while also providing structural support for the skyscraper. The inclination toward this design strategy can be attributed to several notable advantages it presents.

The central core design optimizes the utilization of the existing floor area. By centralizing utilities and vertical transportation within a designated core, it liberates additional space around the building's edges for office or residential purposes, thereby augmenting the overall spatial efficiency of the edifice. Furthermore, the central core design bolsters structural stability. It furnishes a robust and effective load-bearing system, which is of paramount significance, especially in tall structures. This structural stability assumes critical importance in safeguarding the well-being of occupants and the structural soundness of the skyscraper, especially in areas susceptible to seismic events or strong winds.

Concerning load-bearing mechanisms and structural materials, the prominence of outriggered frame systems and composite constructions in the examined cases highlights their efficiency in modern skyscraper architecture. Outrigger frame systems incorporate horizontal and vertical trusses or braces linking the central core to the building's outer edges, dispersing forces and reducing swaying. This system significantly improves the building's structural resilience and stability.

Moreover, the incorporation of composite materials like concrete and steel in the construction of skyscrapers serves as evidence of their robustness and adaptability. Composite constructions provide the means to enhance both structural soundness and spatial efficiency, thereby making significant contributions to the overall effectiveness and safety of tall structures.

These results are by [26, 27], which emphasize the uniformity in architectural and structural preferences observed in diverse case studies. The predilection for the central core strategy, outriggered frame systems, and composite materials highlight the significance of these design and construction approaches in modern skyscraper endeavors. This also mirrors the industry's dedication to attaining a balance between structural robustness and spatial efficiency in the advancement of tall buildings, guaranteeing their effectiveness in urban settings worldwide.

As documented in the research conducted by [26, 27], an inverse relationship between building height and spatial efficiency was identified. This association was attributed to the increased allocation of core space and the utilization of larger structural system components as buildings grew taller. The outcomes concerning the links between spatial efficiency and structural systems, as well as spatial efficiency and building design, aligned with the conclusions reported in [26, 27]. These studies indicated no substantial departure in the impact of load-bearing systems on spatial efficiency, and similar results were observed for building designs, consistent with the current study.

6. Conclusion

This study addresses a significant gap in the existing literature by comprehensively examining space efficiency in supertall buildings, crucial for sustainable architectural design. The findings from the 135 case studies reveal key insights. The average space efficiency of 72.1%, ranging from 55% to 84%, underscores the variability in utilization across different structures. The proportion of core area to the total gross floor area averaged 24.4%, with a range of 11% to 38%, shedding light on spatial distribution trends. The prevalent use of a central core design in skyscrapers, primarily for mixed-use purposes, indicates a common and strategic architectural choice. Additionally, the identified outriggered frame system as the prevailing structural solution, often using composite materials, contributes to the understanding of technical aspects influencing space efficiency. These insights collectively provide valuable direction for architectural designers, offering a foundation to optimize sustainable development in future skyscraper projects. This study underscores the importance of considering space utilization metrics and design principles for achieving enhanced sustainability in the architecture of supertall buildings.

The knowledge derived from this research is anticipated to provide significant guidance, especially for architects, in their efforts to address the issues of space optimization in supertall buildings while maintaining sustainability principles. In a time marked by the continual growth of urban areas, comprehending and improving the use of space in skyscrapers has the potential to influence the creation of more efficient, eco-friendly, and aesthetically impressive cities in the coming years.

7. Future Directions

Potential future avenues for research could include: comparative analysis across regions and cultures, longitudinal study on changing design trends, incorporation of environmental impact assessment, human-centric approach to spatial utilization, technological innovations and structural efficiency, and policy and regulations impact on spatial design.

8. Study Limitations

The study may have limitations in terms of case study selection, potentially biasing the results towards certain types of skyscrapers or specific regions. The selected 135 case studies might not adequately represent the global diversity of supertall buildings. Additionally, the research might have focused on a specific set of variables related to spatial efficiency, core area proportions, and structural systems. However, there could be other crucial variables impacting skyscraper design and sustainability that were not considered in this study.

Conflicts of Interest

The author declares no conflict of interest.

Funding

This research received no external funding.

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Appendix A. Supertall buildings.

#	Building name	Country	City	Height (Meters)	# of Storeys	Completion Date	Function
1	Nakheel Tower	UAE	Dubai	1000	200	NC	M (H/R/O)
2	Burj Khalifa	UAE	Dubai	828	163	2010	M (H/R/O)
3	Suzhou Zhongnan Center	China	Suzhou	729	137	OH	M (H/R/O)
4	Merdeka PNB118	Malaysia	Kuala Lumpur	644	118	UC	M (H/O)
5	Shanghai Tower	China	Shanghai	632	128	2015	M (H/O)
6	Chicago Spire	USA	Chicago	609	150	NC	R
7	Ping An Finance Center	China	Shenzhen	599	115	2017	O
8	Goldin Finance 117	China	Tianjin	596	128	OH	M (H/O)
9	Entisar Tower	UAE	Dubai	577	122	OH	M (H/R)
10	Lotte World Tower	South Korea	Seoul	554	123	2017	M (H/R/O)
11	One World Trade Center	USA	New York	541	94	2014	O
12	Guangzhou CTF Finance Centre	China	Guangzhou	530	111	2016	M (H/R/O)
13	Tianjin CTF Finance Centre	China	Tianjin	530	97	2019	M (H/O)
14	CITIC Tower	China	Beijing	528	108	2018	O
15	Evergrande Hefei Center 1	China	Hefei	518	112	OH	M (H/R/O)
16	Pentominium Tower	UAE	Dubai	515	122	OH	R
17	Busan Lotte Town Tower	South Korea	Busan	510	107	NC	M (H/R/O)
18	TAIPEI 101	Taiwan	Taipei	508	101	2004	O
19	Greenland Jinmao International Financial Center	China	Nanjing	499	102	UC	M (H/O)
20	Shanghai World Financial Center	China	Shanghai	492	101	2008	M (H/O)
21	International Commerce Centre	China	Hong Kong	484	108	2010	M (H/O)
22	Wuhan Greenland Center	China	Wuhan	475	97	NC	M (H/R/O)
23	Central Park Tower	USA	New York	472	98	2020	R
24	Chengdu Greenland Tower	China	Chengdu	468	101	OH	M (H/O)
25	R&F Guangdong Building	China	Tianjin	468	91	OH	M (H/R/O)
26	Lakhta Center	Russia	St. Petersburg	462	87	2019	O
27	Vincom Landmark 81	Vietnam	Ho Chi Minh City	461	81	2018	M (H/R)
28	Changsha IFS Tower T1	China	Changsha	452	94	2018	M (H/O)
29	Petronas Twin Tower 1	Malaysia	Kuala Lumpur	452	88	1998	O
30	Petronas Twin Tower 2	Malaysia	Kuala Lumpur	452	88	1998	O
31	Zifeng Tower	China	Nanjing	450	66	2010	M (H/O)
32	The Exchange 106	Malaysia	Kuala Lumpur	446	95	2019	O
33	Marina 106	UAE	Dubai	445	104	OH	R
34	World One	Mumbai	India	442	117	NC	R
35	KK 100	China	Shenzhen	441	98	2011	M (H/O)
36	Guangzhou International Finance Center	China	Guangzhou	438	103	2010	M (H/O)

37	Multifunctional Highrise Complex - Akhmat Tower	Russia	Grozny	435	102	OH	M (R/O)
38	111 West 57th Street	USA	New York	435	84	2021	R
39	Chongqing Tall Tower	China	Chongqing	431	101	OH	M (H/R/O)
40	Haikou Tower 1	China	Haikou	428	94	UC	M (H/R/O)
41	One Vanderbilt Avenue	USA	New York	427	62	2020	O
42	Marina 101	UAE	Dubai	425	101	2017	M (H/R)
43	432 Park Avenue	USA	New York	425	85	2015	R
44	Trump International Hotel & Tower	USA	Chicago	423	98	2009	M (H/R)
45	Al Hamra Tower	Kuwait	Kuwait City	413	80	2011	O
46	Princess Tower	UAE	Dubai	413	101	2012	R
47	Two International Finance Center	China	Hong Kong	412	88	2003	O
48	LCT The Sharp Landmark Tower	South Korea	Busan	411	101	2019	M (H/R)
49	Guangxi China Resources Tower	China	Nanning	402	86	2020	M (H/O)
50	China Resources Tower	China	Shenzhen	393	68	2018	O
51	23 Marina	UAE	Dubai	392	88	2012	R
52	CITIC Plaza	China	Guangzhou	390	80	1996	O
53	Dynamic Tower	UAE	Dubai	388	80	NC	M (H/R)
54	Shum Yip Upperhills Tower 1	China	Shenzhen	388	80	2020	M (H/O)
55	30 Hudson Yards	USA	New York	387	73	2019	O
56	PIF Tower	Saudi Arabia	Riyadh	385	72	2021	O
57	Shun Hing Square	China	Shenzhen	384	69	1996	O
58	Autograph Tower	Indonesia	Jakarta	382	75	2022	M (H/O)
59	Burj Mohammed Bin Rashid	UAE	Abu Dhabi	381	88	2014	R
60	Guiyang World Trade Center Landmark Tower	China	Guiyang	380	92	OH	M (H/O)
61	Elite Residence	UAE	Dubai	380	87	2012	R
62	Central Plaza	China	Hong Kong	374	78	1992	O
63	Federation Tower	Russia	Moscow	373	93	2016	M (R/O)
64	Golden Eagle Tiandi Tower A	China	Nanjing	368	77	2019	M (H/O)
65	Bank of China Tower	China	Hong Kong	367	72	1990	O
66	St. Regis Chicago	USA	Chicago	362	101	2020	M (H/R)
67	Almas Tower	UAE	Dubai	360	68	2008	O
68	Hanking Center Tower	China	Shenzhen	359	65	2018	O
69	Greenland Group Suzhou Center	China	Suzhou	358	77	UC	M (H/O)
70	Sino Steel International Plaza T2	China	Tianjin	358	83	OH	O
71	II Primo Tower 1	UAE	Dubai	356	79	UC	R
72	Emirates Tower One	UAE	Dubai	355	54	2000	O
73	OKO - Residential Tower	Russia	Moscow	354	90	2015	M (H/R)
74	The Torch	UAE	Dubai	352	86	2011	R
75	Spring City 66	China	Kunming	349	61	2019	O

