buildings

MDPI

Review

Comparative Analysis of Space Efficiency in Skyscrapers with Prismatic, Tapered, and Free Forms

Hüseyin Emre Ilgın [1,*] and Özlem Nur Aslantamer [2]

[1] School of Architecture, Faculty of Built Environment, Tampere University, P.O. Box 600, FI-33014 Tampere, Finland
[2] Department of Interior Architecture and Environmental Design, Faculty of Art, Design and Architecture, Atılım University, Ankara 06830, Turkey; ozlem.aslantamer@atilim.edu.tr
* Correspondence: emre.ilgin@tuni.fi

Abstract: This study offers a thorough comparative analysis of space efficiency in skyscrapers across three distinct forms: prismatic, tapered, and free. By examining case studies from each form category, this research investigates how architectural and structural design features impact space utilization in supertall towers. The findings reveal form-based differences in space efficiency and design element usage. In prismatic skyscrapers, which are primarily residential and utilize concrete outrigger frames, the average space efficiency was around 72%, with the core occupying 24% of the gross floor area (GFA). Tapered skyscrapers, commonly mixed-use with composite outrigger frames, showed an average space efficiency of over 70%, with a core-to-GFA ratio of 26%. Freeform towers, often mixed-use and using composite outrigger frames, demonstrated a space efficiency of 71%, with an average core-to-GFA ratio of 26%. Despite these variations, a consistent trend emerged: as the height of a building increases, there is a general decline in space efficiency, highlighting the challenges in optimizing space in taller structures. This analysis adds to the understanding of skyscraper design and space utilization, providing important insights for architects and urban planners aiming to improve the efficiency of future high-rise developments.

Keywords: comparison; free; prismatic; skyscraper; space efficiency; tapered

Citation: Ilgın, H.E.; Aslantamer, Ö.N. Comparative Analysis of Space Efficiency in Skyscrapers with Prismatic, Tapered, and Free Forms. *Buildings* **2024**, *14*, 3345. https://doi.org/10.3390/buildings14113345

Academic Editors: João Paulo Correia Rodrigues and Marcelo Greco

Received: 17 September 2024
Revised: 18 October 2024
Accepted: 21 October 2024
Published: 22 October 2024

1. Introduction

In the face of rapid urbanization and escalating demands for residential and commercial space, skyscrapers have become central to the development of modern cities [1]. These towering structures, often seen as symbols of economic prosperity and architectural innovation, provide a vertical solution to the spatial limitations faced by densely populated urban environments [2–4]. As the global urban population continues to grow, with projections indicating an increase of over 2.5 billion people by 2050 [5], the importance of efficient land use through vertical construction has never been more critical [6]. In this context, skyscrapers, embodying the concept of vertical cities, have evolved from mere buildings to intricate systems that integrate structural efficiency, spatial utility, and aesthetic value.

The design and form of skyscrapers have undergone significant transformations over the past decades, moving beyond the traditional prismatic shapes to embrace more complex geometries such as tapered and free forms [7–9]. Each of these architectural forms presents distinct characteristics and challenges, particularly concerning space efficiency, a crucial parameter for both economic and environmental sustainability. Space efficiency in skyscrapers is generally described as the ratio of usable floor area to the building's gross floor area (GFA). This metric is vital for evaluating the economic viability, functional performance, and overall sustainability of high-rise buildings.

Prismatic skyscrapers are typically characterized by their straight, vertical lines and symmetrical forms, which make them relatively straightforward to design and construct [10]. The geometric simplicity of prismatic forms allows for efficient use of space, as the floor plans are uniform throughout the height of the building. This uniformity often leads to higher space efficiency, as it minimizes the need for complex structural systems and maximizes the usable floor area. However, in an era where urban skylines are increasingly seen as expressions of cultural identity and technological prowess, the conventional aesthetics of prismatic skyscrapers may be perceived as lacking in architectural dynamism.

In contrast, tapered skyscrapers, which gradually reduce in floor size as they ascend, offer several advantages over their prismatic counterparts [11]. The tapering effect can significantly enhance the building's aerodynamic performance, reducing wind loads and sway, which is especially beneficial for supertall structures. This form also allows for creative architectural expressions and can enhance the visual appeal of the skyline. However, the tapering shape often results in reduced space efficiency, as the decreasing floor area towards the top of the building can lead to underutilized space and increased construction costs.

Freeform skyscrapers represent the latest trend in high-rise design, characterized by their non-linear, often organic shapes that break away from conventional geometric patterns [12]. These forms provide architects with a canvas to experiment with innovative and expressive designs, resulting in iconic structures that stand out in urban landscapes. However, the irregular geometries of freeform skyscrapers present significant challenges in terms of structural engineering and space efficiency. The complex shapes typically require specialized structural systems to support the unconventional loads, and the irregular floor plans can lead to inefficient use of interior space, further complicating the optimization of usable floor area.

Comparison of space efficiency in skyscrapers with prismatic, tapered, and free forms plays a pivotal role in advancing our understanding of high-rise architecture and urban sustainability. As global urbanization accelerates, cities are increasingly reliant on vertical expansion to address the challenges of limited land availability, population growth, and environmental sustainability. This study fills a crucial gap by providing a systematic, data-driven comparison of space efficiency across three distinct skyscraper forms—prismatic, tapered, and freeform—each of which presents unique architectural, functional, and structural characteristics. By analyzing the space efficiency and core-to-GFA ratios of these forms, this study offers critical insights for architects, engineers, and urban planners, helping them make informed decisions about building design based on factors like functional use, aesthetic goals, structural demands, and sustainability considerations. This research not only highlights the spatial trade-offs inherent in each form but also underscores the importance of maximizing usable space to enhance the economic viability of skyscrapers, reduce material consumption, and improve user comfort. Ultimately, this study aids in the advancement of more efficient, cost-effective, and environmentally sustainable skyscrapers, which are essential to the future of sustainable urban growth. Overall, this article aims to conduct this comparative analysis, synthesizing data and findings from three recent architectural studies [13–15] that focus on these diverse forms.

It is worth noting that the interplay between space efficiency and adaptability in tall buildings is a fundamental consideration in contemporary architectural design, particularly in the context of growing urban density and resource constraints. Space efficiency aims to optimize the utilization of available floor area, ensuring that every square meter contributes to functionality, occupant comfort, and economic viability. However, as urban environments evolve, adaptability becomes equally crucial. This refers to the building's capacity to accommodate changes in use, technology, and user needs over time without requiring significant structural alterations. Tall buildings, due to their scale and long lifespan, must be designed with future flexibility in mind, allowing for the reconfiguration of spaces for different functions, tenants, or technological advancements. Achieving this balance often involves the integration of modular design elements, flexible partitions, and advanced building systems that can be easily adjusted. The synergy between space efficiency and adaptability not only enhances the utility and economic performance of high-rise structures but also supports their long-term sustainability, making them resilient to the dynamic nature of urban development and future innovation.

The significance of this research lies in its comprehensive comparative analysis of space efficiency in skyscrapers with prismatic, tapered, and free forms, which addresses a crucial aspect of sustainable high-rise design in rapidly urbanizing environments. The objective of this study is to evaluate how each skyscraper form influences space utilization, and architectural and structural designs, providing valuable insights for architects, engineers, and contractors in optimizing skyscraper design. By examining the trade-offs between space efficiency, architectural expression, and structural performance, this research offers concrete recommendations for selecting appropriate building forms based on specific project goals and urban contexts, ultimately contributing to more efficient, functional, and iconic skyscrapers.

This study focuses exclusively on space efficiency, intentionally omitting other important aspects such as climate change, energy efficiency, and environmental sustainability. The rationale for this exclusion is the lack of comprehensive data across the case studies, making it difficult to conduct a thorough analysis of these sustainability-related parameters. By narrowing its focus, the research aims to provide a more in-depth and precise evaluation of space efficiency without the interference of incomplete or inconsistent information on sustainable design factors. This approach allows for a detailed examination of how architectural and structural elements impact the effective use of space in tall buildings, ensuring that the findings are both robust and relevant. While the absence of sustainability considerations may limit the scope, this focused analysis delivers clear insights into space utilization, laying the groundwork for future research that could integrate a more holistic perspective when the necessary data becomes available.

The sections were structured as follows: First, a comprehensive literature review was conducted. Next, the research methodology was outlined, followed by the presentation of the results. Afterward, the discussion section provided an analysis and interpretation of the findings. Finally, this study concluded by addressing practical implications.

2. Literature Survey

To enhance the understanding of efficient space use, several prominent studies have explored different factors and configurations, offering valuable methodologies and insights. Refs. [16–19] focused on supertall towers serving various purposes such as residential, office, hotel, and mixed-use. Throughout these studies, a frequent application of outrigger systems and central service cores was identified, suggesting a link between height and spatial efficiency.

Exploring less conventional architectural forms, ref. [20] discovered patterns of spatial efficiency in atypical office towers, revealing that design choices greatly impact spatial performance, with conical structures demonstrating notable efficiency. This emphasizes the importance of creative architectural approaches in maximizing space usage. In another study, ref. [21] examined space utilization in residential buildings in Kabul, observing significant discrepancies from regulatory standards due to insufficient consideration of architectural design and building codes. These observations highlight the crucial importance of adhering to regulatory frameworks to maintain spatial efficiency.

Ref. [22] examined how emerging technologies affect space efficiency in densely populated urban settings, suggesting that these innovations have the potential to increase spatial efficiency by two to threefold compared to conventional techniques. This underscores the significant impact that technological advancements can have on the design of urban housing. Meanwhile, ref. [23] investigated the strategic positioning of buildings in corner locations within Sudanese residential zones and found that such placements enhance land use efficiency. This finding highlights the importance of thoughtful placement strategies in architectural planning to optimize land utilization.

Ref. [24] focused on the use of space in hotel properties, highlighting the benefits that come with effective space management within the hospitality industry. In a separate investigation, ref. [25] analyzed the elements affecting load-bearing structures in prismatic high-rise buildings, offering valuable information on the structural components that impact spatial efficiency. Ref. [26] proposed a collaborative method that includes stakeholders early in the design process to improve space utilization, supporting a participatory approach to architectural design.

