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A comparative analysis of space efficiency in skyscrapers: Case studies from the Middle East, Asia, and North America

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Abstract

This study conducts a critical comparative analysis of spatial efficiency in supertall buildings across three major geographic contexts: the Middle East, Asia, and North America. Through the examination of selected case studies representative of each region, the research investigates the interplay between architectural form, structural typology, and the distribution of usable floor area within vertical structures. The findings reveal significant regional variations in spatial efficiency metrics and core-to-GFA (gross floor area) proportions. In the Asian context, towers predominantly adopt a tapered morphological strategy combined with composite structural systems, resulting in an average spatial efficiency of approximately 68%, with vertical service cores occupying nearly 30% of the GFA. Conversely, Middle Eastern high-rises, typically defined by prismatic massing and monolithic concrete structures, demonstrate a higher spatial efficiency—averaging 76%—with a core-to-GFA ratio of around 21%. North American skyscrapers, frequently employing prismatic or setback configurations alongside reinforced concrete systems, exhibit comparable efficiency rates, with an average of 76% and a similarly proportioned core area. Despite these regional divergences, the analysis identifies a consistent inverse correlation between building height and spatial efficiency, underscoring the technical and spatial challenges associated with height-induced inefficiencies in high-rise design. By elucidating these interregional patterns, the study offers valuable insights into the optimization of vertical spatial organization, contributing to the evolving discourse on high-rise architecture and urban densification.

Keywords: space efficiency, comparison, Middle East, Asia, North America, skyscraper

1. Introduction

The modern urban landscape is increasingly defined by the presence of supertall skyscrapers—architectural feats that stand as testaments to human ingenuity, economic ambition, and technological progress (Radović, 2020). These structures, often exceeding 300 meters in height, have become central to the identity of major cities across the globe, symbolizing their status as hubs of global finance, culture, and innovation (Pitroda & Singh, 2016). However, the creation of such towering edifices is not without its challenges (Szołomicki & Golasz-Szołomicka, 2021). Among the most critical of these is the need to optimize space efficiency—a factor that plays a crucial role in determining the economic viability, functional utility, and environmental sustainability of these buildings (Saroglou et al., 2023).

Space efficiency, defined as the ratio of net floor area (NFA) to gross floor area (GFA), is a key metric in the design and operation of skyscrapers (Aslantamer & Ilgın, 2024a). High space efficiency indicates that a larger proportion of the building's total area is available for occupancy or use, which is essential for maximizing the economic returns on investment, particularly in urban environments where land costs are exorbitant. In the context of skyscrapers, achieving high space efficiency is a complex task that involves balancing the demands of structural integrity, safety, and aesthetic appeal with the need to provide functional and economically productive spaces.

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The pursuit of space efficiency in skyscraper design is influenced by a myriad of factors, including regional architectural traditions, local building codes, economic conditions, and environmental challenges. Each region where skyscrapers are built presents its own set of conditions and constraints that shape the approach to space efficiency. This paper focuses on three key regions: the Middle East (Ilgın, 2024), Asia (Ilgın, 2023b), and North America (Aslantamer & Ilgın, 2024b), each of which has emerged as a leader in skyscraper construction but with distinct approaches to addressing the challenges of space efficiency.

Examining these regions comparatively in the context of skyscraper space efficiency is significant because it allows for a nuanced understanding of how diverse environmental, cultural, and economic conditions shape architectural and engineering practices in different parts of the world. Each of these regions presents unique challenges and opportunities in skyscraper design. For instance, Asia's rapid urbanization and high population density necessitate innovative solutions to maximize space efficiency in extremely tall buildings, often within seismic zones, which imposes additional structural demands (Ilgın, 2023b). In contrast, North America, with its established history of skyscraper construction, operates under mature regulatory frameworks that balance safety, functionality, and economic return, leading to different prioritization in design strategies, such as the optimization of core configurations and the use of advanced materials (Aslantamer & Ilgın, 2024a). Meanwhile, the Middle East's architectural landscape is heavily influenced by harsh climatic conditions and a strong cultural emphasis on iconic design, requiring buildings to integrate sophisticated climate control systems and culturally significant features, which impact space efficiency in distinct ways (Ilgın, 2024).

By comparing these regions, we can uncover the interplay between local conditions and global architectural trends, identifying how regional contexts influence the adoption of certain structural systems, building forms, and space utilization strategies. This comparative analysis not only highlights regional innovations and adaptations but also reveals the potential for cross-regional application of best practices, offering insights into how strategies successful in one context might be adapted for use in another. Additionally, understanding these regional differences and commonalities provides a broader framework for addressing global challenges in skyscraper design, such as sustainability and resilience, by fostering a more holistic approach to the optimization of space efficiency. In essence, this comparative study enables a deeper comprehension of the complex dynamics that drive skyscraper design, offering valuable lessons for improving the functionality, sustainability, and economic viability of tall buildings worldwide.

In the Middle East, the rise of skyscrapers is often driven by a combination of factors, including economic diversification, cultural symbolism, and environmental adaptation (Botti, 2023). Cities like Dubai, Abu Dhabi, and Riyadh have become synonymous with ambitious architectural projects that not only push the boundaries of height but also incorporate elements of cultural significance and environmental sustainability. However, achieving space efficiency in this region presents unique challenges. The harsh climatic conditions, characterized by extreme heat and humidity, necessitate the integration of extensive climate control systems, which can reduce the amount of usable space. Additionally, the cultural and symbolic importance of these buildings often leads to design choices that prioritize aesthetic and cultural expression over pure space efficiency (Al-Kodmany, 2024).

In Asia, particularly in rapidly developing cities like Shanghai, Hong Kong, and Shenzhen, the demand for space has driven the construction of some of the tallest buildings in the world (Chaudhary, 2024). The rapid urbanization and economic expansion in these cities have necessitated vertical growth, making skyscrapers an essential solution to the challenge of accommodating large urban populations and commercial activities within limited land areas. However, the push for greater heights in these buildings has often resulted in compromises in space efficiency. The need for robust structural systems to withstand seismic activity and high wind loads, common in these regions, often leads to larger service cores and more complex building forms, which can reduce the usable floor area.