76	The Center	China	Hong Kong	346	73	1998	O
77	NEVA TOWERS 2	Russia	Moscow	345	79	2020	R
78	ADNOC Headquarters	UAE	Abu Dhabi	342	65	2015	O
79	One Shenzhen Bay Tower 7	China	Shenzhen	341	78	2018	M (H/R/O)
80	Comcast Technology Center	USA	Philadelphia	339	59	2018	M (H/O)
81	LCT The Sharp Residential Tower A	Korea	Busan	339	85	2019	R
82	Mercury City Tower	Russia	Moscow	338	75	2013	M (R/O)
83	Hengqin International Finance Center	China	Zhuhai	337	69	2020	M (R/O)
84	Tianjin World Financial Center	China	Tianjin	337	75	2011	O
85	Wilshire Grand Center	USA	Los Angeles	335	62	2017	M (H/O)
86	DAMAC Heights	UAE	Dubai	335	88	2018	R
87	Shimao International Plaza	China	Shanghai	333	60	2006	M (H/O)
88	LCT The Sharp Residential Tower B	Korea	Busan	333	85	2019	R
89	China World Tower	China	Beijing	330	74	2010	M (H/O)
90	Hon Kwok City Center	China	Shenzhen	329	80	2017	M (R/O)
91	3 World Trade Center	USA	New York	329	69	2018	O
92	Keangnam Hanoi Landmark Tower	Vietnam	Hanoi	328	72	2012	M (H/R/O)
93	Golden Eagle Tiandi Tower B	China	Nanjing	328	68	2019	O
94	Salesforce Tower	USA	San Francisco	326	61	2018	O
95	Deji Plaza	China	Nanjing	324	62	2013	M (H/O)
96	Q1 Tower	Australia	Gold Coast	322	78	2005	R
97	Nina Tower	China	Hong Kong	320	80	2006	M (H/O)
98	Sinar Mas Center 1	China	Shanghai	320	65	2017	O
99	Palace Royale	Mumbai	India	320	88	OH	R
100	53 West 53	USA	New York	320	77	2019	R
101	New York Times Tower	USA	New York	319	52	2007	O
102	Chongqing IFS T1	China	Chongqing	316	63	2016	M (H/O)
103	Australia 108	Australia	Melbourne	316	100	2020	R
104	MahaNakhon	China	Bangkok	314	79	2016	M (H/R)
105	CITIC Financial Center Tower 1	China	Shenzhen	312	-	UC	M (R/O)
106	Bank of America Plaza	USA	Atlanta	312	55	1992	O
107	Shenzhen Bay Innovation and Technology Centre Tower 1	China	Shenzhen	311	69	2020	O
108	Menara TM	Malaysia	Kuala Lumpur	310	55	2001	O
109	Ocean Heights	UAE	Dubai	310	83	2010	R
110	Pearl River Tower	China	Guangzhou	309	71	2013	O
111	Fortune Center	China	Guangzhou	309	68	2015	O
112	Guangfa Securities Headquarters	China	Guangzhou	308	60	2018	O
113	The One	Canada	Toronto	308	85	UC	R
114	Burj Rafal	Saudi Arabia	Riyadh	307	68	2014	M (H/R)

115	Amna Tower	UAE	Dubai	307	75	2020	R
116	Noora Tower	UAE	Dubai	307	75	2019	R
117	The Shard	UK	London	306	73	2013	M (H/R/O)
118	Cayan Tower	UAE	Dubai	306	73	2013	R
119	Northeast Asia Trade Tower	South Korea	Incheon	305	68	2011	M (H/R/O)
120	35 Hudson Yards	USA	New York City	304	72	2019	M (H/R)
121	One Manhattan West	USA	New York	303	67	2019	O
122	Two Prudential Plaza	USA	Chicago	303	64	1990	O
123	Jiangxi Nanchang Greenland Central Plaza, Parcel A	China	Nanchang	303	59	2015	O
124	Jiangxi Nanchang Greenland Central Plaza, Parcel B	China	Nanchang	303	59	2015	O
125	Leatop Plaza	China	Guangzhou	303	64	2012	O
126	Kingdom Centre	Saudi Arabia	Riyadh	302	41	2002	M (H/R/O)
127	Capital City Moscow Tower	Russia	Moscow	301	76	2010	R
128	Supernova Spira	India	Noida	300	80	OH	M (H/R)
129	Al Wasl Tower	UAE	Dubai	300	64	UC	M (H/R/O)
130	Torre Costanera	Chile	Santiago	300	62	2014	M (H/O)
131	Abeno Harukas	Japan	Osaka	300	60	2014	M (H/O)
132	Shimao Riverside Block D2b	China	Wuhan	300	53	UC	M (H/O)
133	Aspire Tower	Qatar	Doha	300	36	2007	M (H/O)
134	NBK Tower	Kuwait	Kuwait City	300	61	2019	O
135	Golden Eagle Tiandi Tower C	China	Nanjing	300	60	2019	O

Note on abbreviations: 'M' indicates mixed-use; 'H' indicates hotel use; 'R' indicates residential use; 'O' indicates office use; 'UAE' indicates the United Arab Emirates; 'UC' indicates Under construction; 'NC' indicates Never completed; 'OH' indicates On hold.

Appendix B. Supertall buildings by core type, building form, structural system, and structural material.

#	Building Name	Building Form	Core Type	Structural System	Structural Material
1	Nakheel Tower	Free	Central	Mega column	Composite
2	Burj Khalifa	Setback	Central	Buttressed core	RC
3	Suzhou Zhongnan Center	Tapered	Central	Outriggered frame	Composite
4	Merdeka PNB118	Free	Central	Outriggered frame	Composite
5	Shanghai Tower	Twisted	Central	Outriggered frame	Composite
6	Chicago Spire	Twisted	Central	Outriggered frame	RC
7	Ping An Finance Center	Tapered	Central	Outriggered frame	Composite
8	Goldin Finance 117	Tapered	Central	Trussed-tube	Composite
9	Entisar Tower	Setback	Central	Framed-tube	RC
10	Lotte World Tower	Tapered	Central	Outriggered frame	Composite
11	One World Trade Center	Tapered	Central	Outriggered frame	Composite
12	Guangzhou CTF Finance Centre	Setback	Central	Outriggered Frame	Composite
13	Tianjin CTF Finance Centre	Tapered	Central	Framed-tube	Composite
14	CITIC Tower	Free	Central	Trussed-tube	Composite
15	Evergrande Hefei Center 1	Free	Central	Outriggered frame	Composite
16	Pentominium Tower	Free	Central	Outriggered frame	RC
17	Busan Lotte Town Tower	Free	Central	Outriggered frame	Composite
18	TAIPEI 101	Free	Central	Outriggered frame	Composite
19	Greenland Jinmao International Financial Center	Tapered	Central	Outriggered frame	Composite
20	Shanghai World Financial Center	Tapered	Central	Outriggered frame	Composite
21	International Commerce Centre	Tapered	Central	Outriggered frame	Composite
22	Wuhan Greenland Center	Tapered	Central	Buttressed core	Composite
23	Central Park Tower	Setback	Central	Outriggered frame	RC
24	Chengdu Greenland Tower	Tapered	Central	Outriggered frame	Composite
25	R&F Guangdong Building	Setback	Central	Outriggered frame	Composite
26	Lakhta Center	Twisted	Central	Outriggered frame	Composite
27	Vincom Landmark 81	Setback	Central	Bundled-tube	Composite
28	Changsha IFS Tower T1	Prismatic	Central	Outriggered frame	Composite
29	Petronas Twin Tower 1	Setback	Central	Outriggered frame	RC
30	Petronas Twin Tower 2	Setback	Central	Outriggered frame	RC
31	Zifeng Tower	Free	Central	Outriggered frame	Composite
32	The Exchange 106	Tapered	Central	Outriggered frame	Composite
33	Marina 106	Prismatic	Central	Framed-tube	RC
34	World One	Setback	Central	Buttressed core	RC
35	KK 100	Free	Central	Framed-tube	Composite
36	Guangzhou International Finance Center	Tapered	Central	Outriggered frame	Composite
37	Multifunctional Highrise Complex - Akhmat Tower	Tapered	Central	Framed-tube	Steel