Ref. [27] provided guidance on how digital technologies are shaping interior space layouts, emphasizing the increasing role of digital tools in the field of architectural design. On another front, ref. [28] evaluated how the design of corners and the length of lease spans affect spatial efficiency, discovering that corner modifications had a minor effect, whereas the lease span significantly influenced efficiency outcomes. Furthermore, ref. [29] created a model aimed at maximizing solar radiation capture in cold climates while considering spatial efficiency, demonstrating the connection between sustainable design practices and the optimization of space.

Ref. [30] analyzed how space is utilized in tall office buildings, highlighting the crucial role of load-bearing methods and core layouts in enhancing spatial efficiency. In a separate study, ref. [31] explored the link between optimizing space and reducing overall project expenses in office towers, illustrating the cost advantages associated with efficient spatial design. Meanwhile, ref. [32] examined spatial efficiency ratios in skyscrapers with multiple functions, stressing the necessity for well-designed structural systems and configurations. Together, these studies underscore the intricate nature of achieving spatial efficiency in architecture, emphasizing the value of innovative design, technological integration, compliance with regulations, and thoughtful structural planning.

On the other hand, smart building technologies are essential for enhancing the efficiency of modern infrastructure by integrating interconnected systems and devices [33]. These systems include conventional components such as HVAC, lighting, and electrical networks, along with advanced technologies like sensors, controllers, and energy storage solutions. Together, they facilitate real-time data collection and communication, optimizing overall building performance. Smart buildings can regulate energy usage based on demand and occupancy, utilizing energy meters, storage systems, and sensors to manage lighting, temperature, and air quality. These capabilities not only improve energy efficiency but also enhance occupant comfort, sustainability, and cost-effectiveness.

Advancements in smart building technologies have significantly progressed across various domains, such as communication [34], computing [35], and control systems [36]. However, their implementation often remains fragmented, with systems designed and installed as isolated solutions [37]. For example, in a building with both a demand-controlled ventilation system and an occupancy-responsive lighting system, each system might rely on occupancy data but operate independently due to proprietary technologies that hinder integration. This “one–function–one–box” approach, where each system optimizes its specific function, limits the sharing of data and components, resulting in inefficiencies and higher operational costs [38–40]. The fragmented nature of these systems, combined with a complex and disjointed supply chain, further exacerbates the challenge of creating cohesive smart building environments. A promising alternative is the “application stack paradigm” [41], enabled by innovations in building operating systems (BOS) like XBOS [42], which allows multiple functions to share components, data, and resources through centralized control and management. This holistic approach not only improves system interoperability but also enhances energy efficiency, reduces redundancy, and lowers costs by enabling greater flexibility and scalability. As a result, smart buildings designed with this paradigm can deliver a more seamless, responsive, and sustainable built environment, improving occupant experience while reducing environmental impact.

The shift toward integrated, interoperable systems represents a transformative step in optimizing space, energy use, and overall building performance.

An extensive survey of existing literature highlights a notable lack of research focused on comparing spatial efficiency in contemporary skyscrapers with different forms. To bridge this gap and deepen the understanding of current trends, this paper aims to methodically gather and evaluate data on spatial efficiency in these buildings. Through an in-depth analysis of 110 case studies, this study aims to uncover key architectural and structural characteristics, with the goal of identifying trends and providing valuable insights into this relatively unexplored subject.

3. Research Method

To collect and systematically organize data from 110 cases, a case study methodology was employed (Figure 1). This research approach is widely regarded as an effective tool for gathering and analyzing both qualitative and quantitative data, while also enabling comprehensive literature reviews [43,44]. The case study method is particularly well-suited for the detailed examination of architectural and structural elements in real-world buildings, as it provides a framework for in-depth, context-specific investigation.

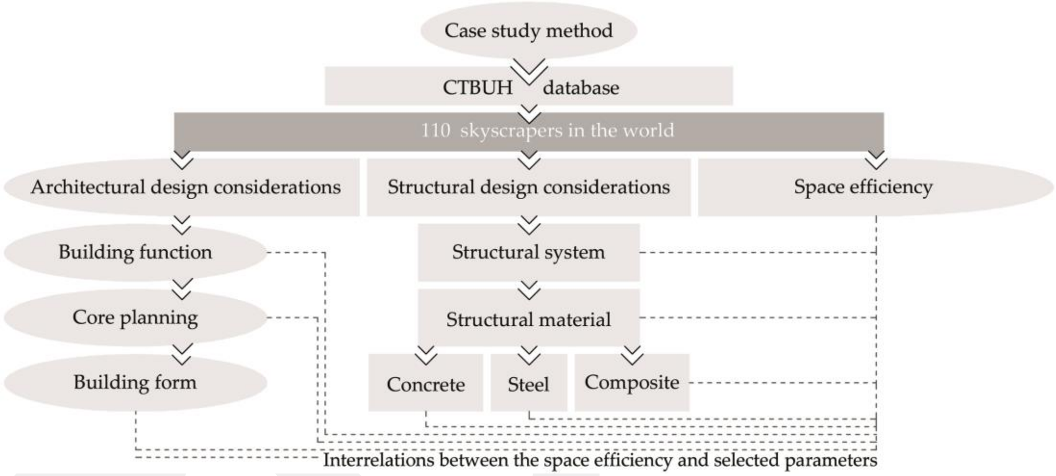


Figure 1. Research method (by authors).

By focusing on individual skyscraper designs, this approach enables researchers to uncover critical insights into the unique design attributes, construction techniques, and structural challenges associated with each building. Through this focused lens, this study not only highlights overarching trends and innovations in modern skyscraper architecture but also uncovers specific variations that may arise due to geographical, cultural, or engineering constraints.

Furthermore, the flexibility of the case study method supports the integration of diverse data sources, including architectural drawings, construction plans, historical documents, and interviews with key stakeholders. This multidimensional approach fosters a holistic understanding of skyscraper design, allowing researchers to triangulate data from multiple perspectives and produce a richer, more nuanced analysis. Such an integrative approach is critical for identifying emergent patterns and addressing complex research questions related to both the aesthetic and functional dimensions of contemporary high-rise buildings.

Ultimately, the use of a case study methodology in this research enables a robust comparative analysis, facilitating the identification of commonalities across cases while also bringing to light novel or anomalous design features that may influence future architectural practices and innovations in skyscraper construction.

In this research, 110 skyscrapers were chosen from the extensive Council on Tall Buildings and Urban Habitat (CTBUH) database [45]. CTBUH is a prominent global non-profit organization dedicated to advancing urban development, with a particular emphasis on sustainability and resilience in urban planning to tackle the issues posed by rapid urbanization and climate change. The organization is well-regarded for establishing criteria for classifying tall buildings and for recognizing outstanding architectural achievements through awards like 'The World's Tallest Building' and 'Buildings of Distinction'. Drawing on data from the CTBUH database, this study classifies buildings exceeding 300 m in height as 'supertall', underscoring their importance and the high level of technical and design expertise required for their construction.

In this research, a carefully curated case study sample was selected to provide a robust and representative analysis of skyscrapers serving various functions across the globe. While geographical limitations and access restrictions impacted the availability of certain cases, the final sample was meticulously assembled to offer a comprehensive view of spatial efficiency and architectural features in tall buildings. The sample comprises a diverse range of skyscrapers: 52 from China, 19 from the UAE, 10 from the United States, 6 from South Korea, 5 from Russia, 3 each from Saudi Arabia and Malaysia, 2 each from Kuwait, India, and Australia, and one each from Canada, Chile, UK, Qatar, Taiwan, Indonesia. This varied selection, shown in Figure 2, enables a detailed exploration of contemporary skyscraper design and spatial approaches across different global regions and urban contexts.