North America, with its longstanding history of skyscraper construction, particularly in cities like New York, Chicago, and Toronto, presents a contrasting approach to space efficiency (Barr & Jedwab, 2023). The skyscrapers in this region have historically been designed with a strong focus on balancing the maximization of usable space with the need to comply with stringent building codes and safety regulations. The evolution of structural systems in North America, such as the development of the tube structure and the use of offset cores, has allowed for the construction of tall buildings that maintain high levels of space efficiency. Additionally, the economic context of North American cities, where the return on investment is closely tied to the amount of leasable space, has driven innovations in building design that prioritize space efficiency.

This paper endeavors to provide a comprehensive exploration of regional variations in space efficiency through a detailed comparative analysis of iconic skyscrapers across the Middle East, Asia, and North America. By systematically examining the architectural designs, structural innovations, and engineering methodologies employed in these buildings, the study seeks to uncover the critical determinants of space efficiency. Furthermore, it aims to elucidate how these determinants are influenced by and adapted to the distinct cultural, economic, and environmental contexts of each region, thereby offering a nuanced understanding of the global diversity in skyscraper design and its implications for sustainable urban development.

The findings of this study are anticipated to offer crucial insights for architects, engineers, urban planners, and policymakers engaged in the design and development of skyscrapers. As urbanization accelerates globally, the demand for efficient and sustainable tall buildings is becoming increasingly urgent (Höjer & Mjörnell, 2018). By dissecting the factors that contribute to space efficiency within various regional contexts, this research aspires to inform and influence the future of skyscraper design. It aims to ensure that these towering structures not only fulfill their functional roles effectively but also continue to symbolize and drive urban progress in a manner that is environmentally responsible and contextually adaptable.

2. Literature Review

In the realm of architectural design, particularly concerning the optimization of interior spatial efficiency, a growing body of literature has investigated a variety of parameters and building typologies across diverse geographic and structural contexts. Tuure and Ilgın (2023) carried out a comprehensive evaluation of timber apartment buildings in Finland, identifying spatial efficiency rates ranging between 78% and 88%. These findings highlight the considerable potential of timber construction in achieving high levels of usable area efficiency, especially within mid-rise residential typologies.

On a broader scale, Ilgın (2021a, 2023a, 2023b, 2024) and Aslantamer and Ilgın (2024a) conducted empirical studies on supertall towers serving residential, commercial, hotel, and mixed-use functions. These investigations consistently point to the frequent application of outrigger systems and centrally positioned service cores as characteristic features, revealing a recurring relationship between increased verticality and the necessity for efficient spatial organization within the structural framework.

Exploring non-standardized building forms, Sev and Özgen (2009) analyzed spatial performance in unconventional office towers. Their research emphasized that architectural form—particularly conical geometries—can significantly enhance spatial efficiency, thereby underlining the critical impact of form-driven design strategies on internal space optimization. Similarly, Ibrahimy et al. (2023) examined residential projects in Kabul, where deviations from planning regulations and insufficient architectural oversight were found to contribute to notable inefficiencies in space utilization. This underscores the regulatory dimension of spatial performance and the importance of design governance in urban residential developments.

The role of emerging technologies in reshaping spatial efficiency paradigms is addressed by Goessler and Kaluarachchi (2023), who explored innovations in high-density urban housing solutions. Their study suggests that such technologies have the capacity to improve spatial efficiency by two to threefold when compared with conventional design practices, signaling a paradigm shift in the way space is conceived and managed in urban architecture. In a different yet related context, Hamid et al. (2022) demonstrated that strategic building placement—specifically positioning structures at corner plots—can significantly enhance land-use efficiency in Sudanese residential layouts, emphasizing the importance of site-responsive planning and context-sensitive design interventions.

Suga (2021) examined spatial utilization strategies within hotel architecture, emphasizing the operational advantages derived from effective space management in hospitality environments. In a structural context, Arslan Kılınç (2019) analyzed key determinants influencing the design of load-bearing systems in prismatic high-rise structures, offering valuable insights into how structural configuration affects usable space. Adopting a user-centered perspective, Von Both (2019) advocated for participatory design methodologies, emphasizing stakeholder collaboration during early design phases as a means to optimize spatial outcomes.

Concurrently, Höjer and Mjörnell (2018) explored the role of digital technologies in shaping interior spatial configurations, underlining the increasing relevance of digital integration in contemporary architectural practice. Addressing specific design variables, Nam and Shim (2016) evaluated the impact of corner articulation and lease span on spatial efficiency, concluding that while modifications to corner geometry had a limited effect, lease span played a more significant role in determining functional space allocation. In a related yet sustainability-oriented study, Zhang et al. (2016) proposed a computational model aimed at maximizing solar gain in cold climates, demonstrating the interdependence between environmental performance and spatial optimization.

Sev and Özgen (2009) contributed to the discourse by assessing spatial performance in office towers, particularly focusing on the influence of structural strategies and core placement in achieving efficient layouts. Saari et al. (2006) linked spatial optimization to project economics, demonstrating that higher space efficiency can directly reduce development costs in commercial high-rise projects. Similarly, Kim and Elnimeiri (2004) investigated spatial efficiency ratios in multifunctional skyscrapers, stressing the importance of structurally efficient systems and well-calibrated spatial layouts. Taken together, these studies reflect the multifaceted nature of spatial efficiency in architectural design, shaped by factors including formal innovation, digital tools, regulatory frameworks, and structural decision-making.

Despite this growing body of research, a notable gap persists in comparative analyses of spatial efficiency across skyscrapers situated in different global contexts. In response to this shortcoming, the present study aims to synthesize and critically assess data from 133 built case studies, focusing on the architectural and structural variables that inform spatial efficiency. Through this comprehensive evaluation, the research seeks to identify recurring patterns and generate insights that contribute to a deeper understanding of space utilization in the vertical architecture of the contemporary urban landscape.