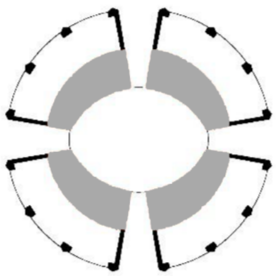
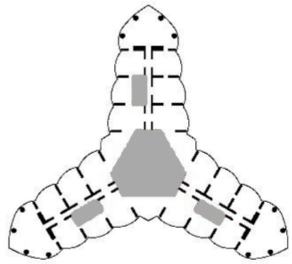
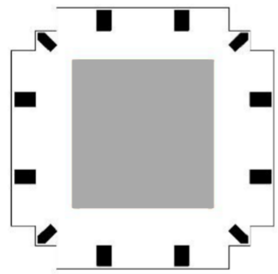
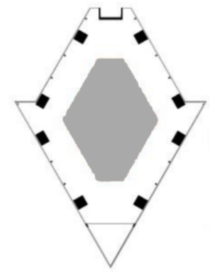
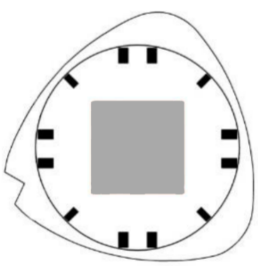
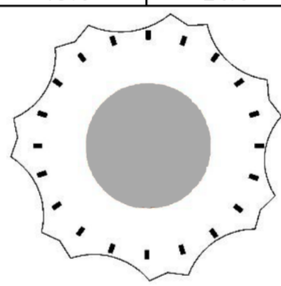
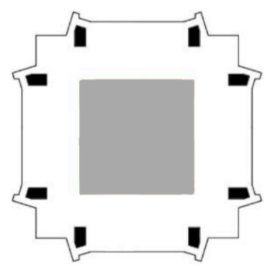
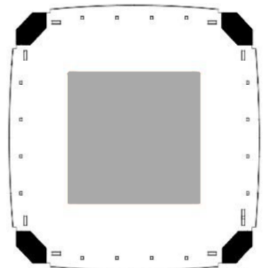
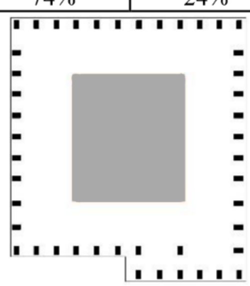
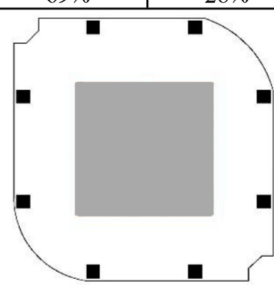
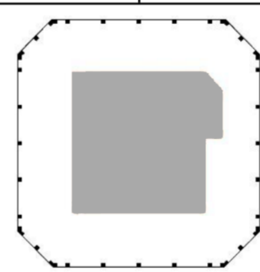
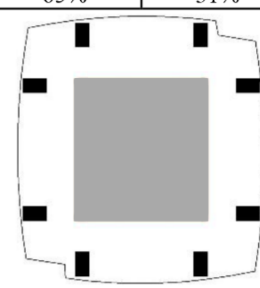
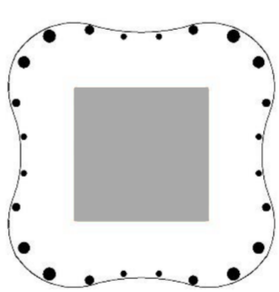
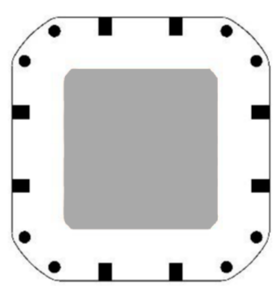
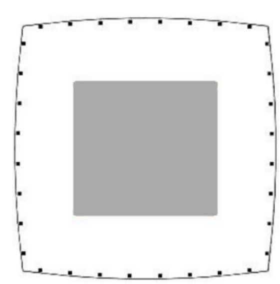
38	111 West 57th Street	Setback	Peripheral	Outriggered frame	RC
39	Chongqing Tall Tower	Tapered	Central	Outriggered frame	Composite
40	Haikou Tower 1	Tapered	Central	Outriggered frame	Composite
41	One Vanderbilt Avenue	Tapered	Central	Outriggered frame	Composite
42	Marina 101	Prismatic	Central	Framed-tube	RC
43	432 Park Avenue	Prismatic	Central	Framed-tube	RC
44	Trump International Hotel & Tower	Setback	Central	Outriggered frame	RC
45	Al Hamra Tower	Free	Central	Shear walled frame	Composite
46	Princess Tower	Prismatic	Central	Framed-tube	RC
47	Two International Finance Center	Setback	Central	Outriggered frame	Composite
48	LCT The Sharp Landmark Tower	Prismatic	Central	Outriggered frame	RC
49	Guangxi China Resources Tower	Tapered	Central	Outriggered frame	Composite
50	China Resources Tower	Tapered	Central	Framed-tube	Composite
51	23 Marina	Prismatic	Central	Outriggered frame	RC
52	CITIC Plaza	Prismatic	Central	Shear walled frame	RC
53	Dynamic Tower	Free	Central	Mega core	RC
54	Shum Yip Upperhills Tower 1	Prismatic	Central	Outriggered frame	Composite
55	30 Hudson Yards	Tapered	Central	Outriggered frame	Steel
56	PIF Tower	Free	Central	Trussed-tube	Composite
57	Shun Hing Square	Free	Central	Outriggered frame	Composite
58	Autograph Tower	Prismatic	Central	Outriggered frame	Composite
59	Burj Mohammed Bin Rashid	Free	Central	Outriggered frame	RC
60	Guiyang World Trade Center Landmark Tower	Tapered	Central	Framed-tube	Composite
61	Elite Residence	Prismatic	Central	Framed-tube	RC
62	Central Plaza	Prismatic	Central	Trussed-tube	Composite
63	Federation Tower	Free	Central	Outriggered frame	Composite
64	Golden Eagle Tiandi Tower A	Tapered	Central	Outriggered frame	Composite
65	Bank of China Tower	Setback	Central (split)	Trussed-tube	Composite
66	St. Regis Chicago	Free	Central	Outriggered frame	RC
67	Almas Tower	Free	Central	Outriggered frame	Composite
68	Hanking Center Tower	Tapered	External	Trussed-tube	Steel
69	Greenland Group Suzhou Center	Free	Central	Outriggered frame	Composite
70	Sino Steel International Plaza T2	Prismatic	Central	Framed-tube	Composite
71	II Primo Tower 1	Prismatic	Central	Outriggered frame	RC
72	Emirates Tower One	Prismatic	Central	Mega column	Composite
73	OKO - Residential Tower	Free	Central	Outriggered frame	RC
74	The Torch	Prismatic	Central	Outriggered frame	RC
75	Spring City 66	Free	Central	Outriggered frame	Composite
76	The Center	Prismatic	Central	Mega column	Composite
77	NEVA TOWERS 2	Prismatic	Central	Outriggered frame	RC