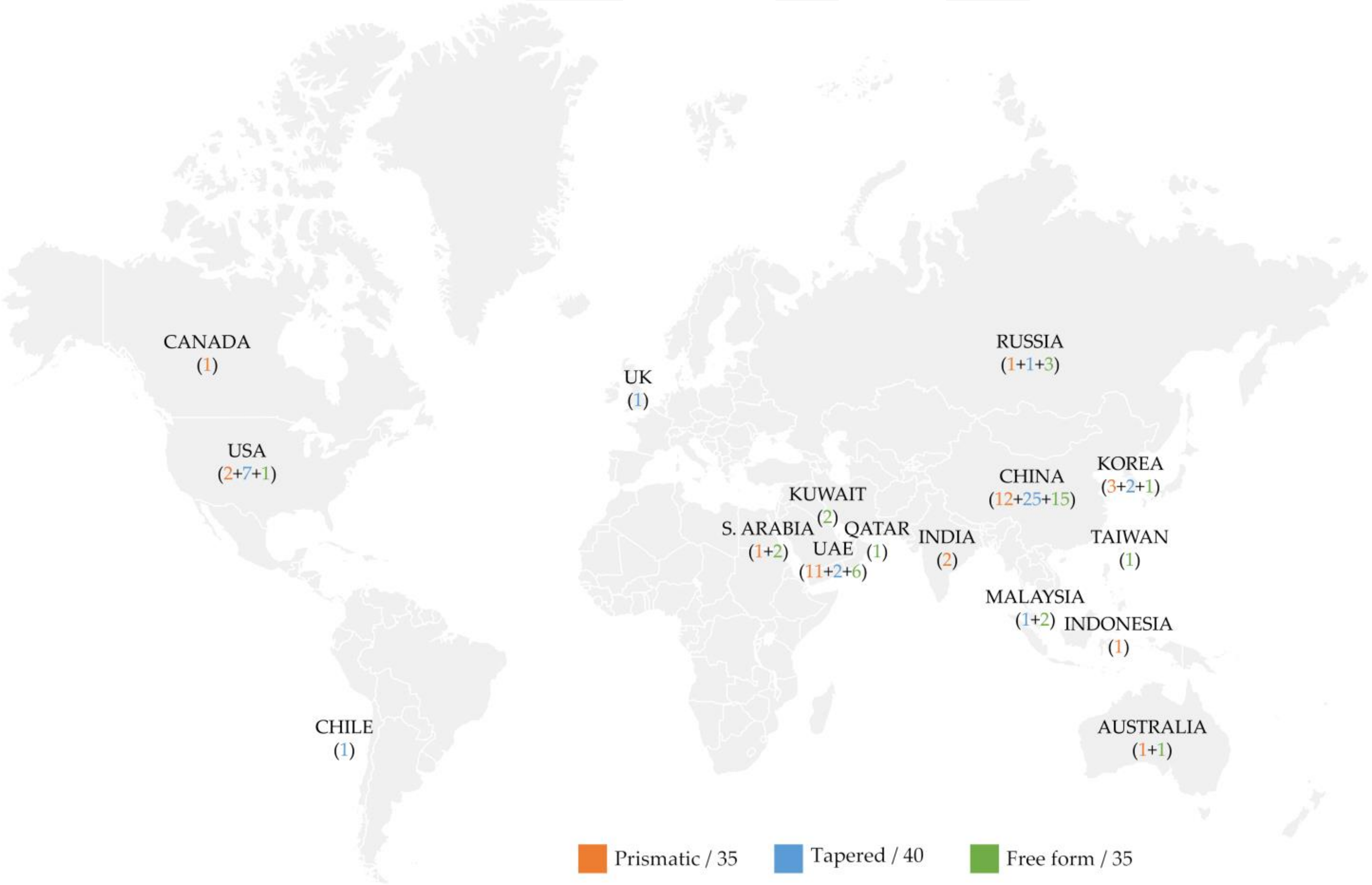


Figure 2. Case studies on the world map (by authors).

In the design of prismatic, tapered, and free-formed skyscrapers, as in many other structures, architectural and structural requirements serve as the fundamental decision-making criteria. These core parameters are crucial in shaping the overall design and function of the building. The key considerations include:

Core Planning: This impacts the arrangement of vertical mobility systems, such as elevators and staircases, as well as the distribution of service shafts and mechanical systems [46]. The positioning and configuration of the core directly influence circulation efficiency and space utilization.

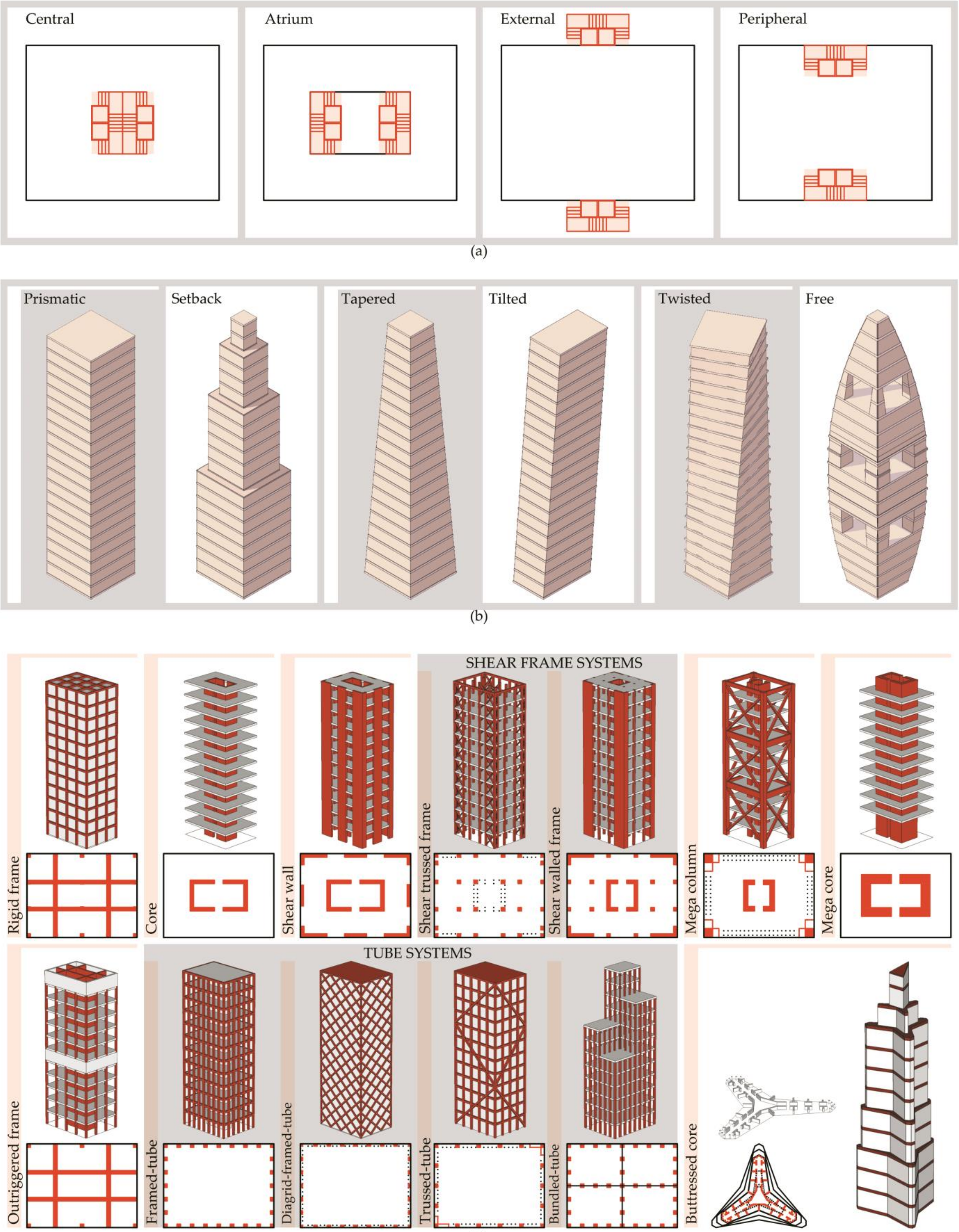
Building Form: The form of the building affects the size and shape of the floor slabs, which in turn dictates the flexibility of interior layouts and the potential for maximizing usable space [30]. The building's geometric form is also a critical factor in determining aesthetic and functional design outcomes.

Structural System: The choice of structural system plays a significant role in determining the dimensions, placement, and efficiency of structural members such as columns and beams [16]. The system selected must balance load distribution, structural integrity, and space efficiency to optimize the building's performance.

Structural Material: The material chosen for the structural elements, whether concrete, steel, or composites, directly influences the size and configuration of the building's load-bearing components [19]. The material's strength, stiffness, and fire resistance determine how compact or expansive the structural framework can be.

These parameters—core planning, building form, structural system, and material selection—govern critical design aspects such as floor slab dimensions, lease span, structural layout, and core arrangement, all of which have a direct impact on space efficiency [47]. As a result, this study focuses on these four design criteria to analyze space efficiency in tall towers.

From an architectural perspective, this study applies the core layout model from [18], which categorizes cores into four main types, as shown in Figure 3a. Additionally, building forms are classified into several distinct categories, as depicted in Figure 3b. Selecting an appropriate structural system is crucial for optimizing space utilization in tall buildings, as it greatly affects the configuration and size of structural components. This research adopts the classification of skyscraper structures provided by [19], presented in Figure 3c. The choice of structural materials, including steel, concrete, and composite materials, plays a significant role in determining the size and placement of structural elements, which directly impacts spatial efficiency. In this context, 'composite' refers to skyscrapers where vertical load-bearing components, such as shear walls and columns, are constructed using a combination of steel, concrete, or both.



(a)

(b)

(c)

Figure 3. Classifications by (**a**) core planning; (**b**) form; and (**c**) structural system (by authors).

4. Results

4.1. Main Design Parameters

Prismatic skyscrapers are known for their simplicity and efficiency in both design and space utilization. The primary architectural consideration in these buildings is the use of a central core, which houses essential services such as elevators, stairwells, and mechanical systems. This centralized core layout is ideal for maximizing space efficiency because it minimizes circulation pathways and ensures consistent floor layouts across levels. However, as the building height increases, the core must grow proportionally to accommodate additional elevators and stairwells, which can reduce usable space.

Prismatic forms are most employed in residential and mixed-use towers, where the simplicity of their layout allows for straightforward construction and the efficient allocation of interior spaces. The regularity in floor plans helps ensure that space utilization is maximized, as the uniformity of the design simplifies the division of the internal space into functional zones.

Tapering form allows for enhanced aesthetics, improved wind resistance, and maximized views from upper floors. However, it introduces more complexity in terms of spatial efficiency. As the floor area decreases with height, the allocation of space becomes more intricate, and core-to-floor ratios must be carefully managed to maintain efficiency.

The primary architectural design consideration for tapered skyscrapers is again the central core strategy, which is widely adopted for its structural efficiency and ability to centralize vertical circulation. This core design is crucial in ensuring that the structural loads are properly distributed, particularly given the unique wind loads that tapered forms must withstand.

Tapered forms are commonly used in mixed-use developments, where the varying floor sizes can accommodate different functions. For example, larger lower floors may house commercial spaces, while smaller upper floors can be designated for residential or office use. This flexibility allows for the efficient use of space within the constraints of the form.

Freeform skyscrapers, which are characterized by their non-uniform and often highly irregular shapes, provide a unique architectural challenge. These forms allow for a great degree of aesthetic freedom and the creation of iconic landmarks, but they also introduce significant difficulties in maintaining high space efficiency. The irregular shapes complicate the core design and require more sophisticated structural systems to handle the non-linear distribution of loads.

The central core remains the most common strategy for vertical circulation in freeform skyscrapers. However, the irregularity of the forms often necessitates the use of complex structural systems, such as outrigger frames, to manage lateral forces and ensure structural stability. The variability in floor sizes and shapes can result in lower space efficiency compared to prismatic and tapered forms, as the irregular geometries lead to more wasted or unusable space. Despite these challenges, freeform designs are favored for their iconic status and ability to create distinctive urban landmarks.