3. Research Method

To collect and organize data from 133 skyscrapers, as shown in Figure 1, a case study methodology was employed. This method is widely used in research to gather both qualitative and quantitative data and to conduct extensive literature reviews (Opoku et al., 2016; Noor, 2008). It allows for a detailed examination of the architectural and structural elements of these projects, enabling a comprehensive investigation of real-world examples. Through this approach, each case can be thoroughly analyzed, providing valuable insights into the distinctive design features and structural characteristics of each tower. By focusing on specific cases, researchers can identify similarities and differences in contemporary skyscraper designs, uncovering new trends and patterns. This method's adaptability allows for the incorporation of a range of data sources, such as architectural drawings and other relevant documents, to achieve a complete understanding.

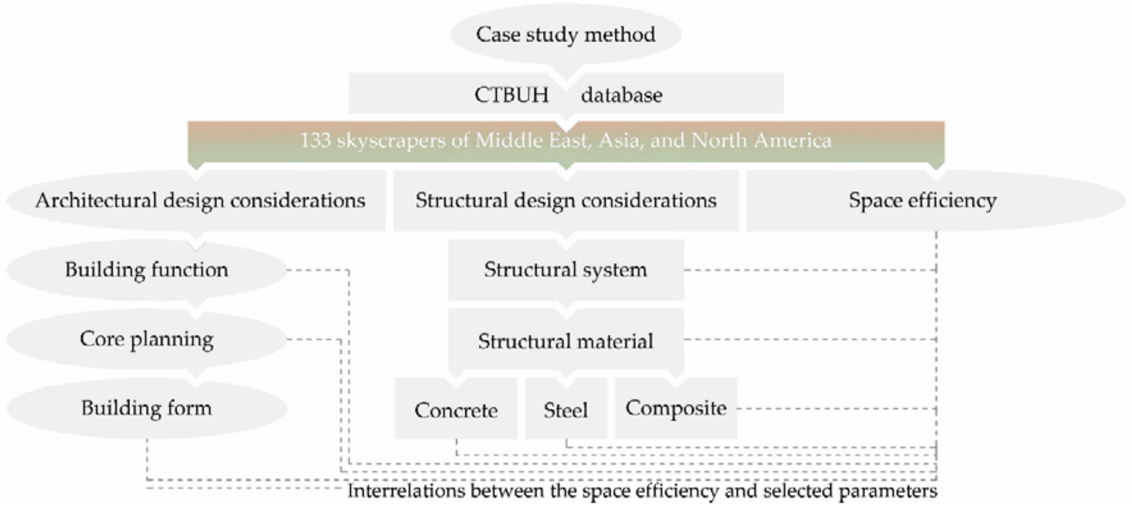


Figure 1 Research method (By authors)

This study draws upon a dataset of 133 skyscrapers sourced from the authoritative Council on Tall Buildings and Urban Habitat (CTBUH) database (CTBUH, 2024), which served as the primary reference for identifying representative high-rise buildings situated across various urban centers in North America and beyond. CTBUH, a globally recognized non-profit institution, plays a critical role in advancing knowledge on vertical urbanism and promoting sustainable and resilient urban development in response to accelerating urbanization and the impacts of climate change. The organization is internationally acknowledged for establishing classification criteria for tall buildings and bestowing honors such as "The World's Tallest Building" and "Buildings of Distinction," thereby shaping global discourse on architectural excellence.

In alignment with CTBUH standards, this research adopts the designation "supertall" for buildings exceeding 300 meters in height, emphasizing the complex design and engineering competencies required for such vertical structures. The selection process for case studies was conducted with methodological rigor to ensure a balanced and meaningful representation of skyscrapers with varied programmatic functions and regional contexts. While access and data availability posed certain geographical constraints, the final sample was strategically curated to enable a comprehensive evaluation of spatial efficiency patterns and design typologies across different high-rise environments.

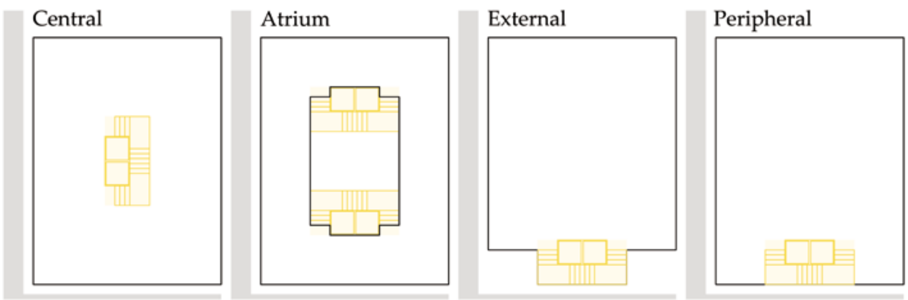
The dataset encompasses a geographically diverse distribution of supertall buildings: 57 located in China, 26 in the United States, 21 in the United Arab Emirates, 5 each from Malaysia and South Korea, 3 each from Saudi Arabia and Canada, 2 each from Mexico, Kuwait, Mumbai, and Vietnam, and one building each from Qatar, India, Japan, Taiwan, and Indonesia. This global sampling—illustrated in Figure 2—provides a robust foundation for cross-regional comparative analysis, facilitating a deeper understanding of contemporary skyscraper morphology and the spatial strategies employed in diverse urban settings.

Figure 2 Case studies on the world map (By authors)