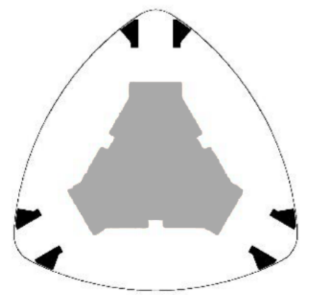
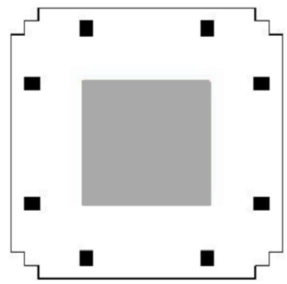
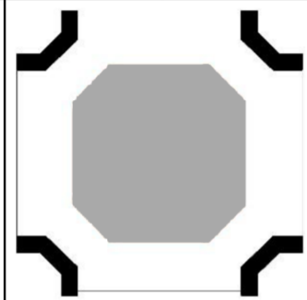
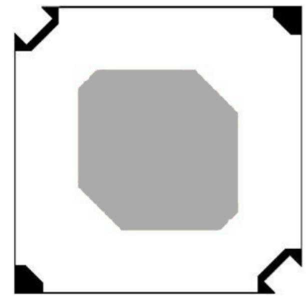
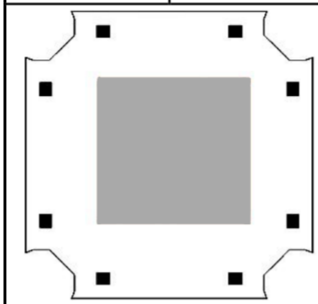
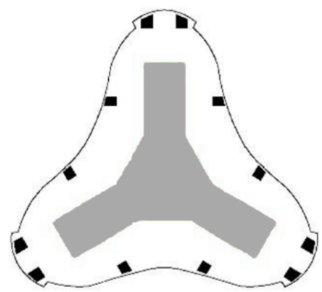
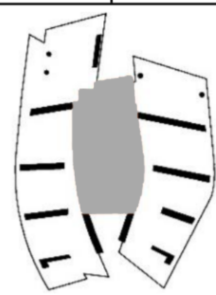
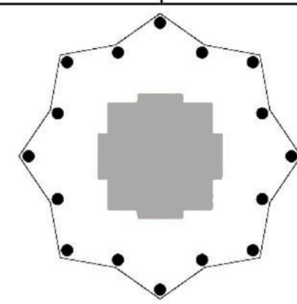
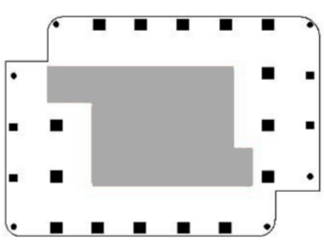
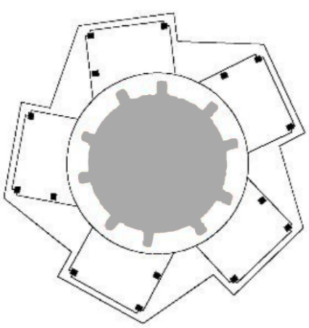
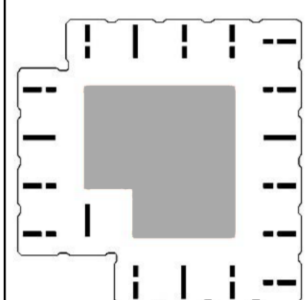
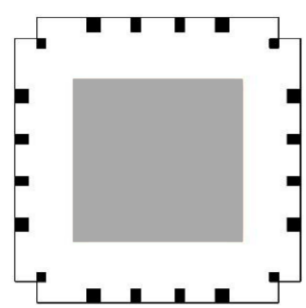
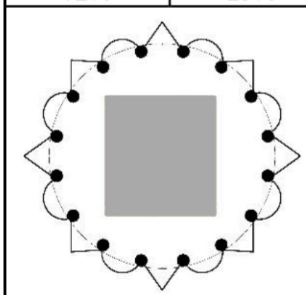
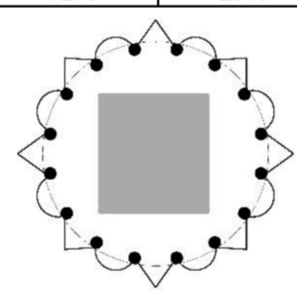
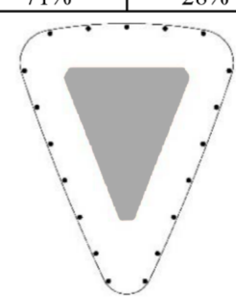
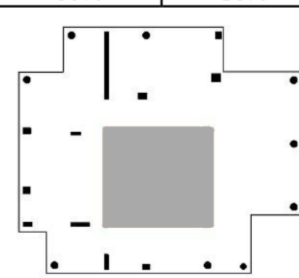
78	ADNOC Headquarters	Prismatic	External	Shear walled frame	RC
79	One Shenzhen Bay Tower 7	Tapered	Central	Outriggered frame	Composite
80	Comcast Technology Center	Setback	Central	Trussed-tube	Composite
81	LCT The Sharp Residential Tower A	Prismatic	Central	Outriggered frame	RC
82	Mercury City Tower	Setback	Central	Framed-tube	RC
83	Hengqin International Finance Center	Free	Central	Outriggered frame	Composite
84	Tianjin World Financial Center	Tapered	Central	Outriggered frame	Composite
85	Wilshire Grand Center	Tapered	Central	Outriggered frame	Composite
86	DAMAC Heights	Tapered	Central	Outriggered frame	RC
87	Shimao International Plaza	Free	Central	Mega column	Composite
88	LCT The Sharp Residential Tower B	Prismatic	Central	Outriggered frame	RC
89	China World Tower	Tapered	Central	Outriggered frame	Composite
90	Hon Kwok City Center	Prismatic	Central	Outriggered frame	Composite
91	3 World Trade Center	Setback	Central	Trussed-tube	Composite
92	Keangnam Hanoi Landmark Tower	Setback	Central	Outriggered frame	RC
93	Golden Eagle Tiandi Tower B	Tapered	Central	Outriggered frame	Composite
94	Salesforce Tower	Tapered	Central	Shear walled frame	Composite
95	Deji Plaza	Prismatic	Central	Outriggered frame	Composite
96	Q1 Tower	Prismatic	Central	Outriggered frame	RC
97	Nina Tower	Prismatic	Central	Outriggered frame	RC
98	Sinar Mas Center 1	Free	Central	Outriggered frame	Composite
99	Palace Royale	Prismatic	Central	Outriggered frame	RC
100	53 West 53	Tapered	Peripheral	Framed-tube	RC
101	New York Times Tower	Prismatic	Central	Outriggered frame	Steel
102	Chongqing IFS T1	Prismatic	Central	Outriggered frame	Composite
103	Australia 108	Free	Central	Outriggered frame	RC
104	MahaNakhon	Free	Central	Outriggered frame	RC
105	CITIC Financial Center Tower 1	Tapered	Central	Framed-tube	Composite
106	Bank of America Plaza	Setback	Central	Mega column	Composite
107	Shenzhen Bay Innovation and Technology Centre Tower 1	Prismatic	Central	Framed-tube	Composite
108	Menara TM	Free	Central	Outriggered frame	RC
109	Ocean Heights	Tapered	Central	Outriggered frame	RC
110	Pearl River Tower	Free	Central	Outriggered frame	Composite
111	Fortune Center	Free	Central	Outriggered frame	Composite
112	Guangfa Securities Headquarters	Tapered	Central	Outriggered frame	Composite
113	The One	Prismatic	Central	Outriggered frame	Composite
114	Burj Rafal	Prismatic	Central	Outriggered frame	Composite
115	Amna Tower	Prismatic	Central	Outriggered frame	RC
116	Noora Tower	Prismatic	Central	Outriggered frame	RC