Overall, all three forms generally adopt a central core strategy for structural efficiency and centralized vertical circulation. However, in freeform skyscrapers, the complexity of the form often necessitates additional structural systems like outrigger frames. Prismatic skyscrapers tend to be the most efficient in terms of space utilization due to their simple, regular floor plans. Tapered skyscrapers strike a balance between aesthetics and efficiency, while freeform skyscrapers, though iconic, often have lower space efficiency due to their irregular shapes. Prismatic forms are well-suited for residential and mixed-use developments where simplicity and efficiency are paramount. Tapered forms are more flexible, accommodating a range of functions such as offices, hotels, and residential spaces. Freeform skyscrapers are primarily used in high-profile, mixed-use projects where the aesthetic impact is a priority.

Prismatic skyscrapers often rely on outrigger frame systems to handle lateral forces such as wind and seismic activity. These systems distribute the load from the core to the perimeter columns, improving overall stability and allowing for flexible placement of columns. This flexibility is essential for maximizing usable interior space, as the outrigger system allows for unobstructed floor plans. Prismatic skyscrapers typically use reinforced concrete as the dominant structural material, chosen for its strength, durability, fire resistance, and cost-effectiveness. In some cases, composite materials are used, combining the tensile strength of steel with the compressive strength of concrete. These materials offer a balance between cost efficiency and structural performance, making them ideal for supporting the vertical loads in prismatic towers. Reinforced concrete accounts for about 57% of prismatic skyscrapers, while composite construction is used in 40% of cases.

In tapered skyscrapers, structural design must accommodate the changing load distribution and wind forces that result from the tapering form. Outrigger frame systems are again the preferred choice, providing the flexibility needed to manage lateral forces and ensure structural stability as the building height increases. The outrigger system's capacity to place perimeter columns at various positions allows for better structural performance in managing the taper's aerodynamic profile, which significantly reduces wind loads.

Composite materials dominate in tapered skyscrapers, accounting for more than 80% of the structural materials used. This combination of steel and concrete provides the necessary balance of strength, fire resistance, and stability needed to support both vertical and lateral loads in these tall, slender structures. The lightweight nature of the tapering upper sections also reduces the overall material requirements, making tapered skyscrapers structurally efficient.

Freeform skyscrapers, with their complex, non-linear geometries, require even more sophisticated structural systems. Like their prismatic and tapered counterparts, freeform skyscrapers commonly employ outrigger frame systems, but these systems must be adapted to support the irregular and asymmetrical load distributions inherent in freeform designs. The flexibility of the outrigger system allows for unique façade designs, enabling architects to realize the full aesthetic potential of freeform structures while maintaining structural integrity.

Given the complexity of freeform geometries, composite materials are again the material of choice, providing the strength and versatility needed to manage the various forces acting on the structure. These materials allow the building to maintain its shape and stability while reducing weight, which is critical for managing the stress created by the irregular form.

Overall, outrigger frame systems are used in all three forms to manage lateral loads and provide stability at height. However, the complexity of freeform designs requires more advanced adaptations of these systems to handle non-linear load distributions. Composite materials, combining steel and concrete, dominate in all three types of skyscrapers. Their ability to balance tensile and compressive forces makes them ideal for both vertical and lateral loads. Reinforced concrete is also widely used in prismatic towers for its fire resistance and cost-effectiveness. Tapered and freeform designs optimize material use by reducing weight at higher levels, enhancing both structural efficiency and aesthetic appeal. In contrast, prismatic forms emphasize simplicity and uniformity, with a focus on maximizing space and cost efficiency.

Tables 1 and 2 show the outcomes on architectural and structural design parameters for prismatic, tapered, and freeform skyscrapers.

Table 1. Comparison of architectural design considerations.

Findings	Prismatic	Tapered	Free
Function	Residential (43%) Office (26%)	Residential (7%) Office (33%)	Residential (11%) Office (40%)

	Mixed-use (31%)	Mixed-use (60%)	Mixed-use (49%)
Core type	Central (97%) External (3%)	Central (100%)	Central (100%)

Table 2. Comparison of structural design considerations.

Findings	Prismatic	Tapered	Free
Material	Concrete (57%) Composite (40%) Steel (3%)	Concrete (10%) Composite (82%) Steel (8%)	Concrete (31%) Composite (69%)
System	Outrigger frame (63%) Tube (25%) Mega column & core (6%) Shear-frame (6%)	Outrigger frame (70%) Tube (20%) Buttressed core (3%) Shear-frame (7%)	Outrigger frame (74%) Tube (9%) Mega column & core (11%) Shear-frame (6%)

4.2. Space Efficiency in Towers with Different Forms

Average space efficiencies of prismatic, tapered, and free towers were 72%, 72%, and 71%, respectively, whereas core area to GFA ratios were 24%, 26%, and 26%, respectively. Values fluctuated from the lowest of 55% and 11% to the highest of 84% and 38%, respectively, as seen in Table 3.

Table 3. Comparison of space efficiency and ratio of core to GFA.

Findings	Prismatic	Tapered	Free
Space efficiency	72% (max. 84%, min. 56%)	72% (max. 84%, min. 55%)	71% (max. 84%, min. 56%)
Core to GFA	24% (max. 36%, min. 12%)	26% (max. 38%, min. 11%)	26% (max. 36%, min. 11%)

As seen in Table 3, prismatic skyscrapers achieve an average space efficiency of 72%, with values ranging between 56% and 84%. The regular, uniform floor plans in prismatic buildings contribute to their generally high space efficiency. These buildings are typically designed with repetitive floorplates, which allow for straightforward spatial planning.

The higher end of space efficiency (up to 84%) is attainable in prismatic buildings because their simple geometries allow for efficient layout and consistent floor use. However, the lower range (56%) may occur in extremely tall or heavily serviced prismatic buildings, where additional circulation cores or structural elements become necessary to manage vertical loads and circulation. The simplicity of prismatic designs is particularly effective in reducing spatial inefficiency caused by irregular shapes, resulting in less wasted or unusable space. Their geometry often makes it easier to optimize floor layouts, especially for commercial or residential functions, which require efficient space distribution.

Tapered skyscrapers also exhibit an average space efficiency of 72%, with a broader range between 55% and 84%. Although they share the same average space efficiency as prismatic buildings, their variability is higher, which can be attributed to the changing floorplate sizes as the building rises. Tapered forms are often narrow towards the top, which creates more challenges in terms of space efficiency. As the floor area decreases with height, the usable space becomes less consistent, leading to more variability in space efficiency. In buildings where this taper is more pronounced, space efficiency may drop towards the lower end of the range (55%). However, the aerodynamic and aesthetic benefits of tapered forms, such as reducing wind loads and improving structural stability, justify this variability. Even so, when carefully designed, tapered buildings can still achieve high efficiency (up to 84%), particularly in the lower sections where floorplates are larger and more efficiently utilized.

Freeform skyscrapers show a slightly lower average space efficiency of 71%, with a range from 56% to 84%. Freeform designs introduce more complexity due to their irregular and often non-repetitive shapes. This complexity can make it difficult to maintain consistently high space efficiency throughout the building. The lower average efficiency in freeform designs is largely due to the irregular geometries, which can result in unusable or inefficiently shaped floor areas, particularly in the corners and peripheries. The dynamic forms may limit the potential to organize space efficiently, particularly in the upper sections or in areas where the form significantly deviates from a standard shape. Nonetheless, freeform designs can still achieve high space efficiency (up to 84%) when the architectural form is well-integrated with efficient spatial planning, particularly on the lower floors or where the design allows for large, flexible interior spaces. These high-efficiency cases often occur in mixed-use buildings or in areas where aesthetic and functional considerations are well-balanced.

On the other hand, prismatic buildings have an average core-to-GFA ratio of 24%, with a range from 12% to 36%. The lower end of this range reflects the inherent efficiency of prismatic forms in managing space. Their simple, uniform layouts allow for compact and centralized core placements, minimizing the need for extensive circulation or mechanical shafts. However, as prismatic buildings grow taller or serve more complex functions, the core size may need to increase to accommodate additional elevators, stairwells, and structural support. This explains the upper limit of 36%, where a larger core reduces the proportion of usable space, particularly in super-tall prismatic towers. In general, the regularity of prismatic designs makes them highly efficient in distributing services, resulting in lower core-to-GFA ratios and more usable floor area, especially in mid-rise buildings or those with straightforward vertical circulation needs.

Tapered buildings exhibit a slightly higher average core-to-GFA ratio of 26%, with a range from 11% to 38%. The increasing structural complexity of tapered forms, especially in the upper sections where the building narrows, often requires a larger proportion of floor space to be dedicated to the core. As the building tapers, the floor area reduces, but the core size does not necessarily shrink at the same rate, leading to a higher core-to-GFA ratio, particularly at the top of the structure. This is a key factor in reducing space efficiency in some tapered skyscrapers, especially as the taper becomes more pronounced. Despite this challenge, tapered buildings can achieve lower core-to-GFA ratios in the lower sections, where the wider floorplates provide more space for circulation and mechanical systems without significantly impacting the usable area.

Freeform buildings share the same average core-to-GFA ratio as tapered buildings (26%), with a range from 11% to 36%. The irregular and asymmetrical shapes of freeform buildings make it challenging to efficiently place the core, often requiring more space to accommodate the structural and mechanical needs. The dynamic geometries of freeform buildings frequently lead to uneven or less centralized core layouts, contributing to a higher core-to-GFA ratio in certain sections of the building. In some cases, this inefficiency is compensated by innovative engineering solutions, but it often results in a greater proportion of floor area being used for non-functional purposes, particularly in areas where the form deviates significantly from a standard shape. However, freeform buildings can still achieve lower core-to-GFA ratios (as low as 11%) in sections where the building's design allows for more compact core placement or where structural demands are lower. Achieving this efficiency requires careful coordination between architectural design and engineering.