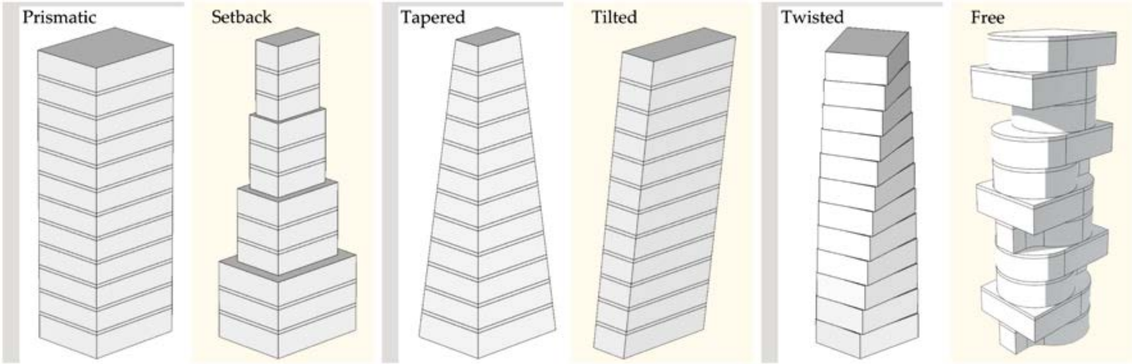
The design of skyscrapers is governed by a dynamic interplay between architectural intent and structural imperatives, with key determinants including core configuration, building function and morphology, as well as the selection of structural systems and materials. From an architectural standpoint, this study adopts the core typology framework proposed by Aslantamer and Ilgın (2024a), which delineates four principal categories of core arrangements (see Figure 3a). In parallel, building massing is classified into a range of formal typologies (see Figure 3b), reflecting diverse design strategies across supertall typologies.

The selection of an appropriate structural system plays a pivotal role in optimizing spatial efficiency within high-rise architecture, as it directly influences the spatial distribution and scale of load-bearing elements. This research draws on the structural classification model articulated by Ilgın (2023a) for the categorization of skyscraper systems (see Figure 3c). Equally critical is the choice of structural material—whether steel, concrete, or hybrid composite systems—which significantly shapes the dimensional properties and spatial layout of structural components, thereby impacting the efficiency of usable floor area.

In the context of this study, the term "composite" refers specifically to skyscrapers employing a hybrid configuration of vertical structural elements, such as shear walls and columns, constructed from steel, concrete, or an integrated combination of both. This material strategy is particularly relevant in addressing both load-bearing requirements and spatial performance within supertall buildings.



(a)



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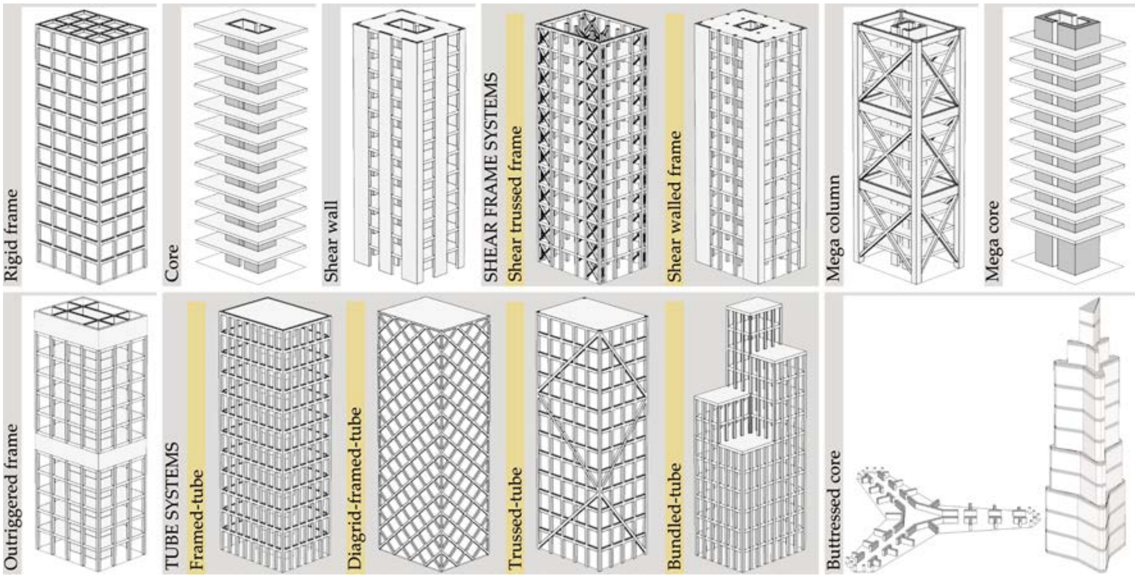

(c)

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

4. Results

4.1. Main Design Parameters

Across the different regions examined, the choice of building function and core typology emerges as a crucial factor in the design of supertall towers. In Asian skyscrapers, there is a strong preference for a central core typology, particularly in mixed-use and office buildings. This typology is favored due to its compact nature, which contributes significantly to structural integrity and provides efficient pathways for fire evacuation and other emergency services (Ilgın, 2023b).

In North America, similar trends are observed. Central core design is predominant in high-rise office and residential buildings, reflecting a preference for structural efficiency and safety. The core houses vital services, including elevators, stairwells, and mechanical systems, which are central to the functionality of the building (Aslantamer & Ilgın, 2024b). This centralized approach helps in reducing the overall footprint of service areas, thereby enhancing usable space.

In contrast, while the Middle Eastern towers also predominantly use central cores, there is a notable trend toward innovative core designs that accommodate the unique aesthetic and functional demands of the region. These include more fluid and adaptable core structures that allow for varied floor plate configurations, catering to a mix of residential, commercial, and hospitality uses within the same tower (Botti, 2023; Al-Kodmany, 2024).

The form of supertall towers is greatly influenced by regional environmental conditions, cultural preferences, and technological advancements. In Asia, a considerable number of skyscrapers adopt tapered forms, which are particularly advantageous in regions where wind loads significantly impact structural design. The tapered form reduces the wind load by decreasing the exposed surface area at higher elevations, thereby enhancing stability and reducing structural material costs. This aerodynamic consideration is crucial in cities like Hong Kong and Shanghai, where high wind speeds can be a major concern (Chaudhary, 2024).

In North America, the architectural design of supertall towers tends to favor more traditional forms such as setback, prismatic, and cylindrical shapes. These forms are not only aesthetically pleasing but also functionally versatile, allowing for a variety of uses from residential to commercial. Setback design, in particular, is employed to reduce wind forces acting on the building and to create a visually appealing step-like appearance that integrates well with the urban skyline (Barr & Jedwab, 2023).

The Middle East, characterized by its unique blend of modernity and tradition, often showcases innovative and bold building forms. Freeform designs and prismatic shapes are particularly popular, reflecting the region's penchant for iconic and symbolic architecture. These forms are often employed to create landmark buildings that stand out in the skyline, serving as cultural and economic symbols (Al-Kodmany, 2024; Botti, 2023). (See Table 1 for a comparative summary of architectural design parameters across the studied regions).