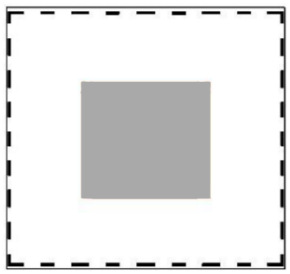
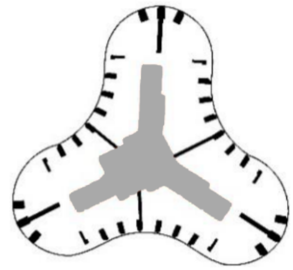
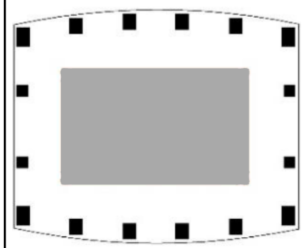
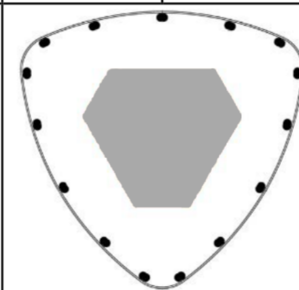
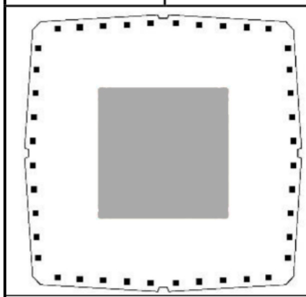
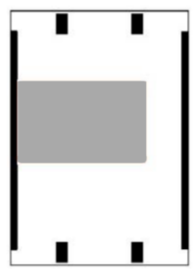
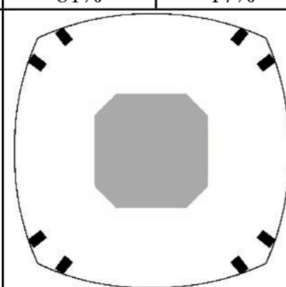
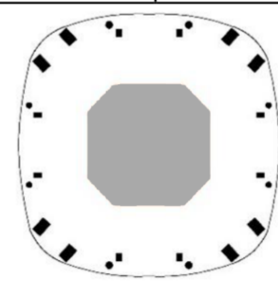
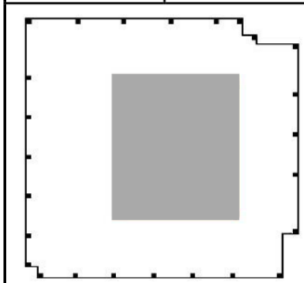
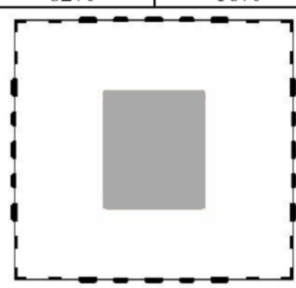
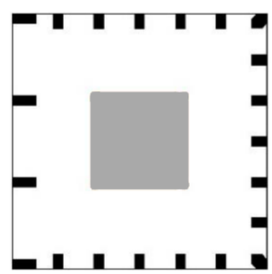
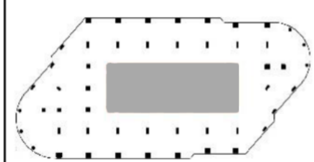
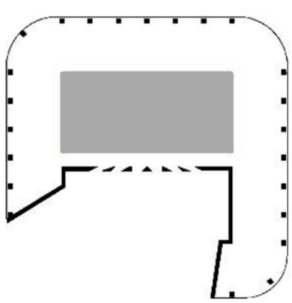
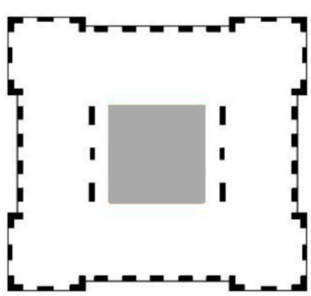
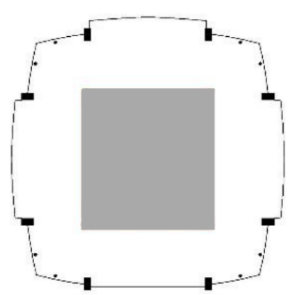
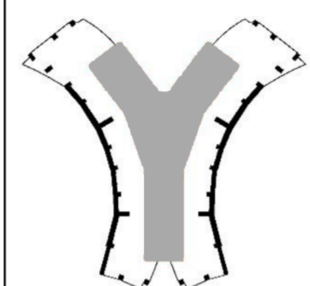
117	The Shard	Tapered	Central	Shear walled frame	Composite
118	Cayan Tower	Twisted	Central	Framed-tube	RC
119	Northeast Asia Trade Tower	Tapered	Central	Outriggered frame	Composite
120	35 Hudson Yards	Setback	Central	Outriggered frame	RC
121	One Manhattan West	Tapered	Central	Shear walled frame	Composite
122	Two Prudential Plaza	Setback	Central	Outriggered frame	RC
123	Jiangxi Nanchang Greenland Central Plaza, Parcel A	Free	Central	Outriggered frame	Composite
124	Jiangxi Nanchang Greenland Central Plaza, Parcel B	Free	Central	Outriggered frame	Composite
125	Leatop Plaza	Prismatic	Central	Trussed-tube	Composite
126	Kingdom Centre	Free	Central	Shear walled frame	RC
127	Capital City Moscow Tower	Free	Central	Outriggered frame	RC
128	Supernova Spira	Prismatic	Central	Outriggered frame	RC
129	Al Wasl Tower	Free	Central	Outriggered frame	Composite
130	Torre Costanera	Tapered	Central	Outriggered frame	RC
131	Abeno Harukas	Setback	Central	Outriggered frame	Composite
132	Shimao Riverside Block D2b	Tapered	Central	Outriggered frame	Composite
133	Aspire Tower	Free	Central	Mega core	RC
134	NBK Tower	Free	Central	Outriggered frame	Composite
135	Golden Eagle Tiandi Tower C	Tapered	Central	Outriggered frame	Composite

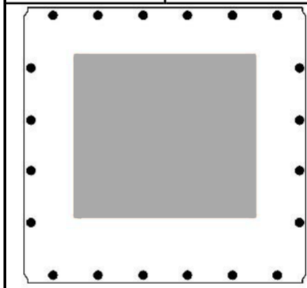
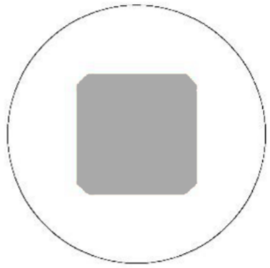
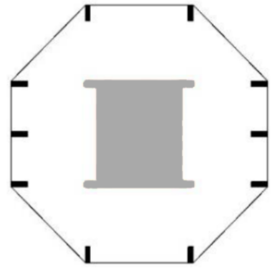
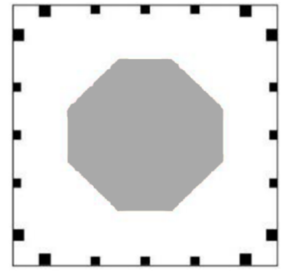
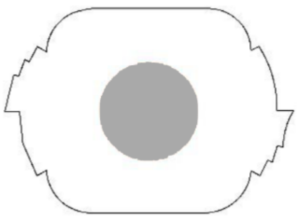
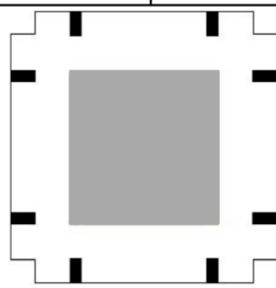
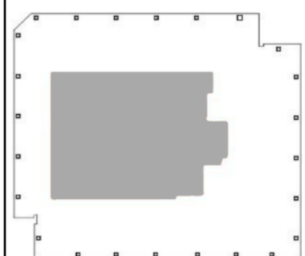
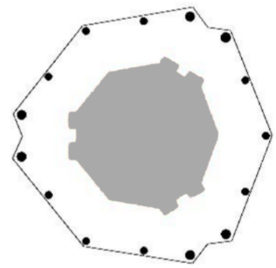
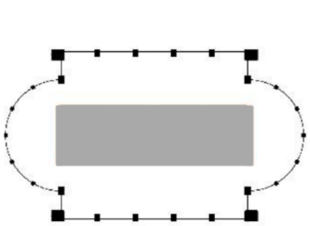
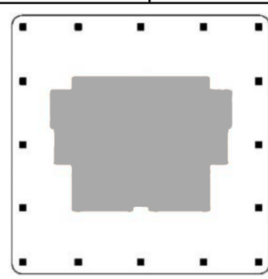
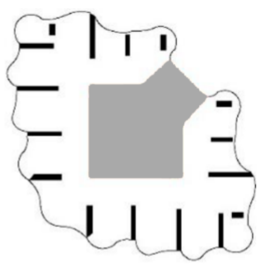
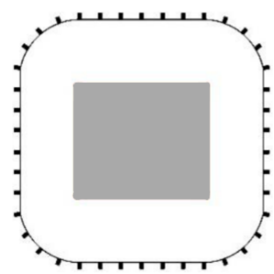
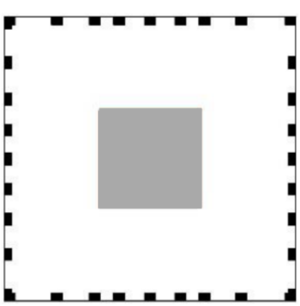
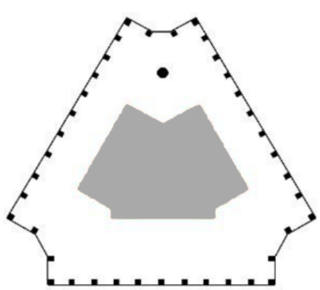
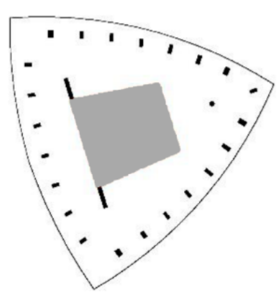
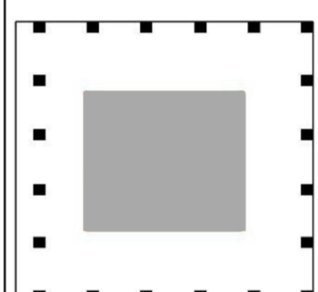
Note on abbreviation: 'RC' indicates reinforced concrete.