In summary, prismatic buildings tend to have better space efficiency and lower core-to-GFA ratios due to their simple, regular geometry, making them easier to optimize for both functional use and circulation. Tapered buildings, while visually and aerodynamically advantageous, experience more variability in space efficiency and core size, particularly as the building narrows toward the top. Freeform buildings, with their irregular and dynamic shapes, present the most challenges in maintaining space efficiency and minimizing core-to-GFA ratios, though they can achieve high performance with careful planning and innovative design solutions. Ultimately, the choice of form depends on balancing aesthetic, structural, and functional considerations, with space efficiency and core-to-GFA ratios serving as key indicators of the building's overall efficiency.

Relation of Space Efficiency and Location, Core Typology, Form, Structural Material, and System

Figures 4–7 provide a comprehensive analysis of empirical data, highlighting the complex relationship between spatial efficiency and the architectural and structural elements that impact it. In these figures, a bar chart on the right visually represents the total number of skyscrapers categorized by relevant classifications, giving a clear snapshot of data distribution. Colored dots represent the spatial efficiency of individual towers in different regions, correlating with their specific design features, offering a visually engaging depiction of these intricate interactions. Additionally, the bars emphasize the prevalence of buildings within the sample that exhibit similar design characteristics.

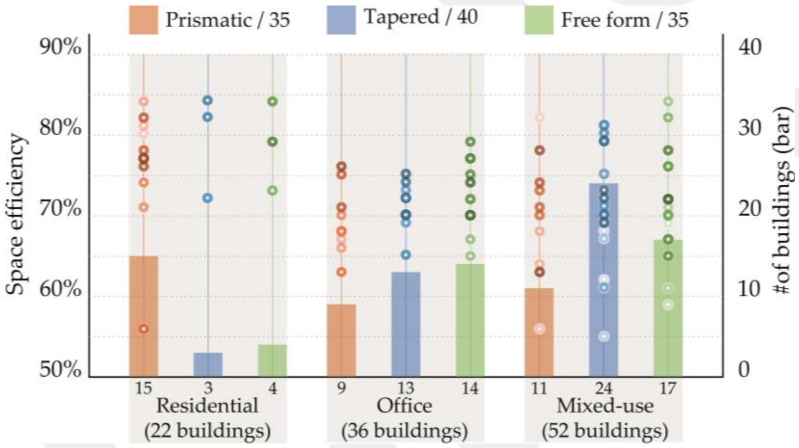


Figure 4. Different forms by function.

Figure 4 illustrates the comparison of space efficiency for three distinct skyscraper forms across residential, office, and mixed-use building functions. Prismatic buildings (orange) generally display lower and more consistent space efficiency. In residential buildings, which account for 15 out of the 22 analyzed, the space efficiency ranges from around 60% to 75%, with a majority of the values clustering near 65%. In office buildings (9 out of 36), the space efficiency increases slightly, ranging from 65% to 75%. For mixed-use buildings (11 out of 52), prismatic forms maintain a similar efficiency range, spanning from 60% to 75%.

Tapered skyscrapers (blue) exhibit more variability in space efficiency, particularly in office and mixed-use buildings. In residential buildings (3 out of 22), the space efficiency is more widely distributed, ranging from 55% to 80%, indicating a larger degree of variability than prismatic forms. In office buildings (13 out of 36), the efficiency spans from 60% to 85%, with several buildings approaching the upper range, showing the tapered form's potential for optimization in commercial applications. In mixed-use buildings (24 out of 52), tapered designs display one of the highest space efficiencies, with values ranging from 60% to 85%.

Freeform skyscrapers (green) also show a broad range of space efficiency, particularly in mixed-use buildings. For residential buildings (4 out of 22), freeform designs exhibit slightly better performance, with efficiency ranging from 65% to 85%. In office buildings (14 out of 36), the efficiency ranges between 60% and 85%, similar to the tapered form but with slightly more variability. In mixed-use buildings (17 out of 52), freeform designs achieve the highest space efficiency, ranging from 65% to 85%, making them well-suited for multifunctional uses.

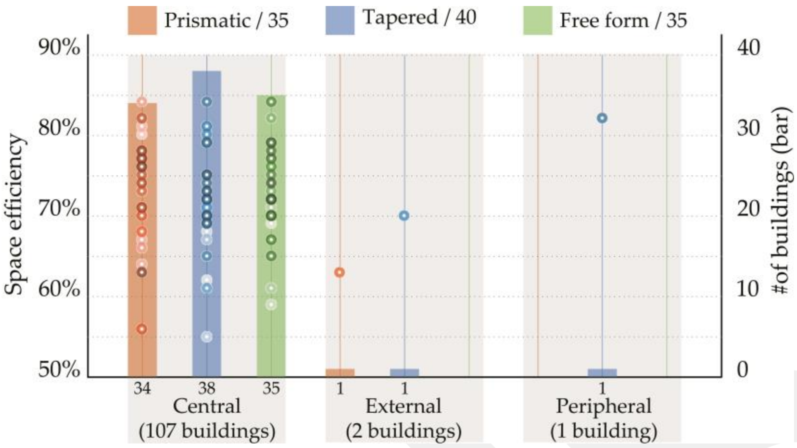


Figure 5. Different forms by core type.

Figure 5 provides a detailed comparison of the space efficiency of skyscrapers with different forms based on three core typologies: central, external, and peripheral cores. Central core typology is the most commonly employed across all three forms, with 107 buildings in total. Prismatic skyscrapers (orange, 34 buildings) have a space efficiency range from 60% to 80%, with most of the data points clustering around 70%. This indicates a moderate level of space efficiency, which is consistent but slightly lower compared to the other forms.

Tapered skyscrapers (blue, 38 buildings) demonstrate a wider range of space efficiency, from 60% to 85%, with several buildings achieving efficiencies above 80%. This suggests that tapered forms can better optimize the central core, possibly due to the varying floor sizes that allow for flexible spatial planning. The higher variability in efficiency reflects the adaptability of the tapered form in balancing structural demands and maximizing usable space.

Freeform skyscrapers (green, 35 buildings) also show a broad range of space efficiency, from 65% to 85%, with many buildings achieving efficiency levels at the higher end of the spectrum (above 80%). Despite the complexity and irregularity of their forms, freeform skyscrapers maintain a high level of space efficiency when using a central core. This performance demonstrates the potential of freeform buildings to be both architecturally expressive and spatially efficient.

External core typology is far less common, with only two buildings represented in the dataset—one prismatic and one tapered. Both buildings show lower space efficiency, with values ranging from 55% to 70%. The prismatic building has an efficiency closer to 60%, while the tapered building shows slightly higher efficiency at around 70%. The lower space efficiency in buildings with external cores suggests that this core typology may limit usable space compared to central cores.

Peripheral core typology is the least represented, with only one tapered building analyzed. This building shows a space efficiency of approximately 65%, indicating a moderate level of efficiency. However, the single data point limits the ability to draw broader conclusions about the effectiveness of the peripheral core in other buildings or forms.

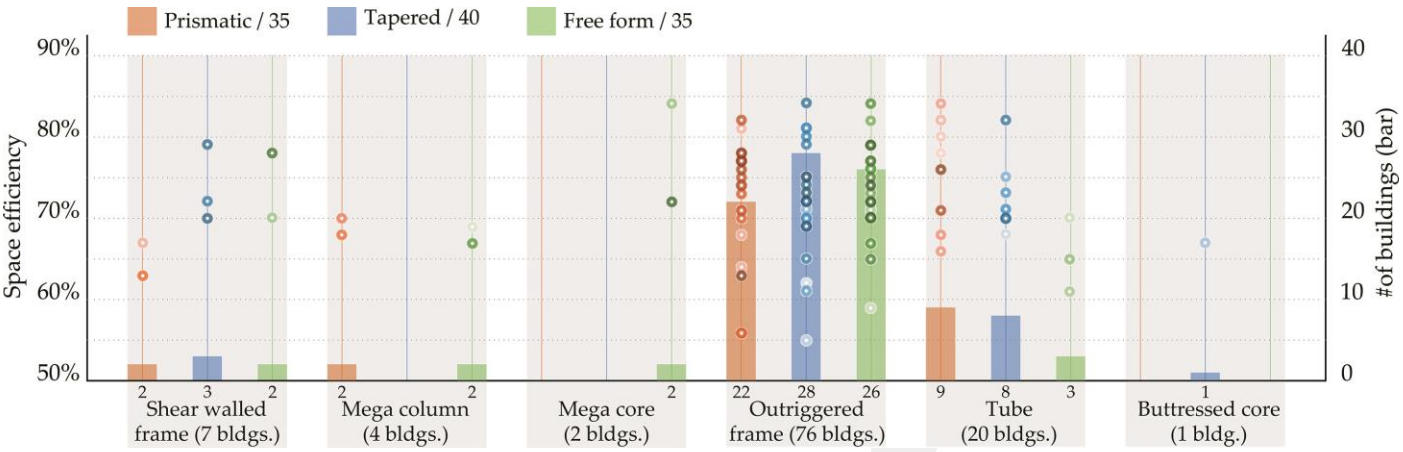


Figure 6. Different forms by structural system.

Figure 6 compares the space efficiency of prismatic, tapered, and freeform skyscrapers across six different structural systems: shear-walled frame, mega column, mega core, outrigger frame, tube, and buttressed core. Shear-walled frame system, represented by 7 buildings (2 prismatic, 3 tapered, and 2 freeform), shows moderate space efficiency across all forms. Prismatic buildings exhibit space efficiency in the range of 60% to 70%, while tapered and freeform buildings demonstrate a broader range, with efficiency spanning from 60% to 80%. Despite its moderate application, the shear-walled frame system does not appear to provide exceptionally high space efficiency compared to other structural systems, especially in prismatic forms.

The mega column system is represented by 4 buildings, all in the tapered and freeform categories. Tapered buildings show a wide range of space efficiency, from 60% to 80%, indicating significant variability in how this system supports spatial optimization. Freeform buildings utilizing the mega column system display slightly higher space efficiency, with values ranging from 65% to 80%. This suggests that the mega column system, while not commonly used, can provide higher space efficiency, particularly in more complex geometries such as freeform skyscrapers.