Table 1 Comparison of Architectural Design Parameters

Findings	Middle East	Asia	North America
Function	**Residential (45%)** Office (22%) Mixed-use (33%)	Residential (5%) Office (38%) **Mixed-use (57%)**	Residential (23%) Office (29%) **Mixed-use (48%)**
Core type	**Central (96%)** External (4%)	**Central (99%)** External (1%)	**Central (90%)** Peripheral (10%)
Form	**Prismatic (45%)** Setback (7%) Tapered (7%) Twisted (4%) Free (37%)	Prismatic (23%) Setback (13%) **Tapered (36%)** Twisted (1%) Free (27%)	Prismatic (26%) **Setback (29%)** Tapered (26%) Free (19%)

The choice of structural system in supertall towers is a critical decision that influences both the building's stability and space efficiency. In Asia, the most common structural system is the outriggered frame system, utilized in over 75% of the cases analyzed. This system involves the use of outrigger trusses that connect the building's core to the outer columns, effectively distributing lateral loads caused by wind or seismic activity across the building's framework. The outriggered frame system provides a high degree of stability and allows for a more flexible placement of outer columns, which is particularly beneficial in maximizing the usable floor space (Ilgın, 2023b).

North American skyscrapers also frequently employ outrigger systems, along with tube systems and mega-columns, depending on the specific requirements of the building. The tube system, for example, forms a rigid structural "tube" by connecting closely spaced perimeter columns with spandrel beams. This configuration is particularly effective in resisting lateral forces, making it ideal for tall buildings in earthquake-prone areas or regions with high wind loads (Ilgın, 2023b; Barr & Jedwab, 2023).

In the Middle East, the structural systems of choice include reinforced concrete cores combined with outrigger frames or diagrids. The use of concrete provides excellent fire resistance and thermal mass, which is advantageous in the region's hot climate. Additionally, the diagrid system, which uses a network of diagonally intersecting beams, allows for greater flexibility in the building's facade design, facilitating the creation of the region's distinctive, iconic tower shapes (Botti, 2023; Al-Kodmany, 2024).

The materials used in the construction of supertall towers play a pivotal role in determining both the structural integrity and space efficiency of the building. In Asia, composite materials—combinations of steel and concrete—are predominant. The steel provides high tensile strength, while the concrete offers compressive strength and fire resistance, creating a robust framework that can withstand the high stresses associated with supertall structures. This combination also allows for thinner floor slabs and reduced column sizes, enhancing the overall space efficiency (Ilgın, 2023b).

North American skyscrapers exhibit a diverse use of materials, including pure steel, reinforced concrete, and composite materials. The choice of material often depends on the building's location, function, and height. Steel is favored for its high strength-to-weight ratio and ease of construction, while reinforced concrete is preferred for its durability and fire resistance. Composite materials are increasingly being used for their ability to provide the benefits of both steel and concrete, optimizing both strength and space (Ilgın, 2021a).

In the Middle East, reinforced concrete remains the material of choice for most supertall towers. This preference is driven by the material's thermal mass, which helps in maintaining stable indoor temperatures in the region's hot climate. Additionally, concrete's fire-resistant properties are critical for ensuring safety in high-rise buildings. Some towers also incorporate steel into their designs to enhance structural flexibility and reduce overall weight, particularly in taller structures where these attributes are essential (Aslantamer & Ilgın, 2024b; Sev & Özgen, 2009) (See Table 2 for a regional comparison of structural systems and material preferences).

Table 2 Comparison of Structural Design Parameters

Findings	Middle East	Asia	North America
Material	**Concrete (70%)** Composite (30%)	Concrete (18%) **Composite (79%)** Steel (3%)	**Concrete (55%)** Composite (39%) Steel (6%)
System	**Outriggered frame (44%)** Tube (26%) Mega column & core (15%) Shear-frame (11%) Buttressed core (4%)	**Outriggered frame (76%)** Tube (17%) Buttressed core (3%) Mega column & core (3%) Shear-frame (1%)	**Outriggered frame (42%)** Tube (16%) Mega column & core (3%) Shear-frame (39%)

4.2. Space Efficiency in Towers in Different Locations

Average space efficiencies of Middle Eastern, Asian, North American towers were 75.5%, 67.5%, and 76%, respectively, whereas core area to GFA ratio were 21.3%, 29.5%, and 21%, respectively. Values fluctuated from the lowest of 55% and 11% to the highest of 84% and 38%, respectively. Table 3 shows the findings on average space efficiency and ratio of core to GFA with those of Middle Eastern, Asian, North American towers.

Table 3 Comparison of Space Efficiency and Ratio of Core to GFA

Findings	Middle East	Asia	North America
Space efficiency	75.5% (max. 84%, min. 63%)	67.5% (max. 82%, min. 55%)	76% (max. 84%, min. 62%)
Core to GFA	21.3% (max. 36%, min. 11%)	29.5% (max. 38%, min. 14%)	21% (max. 31%, min. 13%)

The space efficiency of tall buildings in the Middle East, Asia, and North America varies significantly due to a combination of structural systems, building forms, material choices, and regional environmental, economic, and cultural factors. In Asia, supertall towers often employ outriggered frame systems and composite materials. These systems provide the necessary lateral stability to withstand seismic activities and high winds, which are common in many parts of the region. However, the need for robust structural elements, such as large cores and additional supports, reduces the usable floor area, thereby impacting space efficiency. Additionally, the high density of urban development in Asian cities necessitates mixed-use skyscrapers that combine residential, office, and commercial spaces within a single building. This mix of functions requires diverse floor plans and service core arrangements, which can further limit the efficiency of space use. As a result, the average space efficiency in Asian skyscrapers tends to be lower, around 67.5%, as designers balance the need for structural integrity and functionality with the challenges of optimizing usable space.