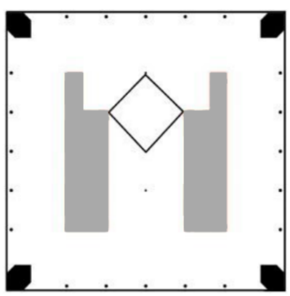
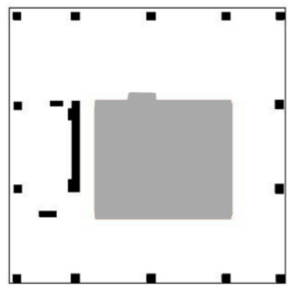
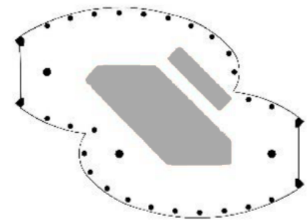
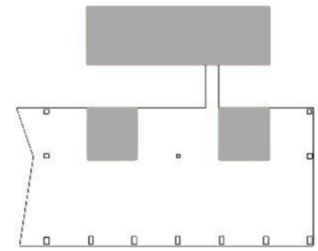
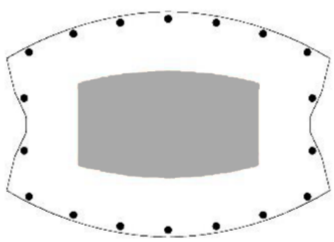
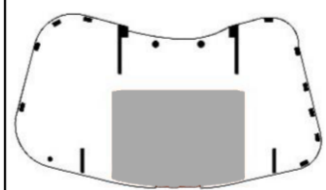
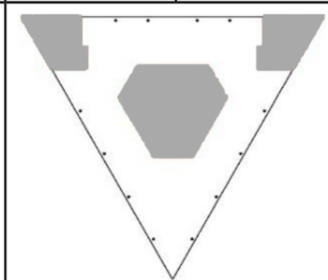
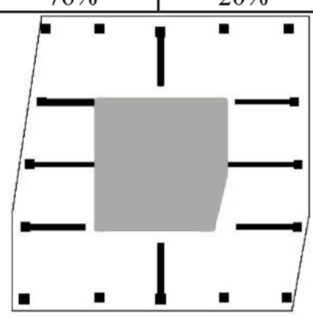
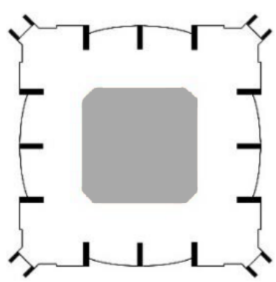
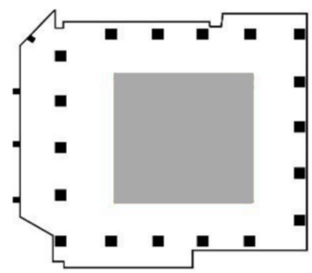
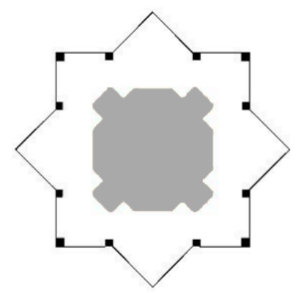
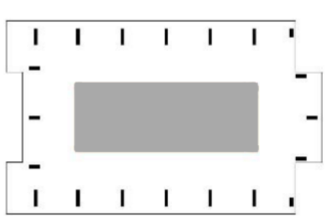
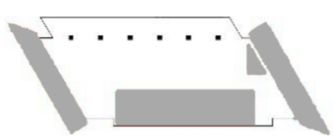
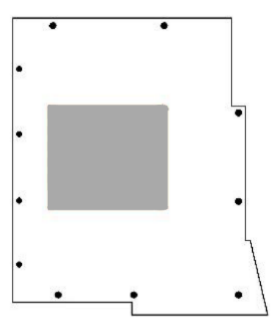
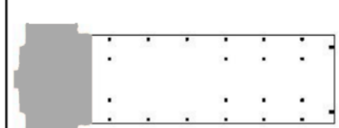
Appendix C: Supertall buildings' floor plan with space efficiency and core/GFA ratio (figure by author).

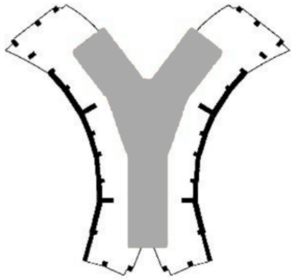
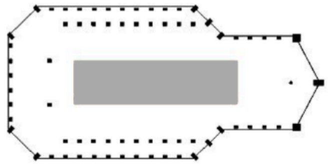
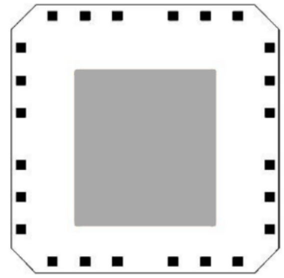
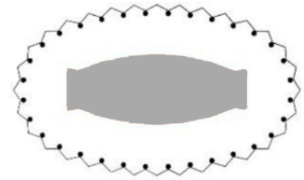
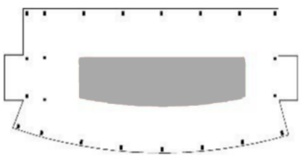
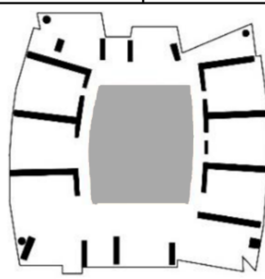
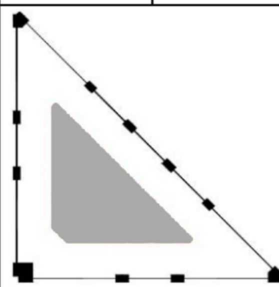
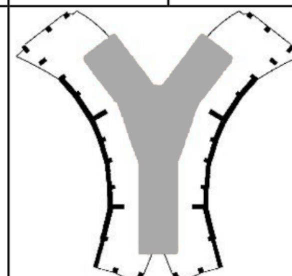
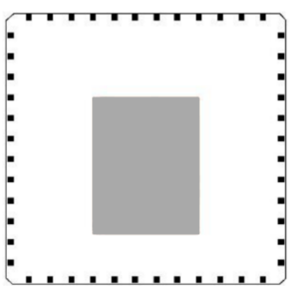
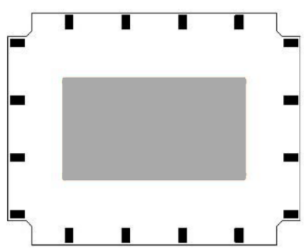
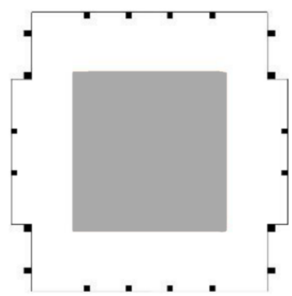
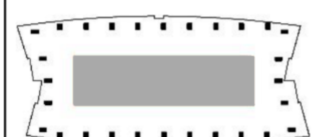
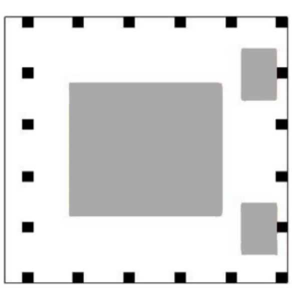
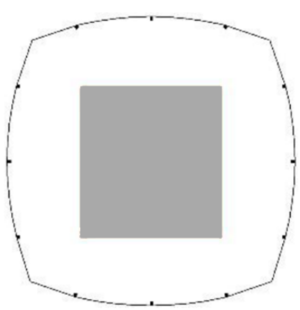
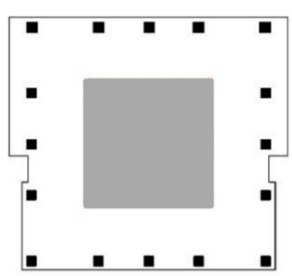
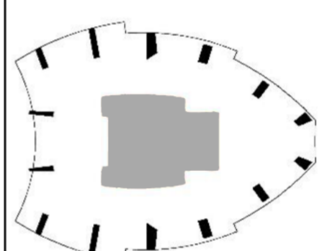
Building name							
Space efficiency*				Core/GFA**			
Nakheel Tower		**Burj Khalifa**		**Suzhou Zhongnan Center**		**Merdeka PNB118**	
69%	26%	80%	16%	62%	33%	65%	31%
							
Low-rise floor		Typical floor		Low-rise floor		Low-rise floor	
Shanghai Tower		**Chicago Spire**		**Ping An Finance Center**		**Goldin Finance 117**	
71%	24%	75%	24%	70%	26%	68%	28%
							
Low-rise floor		Typical floor		Low-rise floor		Ground floor	
Entisar Tower		**Lotte World Tower**		**One World Trade Center**		**Guangzhou CTF Finance Centre**	
74%	24%	69%	28%	70%	30%	65%	31%
							
Low-rise floor		Low-rise floor		Low-rise floor		Low-rise floor	
Tianjin CTF Finance Centre		**CITIC Tower**		**Evergrande Hefei Center 1**		**The Exchange 106**	
70%	27%	70%	25%	59%	37%	70%	29%
							