The mega core system, used in only 2 buildings, both freeform, demonstrates a higher range of space efficiency. These freeform buildings exhibit space efficiency from 70% to 85%, showcasing the system's potential for achieving high levels of spatial efficiency in non-linear building designs. The limited dataset prevents broader conclusions, but it suggests that mega core systems may be particularly well-suited for freeform skyscrapers, where complex geometries demand a robust and flexible structural solution.

The outrigger frame system is the most widely used structural system in the dataset, represented by 76 buildings (22 prismatic, 28 tapered, and 26 freeform). This system shows a wide range of space efficiency across all forms. Prismatic buildings using outrigger frames exhibit efficiency from 60% to 80%, with most data points clustering around 70%. Tapered buildings display a broader spread, ranging from 60% to 85%, with several buildings achieving efficiencies in the higher range. Freeform buildings show the highest levels of efficiency, spanning from 65% to 85%, indicating that the outrigger frame system is particularly effective for complex forms. This widespread use and adaptability of the outrigger frame system highlight its suitability for tall, structurally demanding buildings, and its capacity to maximize space efficiency, especially in non-standard geometries like freeform designs.

The tube system, used in 20 buildings (9 prismatic, 8 tapered, and 3 freeform), shows a more consistent performance. Prismatic and tapered buildings have space efficiency ranging between 60% and 80%, with most values clustering around 70%, reflecting a balanced use of this system for both forms. The freeform buildings in the dataset, though fewer, show slightly higher efficiency, with values ranging from 65% to 80%. This system appears to perform well across all forms, providing stable and efficient structural support, particularly in traditional and linear building designs such as prismatic and tapered forms.

The buttressed core system is the least represented, with only one tapered building using this structural solution. The space efficiency of this building ranges from 55% to 80%, indicating that while the system can be effective, it may also introduce more variability in space efficiency compared to other structural systems. This system is typically used in extremely tall buildings, where lateral stability is a significant concern, but the data suggests that it may not consistently optimize space efficiency.

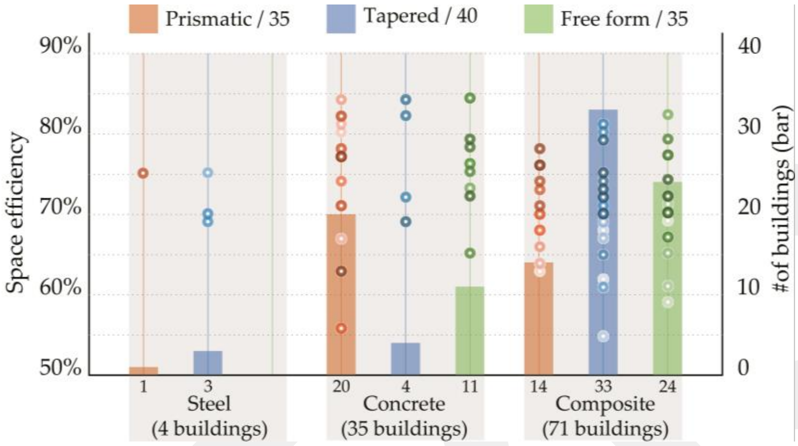


Figure 7. Different forms by structural material.

Figure 7 presents a comparison of space efficiency for prismatic, tapered, and freeform skyscrapers based on three types of structural materials: steel, concrete, and composite. Steel structures are the least represented, with only 4 buildings (1 prismatic, 3 tapered). The prismatic steel building shows a space efficiency of 70%, suggesting that while steel can offer efficient structural solutions for prismatic forms, its use is rare in these configurations. The tapered steel buildings exhibit a broader range of efficiency, from 60% to 75%, indicating moderate efficiency for tapered designs. There are no freeform buildings using steel in this dataset, suggesting that steel is not typically chosen for more complex geometries like freeform skyscrapers, possibly due to material limitations in accommodating non-linear forms.

Concrete is a more commonly used material, represented in 35 buildings (20 prismatic, 4 tapered, 11 freeform). Prismatic concrete buildings show a consistent space efficiency range from 60% to 75%, with most buildings clustered around 70%, indicating reliable performance in terms of space optimization for these simpler forms. In tapered buildings, concrete shows a slightly wider spread, with efficiency ranging from 55% to 80%, indicating that concrete allows for some flexibility in design but may not be as efficient as composite materials in tapered structures. Freeform concrete buildings achieve higher efficiency, with values ranging from 65% to 80%, demonstrating that concrete is a strong choice for more complex forms, likely due to its adaptability in non-linear and irregular shapes.

Composite materials, which combine steel and concrete, dominate the dataset, with 71 buildings (14 prismatic, 33 tapered, 24 freeform). Prismatic composite buildings exhibit space efficiency ranging from 60% to 75%, similar to concrete buildings but with a slightly tighter clustering around 70%. This consistency suggests that composite materials perform well in traditional, regular forms like prismatic skyscrapers. However, tapered buildings using composite materials show a wider and higher range of space efficiency, from 60% to 85%, with many buildings achieving efficiencies above 80%. This demonstrates the superior adaptability of composite materials in tapered designs, where varying floor sizes and complex geometries benefit from the combined strength and flexibility of steel and concrete. Freeform buildings using composite materials also exhibit high space efficiency, ranging from 65% to 85%, similar to tapered designs. This reflects the high structural efficiency of composite materials in complex, irregular skyscrapers, where spatial optimization is critical.

Steel is used sparingly, with space efficiency for prismatic and tapered buildings ranging from 60% to 75%, and no representation in freeform structures. While steel can offer moderate efficiency, its limited use suggests that it may not be the preferred material for maximizing space in high-rise buildings, particularly in more complex forms.

Concrete performs well, especially in freeform buildings, with space efficiency ranging from 65% to 80%. Prismatic concrete buildings are consistent, with efficiency clustering around 70%, while tapered concrete buildings show more variability, ranging from 55% to 80%. Concrete is a versatile material but may be slightly less efficient than composite in more dynamic forms like tapered and freeform skyscrapers.

Composite materials are the most efficient and widely used across all forms. Tapered buildings using composite materials exhibit the highest efficiency, with values ranging from 60% to 85%, and many achieving over 80% efficiency. Similarly, freeform buildings using composite materials also demonstrate high space efficiency, ranging from 65% to 85%, showing the material's ability to accommodate both complex geometries and high spatial optimization. Prismatic buildings using composite materials are consistent with other materials, showing efficiency between 60% and 75%.

Composite materials stand out as the best-performing structural solution for achieving high space efficiency, especially in tapered and freeform skyscrapers, where efficiency ranges from 60% to 85%. The flexibility of composite materials allows for better optimization of space in non-linear and irregular geometries. Concrete also performs well, particularly in freeform structures, with space efficiency values up to 80%, while steel, though less commonly used, offers moderate efficiency in prismatic and tapered buildings, generally ranging between 60% and 75%. Overall, composite materials provide the highest level of space efficiency across all forms, particularly for more complex architectural designs.

5. Discussion

The comparative analysis of space efficiency in skyscrapers with prismatic, tapered, and free forms provides a comprehensive understanding of how different architectural designs influence the utilization of internal space, construction feasibility, and overall functionality. Each form presents distinct advantages and limitations, shaping its suitability for specific contexts and influencing decisions in skyscraper design.

Prismatic skyscrapers, characterized by their straightforward, uniform geometry, and vertical alignment, typically achieve the highest levels of space efficiency among the three forms analyzed. This efficiency is largely due to the simplicity and regularity of prismatic designs, which facilitate a standard approach to structural systems and material use. The consistency in floor plans throughout the building height allows for optimal placement and organization of service cores, structural elements, and usable floor space, thereby maximizing the ratio of net floor area to GFA.

The high space efficiency of prismatic forms translates to significant economic benefits. These skyscrapers are often more cost-effective to construct and maintain, as their design requires fewer custom solutions and allows for the use of standardized components. This efficiency not only reduces construction time and costs but also enhances the building's marketability by maximizing the rentable or sellable space. For developers and investors, prismatic skyscrapers represent a financially viable option, especially in high-density urban areas where maximizing usable space is paramount.

However, the uniformity and simplicity of prismatic designs can be perceived as visually monotonous, lacking the architectural dynamism that is increasingly sought after in modern urban environments. In cities aiming to create distinctive skylines and cultural landmarks, prismatic skyscrapers may fall short in terms of aesthetic appeal and symbolic representation. Despite these aesthetic limitations, prismatic forms remain a practical and efficient choice for urban contexts where functionality and cost-effectiveness are prioritized.

Tapered skyscrapers, which feature a gradual reduction in floor area as they ascend, offer a different set of spatial and structural considerations. The tapering design is particularly advantageous in improving a building's aerodynamic performance, significantly reducing wind loads and sway. This attribute is critical for super-tall structures, where wind forces become a major concern. The tapering effect also allows for a more varied and aesthetically pleasing silhouette, contributing to a dynamic skyline and enhancing the building's visual impact.

However, the reduction in floor area towards the top of the building introduces challenges in terms of space efficiency. The tapering shape results in smaller upper floors, which can lead to underutilized spaces and complicate the integration of service cores, mechanical systems, and structural supports. These constraints often necessitate more complex and costly structural solutions to maintain stability and functionality, reducing the overall economic efficiency of the building. Despite these drawbacks, tapered skyscrapers are highly valued for projects where aesthetic considerations and structural performance are prioritized over maximizing internal space.

The trade-offs associated with tapered designs highlight the importance of context in skyscraper construction. While they may not offer the highest space efficiency, tapered forms provide significant benefits in terms of structural resilience and architectural expression. In regions prone to high winds or seismic activity, or where visual impact is a key consideration, tapered skyscrapers offer a compelling option that balances form and function.

Freeform skyscrapers represent the most innovative and complex category of high-rise buildings analyzed in this study. Defined by their non-linear, often organic shapes, freeform designs break away from traditional geometric patterns and offer architects a canvas for creativity and experimentation. These structures often become iconic landmarks, contributing significantly to a city's identity and attracting tourism, investment, and public interest.