In North America, tall buildings typically achieve higher space efficiency, averaging around 76%, due to different architectural and structural design approaches. The prevalent use of tube systems, outrigger systems, and mega-columns allows for maximizing interior space while ensuring the building's stability. The tube system, for instance, forms a rigid structural "tube" around the building's perimeter, which efficiently resists lateral forces such as wind and seismic loads. This design strategy minimizes the need for internal structural elements, allowing for more open and flexible floor plans. Moreover, North American skyscrapers often utilize regular, prismatic, and setback forms that are conducive to efficient space planning. These shapes reduce wind loads and create uniform floor plates, facilitating higher space efficiency. The strategic use of high-strength materials like steel and concrete further enhances the ability to optimize floor space, as these materials allow for thinner walls and smaller columns without compromising structural integrity.

In contrast, the architectural and structural design of tall buildings in the Middle East is often driven by a desire to create iconic landmarks that reflect cultural values and economic ambition. As a result, space efficiency may be lower due to the emphasis on unique and often complex building forms, such as freeform and prismatic designs. These forms are chosen not only for their aesthetic appeal but also for their ability to make bold architectural statements in the skyline. However, these designs typically involve irregular floor plates and require additional structural supports to maintain stability, which can significantly reduce usable space. Additionally, the Middle East's harsh climate necessitates the use of reinforced concrete for its excellent thermal mass and fire resistance. While effective for creating comfortable indoor environments and ensuring safety, reinforced concrete often results in thicker walls and larger columns, which occupy more floor space. Consequently, the average space efficiency in Middle Eastern skyscrapers is often lower compared to North American counterparts, as designers prioritize aesthetics and cultural symbolism over maximizing usable space.

Overall, the differences in space efficiency among tall buildings in Asia, North America, and the Middle East are a reflection of the diverse design philosophies and regional needs. In North America, there is a strong emphasis on maximizing return on investment through efficient use of space, leading to the adoption of regular forms and advanced structural systems that optimize both strength and space. In Asia, the rapid urbanization and high population densities drive the need for multifunctional buildings that can accommodate various uses within a single structure, often at the expense of space efficiency due to the need for robust structural systems and diverse floor layouts. Meanwhile, in the Middle East, the cultural emphasis on creating landmark buildings results in a focus on unique architectural forms and robust structural systems to handle the extreme climate, which can reduce space efficiency. Understanding these regional differences is crucial for architects and engineers as they design super-tall buildings that meet the unique environmental, economic, and cultural requirements of each area, balancing the need for efficient space use with other design priorities.

Relation of Space Efficiency and Location, Core Typology, Form, Structural Material, and System Figures 4, 5, 6, 7, 8 present a detailed analysis of empirical data, illustrating the intricate relationship between spatial efficiency and the various architectural and structural elements that influence it. In these figures, a bar chart on the right side effectively shows the total number of towers grouped by relevant classifications, offering a clear overview of data distribution. Colored dots indicate the spatial efficiency of individual towers across different regions in relation to their specific design features, creating a compelling visual representation of this complex interaction. Moreover, bars highlight the frequency of buildings within the sample that share the same design characteristics.

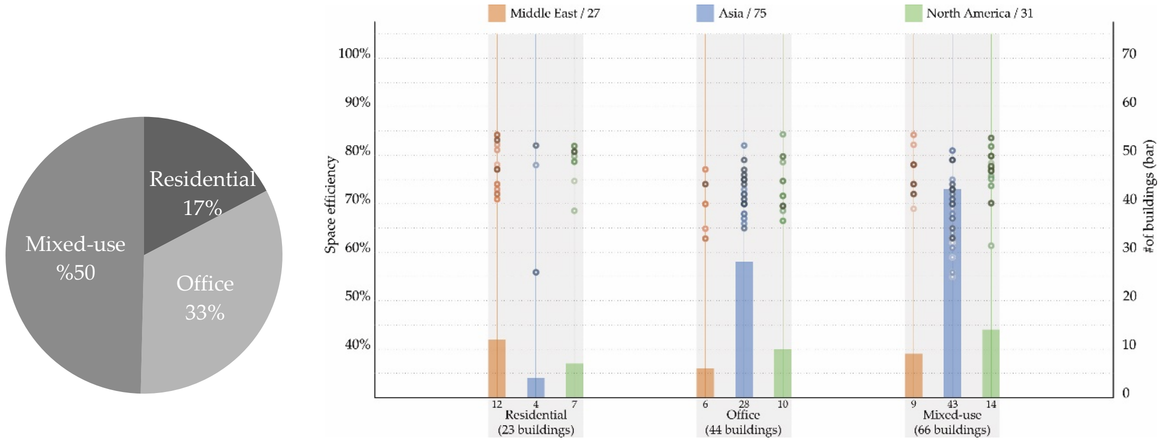

Figure 4 Different locations by function

Figure 4 presents a comparative analysis of space efficiency in skyscrapers, categorized by function across three regions. In the Middle East, residential buildings exhibit a notably high space efficiency, predominantly clustering around 70% to 80%, which suggests a design focus on maximizing usable space, potentially driven by regional standards or economic considerations. Office buildings in the Middle East dis-play a slightly lower space efficiency range, mostly between 60% and 70%, indicating some variation but generally maintaining a high standard.

In contrast, Asia shows a broader distribution of space efficiency across all building functions. Residential buildings in Asia have space efficiencies ranging from 40% to 80%, with a median around 60%, reflecting diverse architectural designs and possibly varied building codes or market demands. Asian office buildings exhibit a wide efficiency range from 40% to 80%, with a significant concentration around 50% to 60%, highlighting varied approaches to core design and space allocation. Mixed-use buildings in Asia have efficiencies ranging widely, from 50% to nearly 90%, with a dense clustering around 60% to 70%, suggesting flexibility in design strategies to accommodate multiple uses.

North American skyscrapers also show variability in space efficiency, but with less dispersion than in Asia. Residential buildings in North America have efficiencies ranging from 50% to 70%, with a significant number around 60%, indicating a balance between design flexibility and efficiency. Office buildings show a similar pattern, with efficiencies mostly between 50% and 70%, aligning closely with residential buildings. Mixed-use buildings in North America exhibit space efficiencies ranging from 50% to 80%, with a notable concentration around 60% to 70%, suggesting a common approach to multi-use space planning.