Low-rise floor		Ground floor		Typical floor		Typical floor	

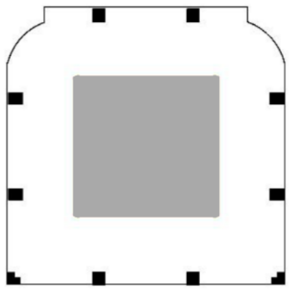
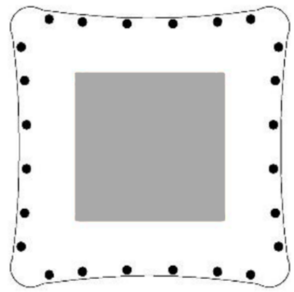
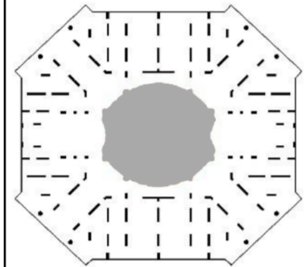
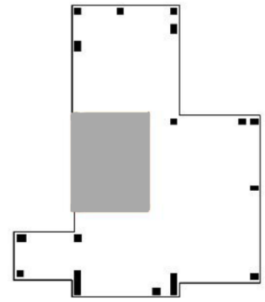
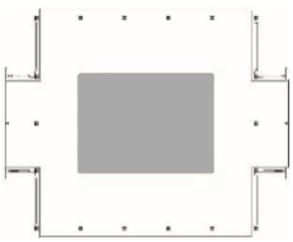
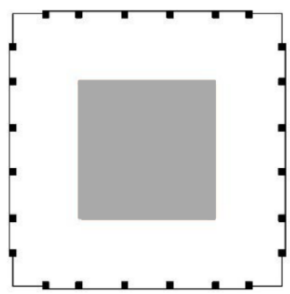
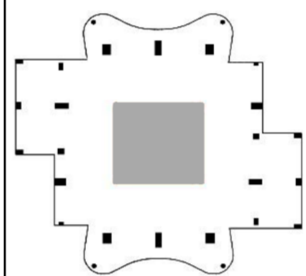
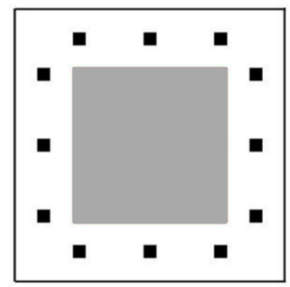
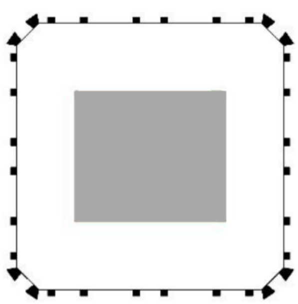
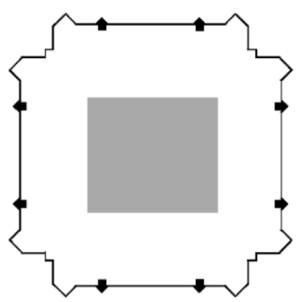
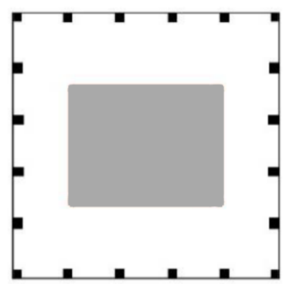
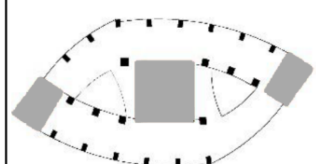
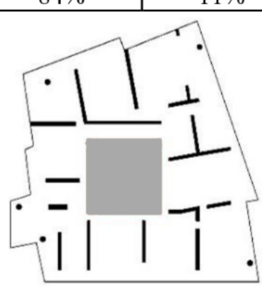
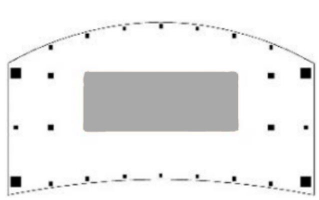
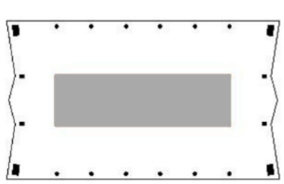
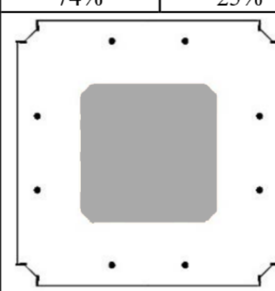
Busan Lotte Town Tower		TAIPEI 101		Greenland Jinmao International Financial Center		Shanghai World Financial Center	
70%	27%	72%	25%	55%	37%	69%	28%
							
Low-rise floor		Typical floor		Ground floor		Low-rise floor	
International Commerce Centre		**Wuhan Greenland Center**		**Pentominium Tower**		**Chengdu Greenland Tower**	
69%	29%	67%	30%	73%	21%	72%	24%
							
Low-rise floor		Low-rise floor		Typical floor		Ground floor	
R&F Guangdong Building		**Lakhta Center**		**Vincom Landmark 81**		**Changsha IFS Tower T1**	
68%	29%	67%	32%	69%	28%	63%	34%
							
Low-rise floor		Typical floor		Low-rise floor		Low-rise floor	
Petronas Twin Tower 1		**Petronas Twin Tower 1**		**Zifeng Tower**		**Central Park Tower**	
72%	25%	72%	25%	71%	28%	80%	18%
							
Typical floor		Typical floor		Ground floor		Typical floor	

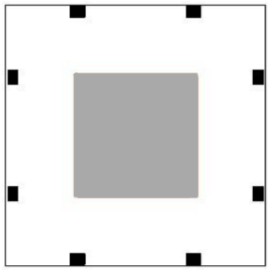
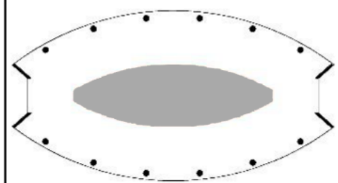
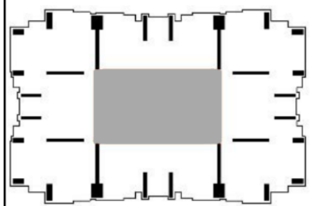
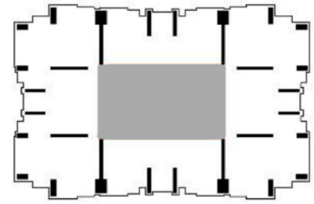
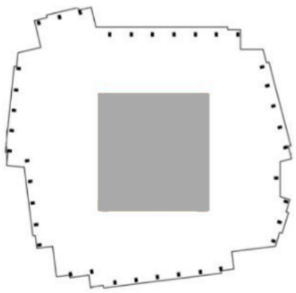
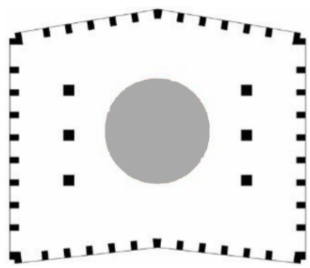
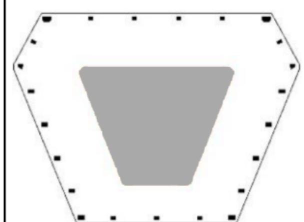
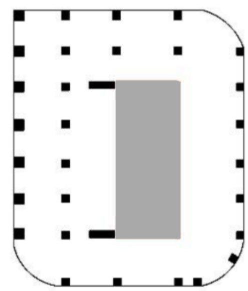
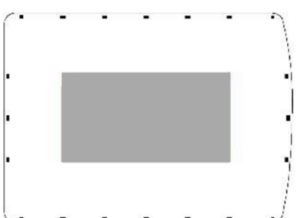
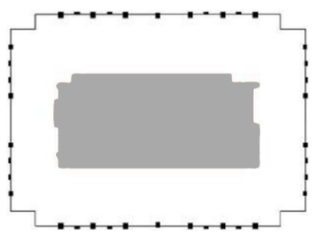
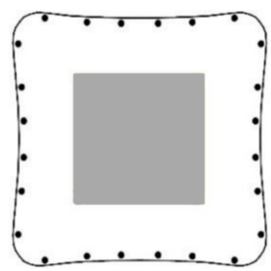
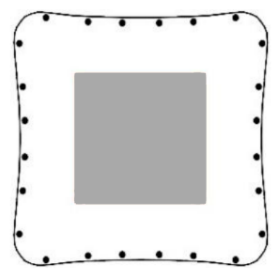
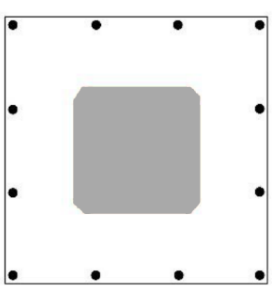
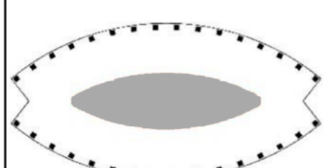
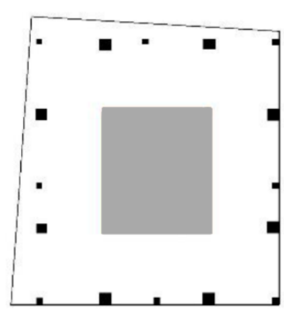
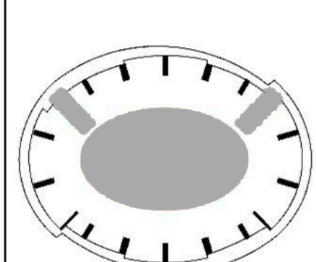
Marina 106		**World One**		**KK 100**		**Guangzhou International Finance Center**	
78%	20%	78%	16%	61%	34%	71%	27%
							