However, the irregular geometries of freeform skyscrapers pose substantial challenges in terms of space efficiency and structural integrity. The non-standard shapes require specialized structural systems capable of accommodating unconventional loads and maintaining stability. These systems often involve advanced materials and engineering techniques, which can increase both the cost and complexity of construction. Additionally, the irregular floor plans associated with freeform designs can lead to inefficient use of internal space, as the layouts may not align well with standard planning practices, resulting in wasted areas or reduced flexibility in space usage.

Despite these challenges, freeform skyscrapers offer unique advantages that can justify their use in specific contexts. Their distinctive designs can enhance the aesthetic value of a skyline, serve as cultural symbols, and contribute to a city's global image. Furthermore, freeform buildings can provide a variety of interior spaces that offer unique user experiences and support diverse functionalities, making them suitable for mixed-use developments or projects that prioritize iconic architecture over traditional efficiency metrics.

The successful implementation of freeform skyscrapers needs a holistic method that incorporates architectural design, structural engineering, and urban planning. By leveraging advanced digital modeling tools and innovative construction techniques, architects and engineers can optimize the balance between form and function, creating buildings that are not only visually striking but also structurally sound and functionally effective.

The findings of this study underscore the critical role of space efficiency in sustainable urban development and the need to balance aesthetic aspirations with practical considerations in skyscraper design. In densely populated urban areas where land is scarce and expensive, maximizing usable space is essential to guarantee the financial feasibility and ecological sustainability of high-rise structures. Prismatic forms, with their high space efficiency and cost-effectiveness, are well-suited for these contexts, providing a straightforward solution to the challenges of urban density.

However, as cities increasingly seek to distinguish themselves through iconic architecture and sustainable design, the trade-offs associated with tapered and freeform designs become more relevant. While these forms may offer less space efficiency, they provide opportunities for architectural innovation and can contribute to the cultural and economic vitality of a city. For instance, freeform skyscrapers, despite their lower space efficiency, can incorporate sustainable design features such as green roofs, natural ventilation, and renewable energy systems, enhancing their environmental performance and social value.

The choice of skyscraper form should be guided by careful consideration of the specific needs and goals of the project, as well as the broader urban context in which it is situated. For cities looking to balance density with iconic architecture, a mix of prismatic, tapered, and freeform skyscrapers may provide the optimal solution, combining the efficiency of traditional forms with the aesthetic and symbolic value of more innovative designs.

This study provides a foundational understanding of the relationship between skyscraper form and space efficiency, but there is ample scope for further research to explore these dynamics in greater depth. Future studies could examine the impact of different structural systems, materials, and core configurations on space efficiency across various building forms. For instance, research into the use of hybrid structural systems or innovative materials such as cross-laminated timber could provide valuable insights into new ways of optimizing space efficiency and sustainability in high-rise construction.

Additionally, exploring the lifecycle environmental impacts of each form could offer a more comprehensive understanding of their long-term sustainability. This could include analyses of energy consumption, carbon emissions, and resource use throughout the building's lifecycle, from construction to demolition. Such studies could help identify best practices for designing skyscrapers that minimize environmental impacts while maximizing social and economic benefits.

Comparative analyses of other emerging architectural typologies, such as twisted or leaning skyscrapers, could also contribute to a more nuanced understanding of space efficiency in high-rise design. By expanding the scope of research and exploring new dimensions of skyscraper design, the architectural community can continue to innovate and optimize the use of space in urban environments, ultimately contributing to more sustainable and vibrant cities.

As observed in numerous studies [16–18,48], central cores are widely favored in prismatic, tapered, and freeform tall buildings due to their extensive functional and design advantages. One of their key benefits is the optimization of usable space along the building's perimeter, which enhances access to natural light and provides improved views—factors that greatly elevate the living and working experience for occupants. Additionally, central cores contribute significantly to fire safety by creating shorter, more efficient evacuation routes, ensuring rapid and secure exits during emergencies. Their design versatility allows architects to experiment with a broader array of architectural concepts while preserving the building's structural integrity. Central cores also seamlessly integrate with a variety of architectural styles, making them adaptable to both contemporary and traditional designs. This balance of functionality, safety, and aesthetic flexibility positions central cores as an essential feature in modern high-rise buildings, offering a practical and effective solution for maximizing both space efficiency and occupant comfort.

This research, in contrast to studies on office [17] and mixed-use towers [19], aligns with findings from residential towers [16], showing that concrete was the preferred material for prismatic tall buildings. Concrete's selection is likely due to its exceptional compressive strength, durability, and fire resistance, making it well-suited for preserving structural integrity in high-rise construction [49–51]. Concrete's inherent qualities ensure that prismatic buildings can endure both vertical loads and fire hazards effectively, contributing to their long-term safety and resilience. Meanwhile, tapered and freeform towers predominantly utilized composite materials, which combine the tensile strength of steel with the fire resistance and stiffness of concrete. This combination provides both structural flexibility and improved safety, enabling these materials to better handle the complex geometries and loads associated with non-linear building forms. The widespread application of composites in these advanced designs reflects a strategic approach that balances high-performance requirements with safety concerns, catering to the specific challenges of modern skyscraper construction [52–54]. This material choice highlights the careful consideration of both engineering demands and architectural innovation in the evolving landscape of tall building design.

Consistent with prior studies [16,19], the outrigger frame system emerged as the most frequently utilized structural solution in the towers analyzed in this study. This broad adoption is due to several key advantages [55–57]. Firstly, the system offers significant flexibility in the placement of exterior columns, providing architects with greater freedom to explore dynamic and innovative façade designs. This adaptability allows for more creative architectural expression while maintaining the structural integrity of the building. Moreover, the outrigger frame system enhances the stability of taller structures by effectively distributing lateral forces, such as wind and seismic loads, across the building. This makes it particularly well-suited for skyscrapers that reach extreme heights, as it ensures both safety and performance without sacrificing design versatility. Additionally, by improving the efficiency of load transfer, the system enables taller buildings to achieve slimmer profiles, further supporting contemporary architectural trends. The widespread use of this structural approach reflects its ability to balance the demands of structural resilience, height, and design freedom, making it a cornerstone of modern high-rise construction.

6. Conclusions

This study offers a concise comparison of space efficiency in prismatic, tapered, and freeform skyscrapers, focusing on their unique advantages and challenges. Prismatic forms, with their straightforward geometry and construction, provide the highest space efficiency, making them ideal for projects prioritizing cost-effectiveness and space maximization. Tapered skyscrapers strike a balance between aesthetics and performance, well-suited for environments requiring enhanced wind resistance or visual appeal, though with some reduction in space efficiency. Freeform skyscrapers prioritize iconic and innovative design but face greater challenges in terms of space efficiency and construction complexity. The choice of skyscraper form should align with the project's objectives, whether prioritizing space optimization, aesthetic impact, or a balance of both. By refining structural and construction strategies for each form, professionals can create efficient, resilient skyscrapers that contribute to vibrant urban landscapes.

Author Contributions: Conceptualization, H.E.I.; methodology, H.E.I. and Ö.N.A.; software, H.E.I.; formal analysis, H.E.I. and Ö.N.A.; investigation, H.E.I. and Ö.N.A.; writing—original draft preparation, H.E.I.; writing—review and editing, H.E.I. and Ö.N.A.; supervision, H.E.I. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The data presented in this study are available in this article.

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

References

1. Yu, Y.; Yang, C.; Hu, Q.; Kong, S. Towering sustainability: Unraveling the complex effects of skyscrapers on urban resilience. *Environ. Impact Assess. Rev.* **2024**, *108*, 107614.
2. Novikov, S.; Gimazutdinova, E. The vertical cities: Reality or utopia of the future. In Proceedings of the 2nd International Scientific Conference on Socio-Technical Construction and Civil Engineering (STCCE–2021), Kazan, Russia, 21–28 April 2021; EDP Sciences: Les Ulis, France, 2021; Volume 274, p. 01014.
3. Li, Y.; Du, H.; Sezer, C. Sky gardens, public spaces and urban sustainability in dense cities: Shenzhen, hong kong and singapore. *Sustainability* **2022**, *14*, 9824.
4. Zaręba, A.; Krzemińska, A.; Kozik, R. Urban vertical farming as an example of nature-based solutions supporting a healthy society living in the urban environment. *Resources* **2021**, *10*, 109.
5. Bahar, N.H.; Lo, M.; Sanjaya, M.; Van Vianen, J.; Alexander, P.; Ickowitz, A.; Sunderland, T. Meeting the food security challenge for nine billion people in 2050: What impact on forests? *Glob. Environ. Chang.* **2020**, *62*, 102056.