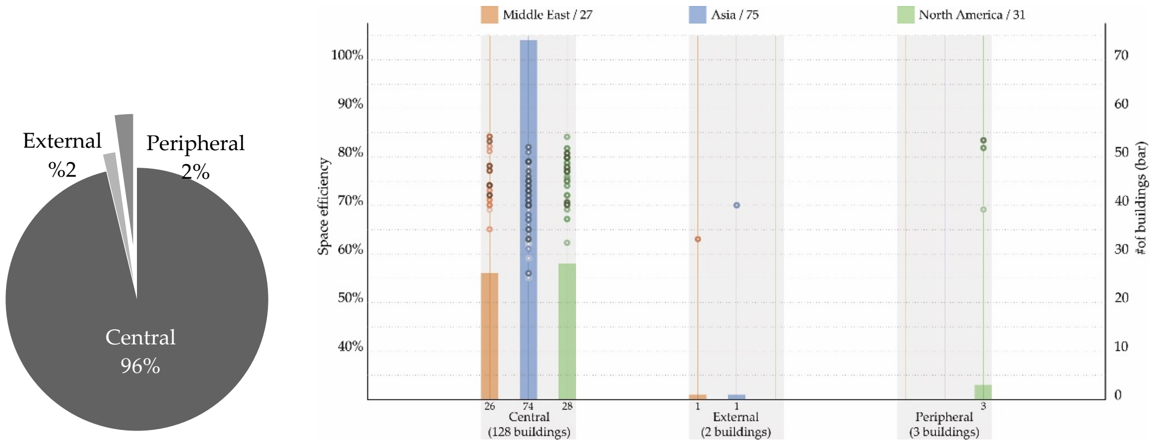

Figure 5 Different locations by core type

Figure 5 illustrates the relationship between core types and space efficiency across skyscrapers in the Middle East, Asia, and North America. The majority of the buildings in the dataset utilize a central core, with 128 buildings represented. Among these, Asian buildings exhibit a wide range of space efficiencies, from approximately 40% to 90%, with a significant clustering between 50% and 70%. This broad distribution suggests a variety of architectural approaches and core configurations, potentially influenced by diverse building regulations and market demands in Asia. In the Middle East, buildings with central cores show a more concentrated range of space efficiencies, mostly between 60% and 80%, indicating a regional preference for maximizing usable space within this core type, possibly due to stricter building codes or design practices favoring higher efficiency. North American skyscrapers with central cores demonstrate space efficiencies ranging from around 50% to 80%, with a noticeable cluster around 60% to 70%, reflecting a balanced approach to core placement and space utilization that aligns closely with both Asian and Middle Eastern practices.

Figure 5 also highlights the less common core types external and peripheral. The data for buildings with external cores is minimal, with only two buildings represented: one in the Middle East with a space efficiency of approximately 50% and one in Asia with a slightly higher efficiency around 60%. This limited data suggests that external core designs may not be widely adopted or could indicate specific architectural or functional requirements that affect their space efficiency. For buildings with peripheral cores, all three represented are located in North America, showing space efficiencies ranging from 40% to 60%. This indicates that peripheral cores may offer lower space efficiency compared to central cores, possibly due to the increased perimeter circulation space required. The concentration of peripheral core buildings in North America and their relatively lower efficiency might reflect regional architectural trends or design strategies that prioritize different aspects of building functionality over maximizing usable space.

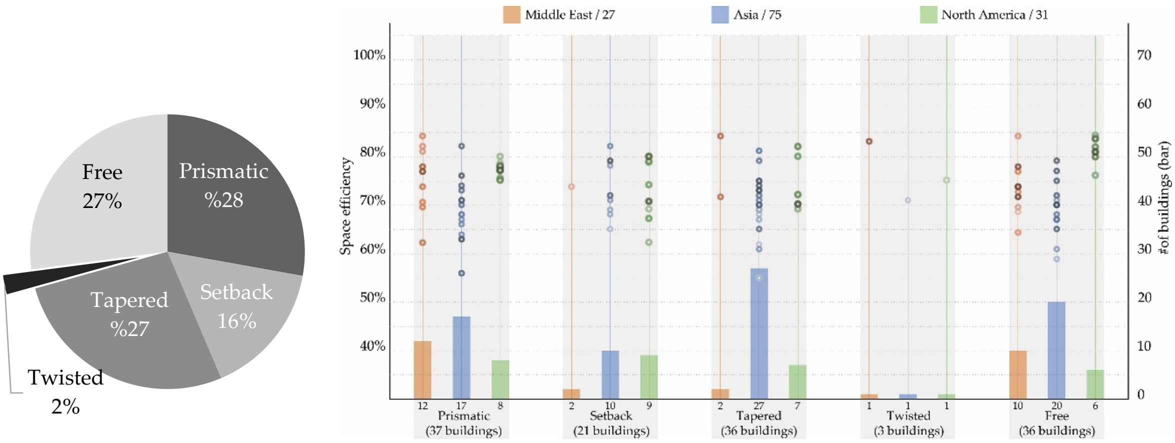

Figure 6 Different locations by form

Figure 6 provides a detailed analysis of the relationship between building forms prismatic, setback, tapered, twisted, and free and space efficiency across skyscrapers in the Middle East, Asia, and North America. Space efficiency, shown as a percentage on the y-axis, represents the ratio of usable floor area to the total floor area, serving as an indicator of how effectively space is utilized within different building forms.

Prismatic buildings, the most common form with 37 buildings represented, dis-play significant regional differences in space efficiency. In the Middle East, prismatic buildings show high space efficiency, predominantly ranging from 60% to 80%, with a notable clustering around 70% to 80%. This suggests a regional emphasis on maximizing usable space through straightforward, vertical designs. In Asia, prismatic buildings have a broader distribution, with space efficiencies ranging from 40% to 80%, but with a concentration between 50% and 70%. This variability reflects a wide range of design practices and possibly more diverse building regulations or market needs. North

American prismatic buildings exhibit efficiencies predominantly between 60% and 80%, indicating a consistent approach to balancing space utilization and building form.