Typical floor		Typical floor		Low-rise floor		Typical floor	
Multifunctional Highrise Complex - Akhmat Tower		**111 West 57th Street**		**Chongqing Tall Tower**		**Haikou Tower 1**	
75%	23%	69%	24%	81%	17%	75%	22%
							
Low-rise floor		Typical floor		Low-rise floor		Low-rise floor	
One Vanderbilt		**Marina 101**		**432 Park Avenue**		**Trump International Hotel & Tower**	
72%	27%	82%	16%	80%	14%	62%	18%
							
Ground floor		Typical floor		Typical floor		Low-rise floor	
Al Hamra Tower		**Princess Tower**		**Two International Finance Center**		**LCT The Sharp Landmark Tower**	
70%	26%	82%	12%	71%	28%	56%	36%
							
Low-rise floor		Typical floor		Typical floor		Typical floor	

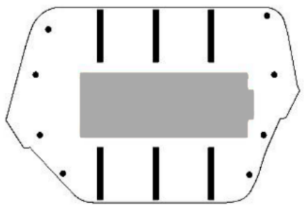
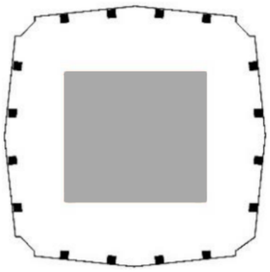
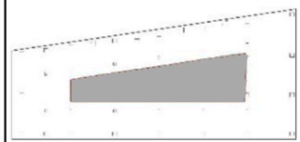
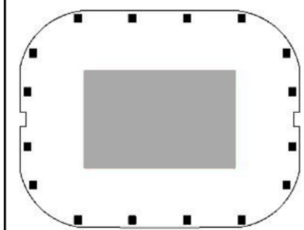
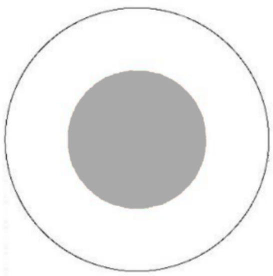
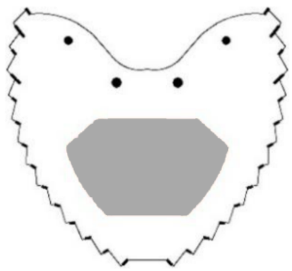
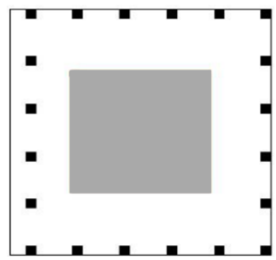
Guangxi China Resources Tower	**China Resources Tower**	**23 Marina**	**CITIC Plaza**
61% | 38%	73% | 26%	81% | 17%	67% | 22%
			
Typical floor	Typical floor	Typical floor	Typical floor
Dynamic Tower	**Shum Yip Upperhills Tower 1**	**30 Hudson Yards**	**PIF Tower**
84% | 16%	64% | 33%	69% | 30%	65% | 33%
			
Low-rise floor	Typical floor	Low-rise floor	Typical floor
Shun Hing Square	**Autograph Tower**	**Burj Mohammed Bin Rashid**	**Guiyang World Trade Center Landmark Tower**
67% | 26%	68% | 31%	73% | 21%	71% | 27%
			
Typical floor	Typical floor	Typical floor	Low-rise floor
Elite Residence	**Central Plaza**	**Federation Tower**	**Golden Eagle Tiandi Tower A**
84% | 12%	66% | 25%	82% | 16%	70% | 27%
			
Typical floor	Typical floor	Typical floor	Typical floor

Bank of China Tower		St. Regis Chicago		Almas Tower		Hanking Center Tower	
82%	15%	76%	21%	77%	21%	70%	29%
							
Low-rise floor		Typical floor		Typical floor		Typical floor	
Greenland Group Suzhou Center		**Sino Steel International Plaza T2**		**Il Primo Tower 1**		**Emirates Tower One**	
70%	29%	68%	27%	71%	28%	70%	30%
							
Low-rise floor		Typical floor		Typical floor		Typical floor	
OKO – Residential Tower		**The Torch**		**Spring City 66**		**The Center**	
76%	20%	74%	22%	70%	27%	68%	29%
							
Low-rise floor		Typical floor		Low-rise floor		Typical floor	
NEVA TOWERS 2		**ADNOC Headquarters**		**One Shenzhen Bay Tower 7**		**Comcast Technology Center**	
77%	22%	63%	36%	81%	18%	74%	25%
							
Typical floor		Low-rise floor		Low-rise floor		Typical floor	

LCT The Sharp Residential Tower A	56%	16%		Typical floor
Mercury City Tower	80%	18%		Low-rise floor
Hengqin International Finance Center	67%	31%		Ground floor
Tianjin World Financial Center	72%	26%		Typical floor
Wilshire Grand Center	80%	19%		Typical floor
DAMAC Heights	72%	19%		Typical floor
Shimao International Plaza	67%	29%		Low-rise floor
LCT The Sharp Residential Tower B	56%	16%		Typical floor
China World Tower	79%	19%		Low-rise floor
Hon Kwok City Center	70%	28%		Typical floor
3 World Trade Center	67%	31%		Low-rise floor
Keangnam Hanoi Landmark Tower	72%	26%		Low-rise floor
Golden Eagle Tiandi Tower B	65%	32%		Typical floor
Salesforce Tower	72%	27%		Low-rise floor
Deji Plaza	73%	24%		Typical floor
Q1 Tower	78%	17%		Typical floor

Nina Tower		Sinar Mas Center 1		Palace Royale		53 West 53	
71%	27%	72%	26%	82%	14%	82%	16%
							
Typical floor		Low-rise floor		Typical floor		Typical floor	
New York Times Tower		**Chongqing IFS T1**		**Australia 108**		**MahaNakhon**	
75%	25%	74%	25%	84%	14%	65%	32%
							
Low-rise floor		Typical floor		Typical floor		Low-rise floor	
CITIC Financial Center Tower 1		**Bank of America Plaza**		**Shenzhen Bay Innovation and Technology Centre Tower 1**		**Menara TM**	
70%	27%	78%	21%	71%	26%	75%	22%
							
Typical floor		Typical floor		Typical floor		Ground floor	
Ocean Heights		**Pearl River Tower**		**Fortune Center**		**Guangfa Securities Headquarters**	
84%	11%	79%	19%	77%	22%	74%	25%
							
Typical floor		Typical floor		Typical floor		Low-rise floor	

The One		Burj Rafal		Amna Tower		Noora Tower	
76%	22%	78%	21%	77%	17%	77%	17%
							
Typical floor		Typical floor		Typical floor		Typical floor	
The Shard		**Cayan Tower**		**Northeast Asia Trade Tower**		**35 Hudson Yards**	
79%	20%	83%	12%	72%	26%	80%	16%
							
Low-rise floor				Low-rise floor		Typical floor	
One Manhattan West		**Two Prudential Plaza**		**Jiangxi Nanchang Greenland Central Plaza, Parcel A**		**Jiangxi Nanchang Greenland Central Plaza, Parcel B**	
70%	29%	69%	29%	70%	28%	70%	28%
							
Low-rise floor		Low-rise floor		Ground floor		Ground floor	
Leatop Plaza		**Kingdom Centre**		**Capital City Moscow Tower**		**Supernova Spira**	
76%	22%	78%	20%	79%	19%	63%	33%
							
Typical floor		Typical floor		Typical floor		Low-rise floor	

Al Wasl Tower		**Torre Costanera**		**Abeno Harukas**		**Shimao Riverside Block D2b**	
74%	22%	69%	30%	79%	19%	73%	26%
							
Low-rise floor		Typical floo		Low-rise floor		Ground floor	
Aspire Tower		**NBK Tower**		**Golden Eagle Tiandi Tower C**			
72%	28%	74%	24%	75%	23%		
							
Low-rise floor		Typical floor		Typical 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.