6. Sodoma, R.; Shmatkovska, T.; Dziamulych, M.; Vavdiiuk, N.; Kutsai, N.; Polishchuk, V. Economic efficiency of the land resource management and agricultural land-use by agricultural producers. *Manag. Theory Stud. Rural. Bus. Infrastruct. Dev.* **2021**, *43*, 524–535.
7. Yung CS, Y.; Ismail, L.H.; Abd Wahab, I.; Hanapi, N.A. Skyscrapers architectural form effects on airflow. *J. Des. + Built* **2021**, *14*.
8. Budini, A.; Vesho, N.; Perna, V.; Gjuzi, O. Investigations On the Optimization of the Geometric Shapes of Skyscrapers Applications through numerical simulations in the context of Tirana. *Int. J. Sci. Res. Civ. Eng.* **2022**, *6*, 41–50.
9. Jung, C.; Awad, R.; Awad, J. A study of optimal design process for complex-shaped skyscrapers' structural systems in United Arab Emirates. *Ain Shams Eng. J.* **2022**, *13*, 101683.
10. Goncikowski, M. Landmarks of the metropolis, the types of forms of varsovian skyscrapers as compared to global precedence. *Buildings* **2022**, *12*, 1507.
11. Sungur, S.E.; Arpacioglu, U.T.; Ozgunler, M.; Elcin, S.; Arpacioglu, U.T.; Ozgunler, M. London the Shard analysis in the context of parametric and sustainable skyscraper design. *Res. Eng. Struct. Mater.* **2021**, *7*, 661–675.
12. Soliman, M.A.; Khorshid, K.; Radwan, A. Local Architectural Freeform: Between Theory and Practice. *J. Al-Azhar Univ. Eng. Sect.* **2024**, *19*, 426–447.
13. Ilgın, H.E.; Aslantamer, Ö.N. Investigating Space Utilization in Skyscrapers Designed with Prismatic Form. *Buildings* **2024**, *14*, 1295.
14. Ilgın, H.E. Space Efficiency in Tapered Super-Tall Towers. *Buildings* **2023**, *13*, 2819.
15. Ilgın, H.E. Efficiency of Space Utilization in Supertall Towers with Free Forms. In *The Costs of Climate Change Mitigation Innovations: A Pragmatic Outlook*; Ting, D.S.-K., Stagner, J.A., Eds.; CRC Press Taylor & Francis Group: Boca Raton, FL, USA, 2024; ISBN 9781032516813.
16. Ilgın, H.E. Space efficiency in contemporary supertall residential buildings. *Architecture* **2021**, *1*, 25–37.
17. Ilgın, H.E. Space efficiency in contemporary supertall office buildings. *J. Archit. Eng.* **2021**, *27*, 4021024.
18. Aslantamer, Ö.N.; Ilgın, H.E. Space Efficiency in Tall Hotel Towers. *Buildings* **2024**, *14*, 2051.
19. Ilgın, H.E. A study on space efficiency in contemporary supertall mixed-use buildings. *J. Build. Eng.* **2023**, *69*, 106223.
20. Okbaz, F.T.; Sev, A. A model for determining the space efficiency in non-orthogonal high rise office buildings. *J. Fac. Eng. Archit. Gazi Univ.* **2023**, *38*, 113–125.
21. Ibrahimy, R.; Mohmmand, M.A.; Elham, F.A. An Evaluation of Space Use Efficiency in Residential Houses, Kabul City. *J. Res. Appl. Sci. Biotechnol.* **2023**, *2*, 1–6.
22. Goessler, T.; Kaluarachchi, Y. Smart Adaptive Homes and Their Potential to Improve Space Efficiency and Personalisation. *Buildings* **2023**, *13*, 1132.
23. Hamid, G.M.; Elsawi, M.; Yusra, O. The Impacts of Spatial Parameters on Space Efficiency in Hybrid Villa-Apartments in Greater Khartoum, Sudan. *J. Archit. Plan.* **2022**, *34*, 425–440.
24. Suga, R. Space Efficiency in Hotel Development. Master's Thesis, Business Administration with a Specialization in Real Estate Management and Development, MODUL University Vienna, Vienna, Austria, 2021.
25. Arslan Kılınç, G. Improving a Model for Determining Space Efficiency of Tall Office Buildings. Ph.D. Thesis, Department of Architecture, Mimar Sinan Fine Art University, Istanbul, Turkey, 2019. (In Turkish)
26. Von Both, P. A stakeholder-and function-based planning method for space-efficient buildings. *IOP Conf. Ser. Earth Environ. Sci.* **2019**, *323*, 012040.
27. Höjer, M.; Mjörnell, K. Measures and steps for more efficient use of buildings. *Sustainability* **2018**, *10*, 1949.
28. Nam, H.J.; Shim, J.H. An analysis of the change in space efficiency based on various tall building corner shapes and lease spans. *J. Archit. Inst. Korea Plan. Des.* **2016**, *32*, 13–20.
29. Zhang, L.; Zhang, L.; Wang, Y. Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China. *Sol. Energy* **2016**, *132*, 38–50.
30. Sev, A.; Özgen, A. Space efficiency in high-rise office buildings. *METU J. Fac. Archit.* **2009**, *26*, 69–89.
31. Saari, A.; Tissari, T.; Valkama, E.; Seppänen, O. The effect of a Redesigned Floor Plan, Occupant Density and the Quality of Indoor Climate on the Cost of Space, Productivity and Sick Leave in an Office Building—A Case Study. *Build. Environ.* **2006**, *41*, 1961–1972.
32. Kim, H.; Elnimeiri, M. Space efficiency in multi-use tall building. In Proceedings of the Tall Buildings in Historical Cities-Culture and Technology for Sustainable Cities, Seoul, Republic of Korea, 10–13 October 2004.
33. Parekh, R. Automating the design process for smart building technologies. *World J. Adv. Res. Rev.* **2024**, *23*, 1213–1234.
34. Apanavičienė, R.; Shahrabani, M.M.N. Key factors affecting smart building integration into smart city: Technological aspects. *Smart Cities* **2023**, *6*, 1832–1857.
35. Zhang, F.; Chan, A.P.; Li, D. Developing smart buildings to reduce indoor risks for safety and health of the elderly: A systematic and bibliometric analysis. *Saf. Sci.* **2023**, *168*, 106310.
36. Selvaraj, R.; Kuthadi, V.M.; Baskar, S. Smart building energy management and monitoring system based on artificial intelligence in smart city. *Sustain. Energy Technol. Assess.* **2023**, *56*, 103090.
37. Goyal, S.; Ingley, H.A.; Barooah, P. Occupancy-based zone-climate control for energy-efficient buildings: Complexity vs. Performance. *Appl. Energy* **2013**, *106*, 209–221.
38. Sharma, V.; Mistry, V. Human-centric HVAC control: Balancing comfort and energy efficiency. *Eur. J. Adv. Eng. Technol.* **2023**, *10*, 42–48.

39. Barone, G.; Buonomano, A.; Forzano, C.; Giuzio, G.; Palombo, A.; Russo, G. A new thermal comfort model based on physiological parameters for the smart design and control of energy-efficient HVAC systems. *Renew. Sustain. Energy Rev.* **2023**, *173*, 113015.
40. Ibarra, A.M.; González-Vidal, A.; Skarmeta, A. PLEIAData: Consumption, HVAC, temperature, weather and motion sensor data for smart buildings applications. *Sci. Data* **2023**, *10*, 118.
41. Taneja, J.; Krioukov, A.; Dawson-Haggerty, S.; Culler, D. Enabling Advanced Environmental Conditioning with a Building Application Stack. In Proceedings of the 2013 International Green Computing Conference (IGCC), Arlington, VA, USA, 27–29 June 2013; pp. 1–10.
42. Fierro, G.; Culler, D.E. Xbos: An Extensible Building Operating System. In Proceedings of the 2nd ACM International Conference on Embedded Systems for Energy-Efficient Built Environments, Seoul, Republic of Korea, 4–5 November 2015; pp. 119–120.
43. Opoku, A.; Ahmed, V.; Akotia, J. Research Methodology in the Built Environment: A Selection of Case Studies, 2nd ed.; Ahmed, V., Opoku, A., Aziz, Z., Eds.; Routledge: London, UK, 2016; pp. 29–32.
44. Noor KB, M. Case study: A strategic research methodology. *Am. J. Appl. Sci.* **2008**, *5*, 1602–1604.
45. CTBUH Council on Tall Buildings and Urban Habitat. Illinois Institute of Technology, S.R. Crown Hall, 3360 South State Street, Chicago, Illinois, USA. Available online: www.ctbuh.org (accessed on 18 October 2024).
46. Trabucco, D. An analysis of the relationship between service cores and the embodied/running energy of tall buildings. *Struct. Des. Tall Spec. Build* **2008**, *17*, 941–952.
47. Ali, M.M.; Armstrong, P.J. *Architecture of Tall Buildings*; Council on Tall Buildings and Urban Habitat Committee 30; McGraw-Hill: New York, NY, USA, 1995.
48. Tugrul Okbaz, F. Evaluation of space efficiency criteria in high-rise buildings based on functions: A case study of Türkiye. *Archit. Eng. Des. Manag.* **2024**, 1–18. https://doi.org/10.1080/17452007.2024.2404115.
49. Filaj, E.; Deneko, E.; Moezzi, R.; Gheibi, M.; Annuk, A. Ensuring Structural Integrity: An Evaluation of Vertical Shortening in Tall Concrete Buildings. *CivilEng* **2024**, *5*, 191–208.
50. Salmassi, M.A.; Kheyroddin, A.; Hemmati, A. Enhancement of the performance of two tall buildings with end shear walls using nonlinear time history analysis: A case study. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2024**, *48*, 2019–2029.
51. Ujwal, M.S.; Kumar, G.S.; Sathvik, S.; Ramaraju, H.K. Effect of soft story conditions on the seismic performance of tall concrete structures. *Asian J. Civ. Eng.* **2024**, *25*, 3141–3149.
52. Paksoy, A.; Aydogdu, I.; Akin, A. Cost optimization of tall buildings having tube composite columns using social spider algorithm. *Struct. Des. Tall Spec. Build.* **2024**, *33*, e2122.
53. Qing, Z.Q.; Na, Z.L. A comparative analysis of RCC and composite buildings using the new plastic deformation (PD) method. *Sci. Rep.* **2024**, *14*, 5666.
54. Patel, P.; Patel, M. Analysis and Design of Conjoined Tall buildings. *Nirma Univ. J. Eng. Technol.* **2024**, *1*, 1–7.
55. Fallahi, H.; Rahgozar, R.; Sharifi, Y. Optimum Location for Outrigger and Belt Truss System in Tall Buildings with Step-Jump in Shear Core Using Energy Method. *Iran. J. Sci. Technol. Trans. Civ. Eng.* **2024**, 1–10. https://doi.org/10.1007/s40996-024-01471-0.
56. Shan, W.; Lin, X.; Zhou, X.; Dong, B. Influence of outrigger truss system on the seismic fragility of super high-rise braced mega frame-core tube structure. *J. Build. Eng.* **2023**, *76*, 107015.
57. Xing, L.; Gardoni, P.; Zhou, Y.; Zhang, P. DNN-metamodeling and fragility estimate of high-rise buildings with outrigger systems subject to seismic loads. *Reliab. Eng. Syst. Saf.* **2024**, *253*, 110572.