Setback buildings, which are less common with only 21 examples, show regional variation in space efficiency. In the Middle East, setback buildings have a narrow efficiency range, mostly between 60% and 70%, while in Asia, the efficiencies are more varied, ranging from 40% to 70%, with a concentration around 50%. In North America, setback buildings demonstrate a broader efficiency range from 50% to 80%, indicating more flexibility or variation in design strategies that balance aesthetic considerations with functional space.

Tapered buildings, represented by 36 examples, show significant variation, especially in Asia. Asian tapered buildings have space efficiencies ranging from 40% to nearly 80%, with a substantial concentration around 50% to 60%, reflecting diverse architectural strategies and potentially different design priorities. In contrast, North American and Middle Eastern tapered buildings generally show higher space efficiencies, clustering around 60% to 80%, suggesting a more uniform approach to this form that prioritizes space utilization.

Twisted forms are the least common, with only three buildings represented across the regions. These buildings show a range of space efficiencies from around 40% to 70%, indicating that the twisted form, while architecturally distinctive, may pose challenges to achieving high space efficiency due to its complex geometry and structural requirements.

Free forms, with 36 buildings, exhibit the widest range of space efficiencies across all regions. In the Middle East, free-form buildings have efficiencies ranging from 60% to 80%, reflecting a focus on maintaining high space efficiency even with more flexible and unique designs. In Asia, the space efficiency of free-form buildings varies significantly, from 40% to 80%, indicating diverse design approaches and a wide range of architectural expressions. North American free-form buildings have space efficiencies ranging from 50% to 80%, suggesting that while this form allows for creative freedom, there is also an effort to optimize space utilization.

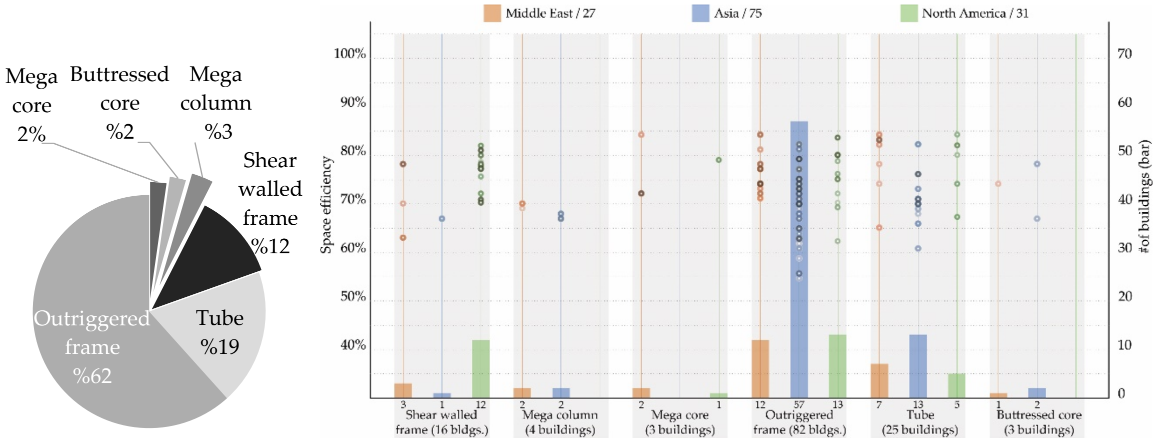

Figure 7 Different locations by system

Figure 7 provides a detailed analysis of the relationship between different structural systems and space efficiency in skyscrapers across the Middle East, Asia, and North America. Shear walled frame systems, represented by 16 buildings, show significant regional variations in space efficiency. In North America, these buildings demonstrate high space efficiency, ranging from approximately 70% to 80%, suggesting a design emphasis on maximizing usable space within this structural configuration. In contrast, the Middle East and Asia show broader ranges for shear walled frames, with the Middle East ranging from about 60% to 80% and Asia from 60% to 70%. This variation indicates diverse design practices and regional preferences in optimizing space with shear walled frames, reflecting different architectural standards or construction techniques.

Mega column systems, with only four buildings represented, have consistent space efficiency in the Middle East and Asia, with efficiencies ranging from around 60% to 70%. This consistency suggests that the use of mega columns in these regions focuses on balancing structural capacity with space optimization, potentially due to the system's ability to support large open spaces and accommodate varied floor plans. The absence of North American buildings with mega column systems in the dataset might indicate a regional preference for other structural systems that align more closely with local building codes and architectural trends.

Mega core systems, although represented by only three buildings, show varied space efficiencies across regions. In North America, mega core systems achieve high space efficiency, with values around 70% to 80%, indicating a strong focus on space utilization in conjunction with structural stability. In the Middle East, the efficiency of mega core systems is slightly lower, around 60%, suggesting regional differences in de-sign strategies or structural demands.

Outriggered frames, the most common structural system in the dataset with 82 buildings, exhibit a wide range of space efficiencies across all regions. In Asia, these buildings show a broad efficiency range from 40% to 80%, with a significant clustering around 50% to 70%, highlighting a variety of design approaches and engineering solutions to optimize space. The Middle East demonstrates a narrower range for outriggered frames, from 60% to 80%, with many buildings concentrated around 70%, reflecting a regional emphasis on achieving high space efficiency through this structural system. North American buildings with outriggered frames also show a wide range of efficiencies from 50% to 80%, suggesting diverse architectural strategies and a balance between structural robustness and space optimization.

Tube systems, represented by 25 buildings, show diverse space efficiency out-comes across regions. In Asia, buildings with tube structures have space efficiencies ranging from 40% to 70%, with a concentration around 50% to 60%, indicating varied architectural practices and structural requirements. North American and Middle Eastern tube-structured buildings exhibit higher efficiencies, predominantly between 60% and 80%, suggesting that in these regions, tube systems are optimized to maximize usable space while maintaining structural integrity.

Buttressed core systems, represented by three buildings, show distinct regional variations in space efficiency. The single building in the Middle East has a space efficiency around 50%, while the two buildings in North America exhibit higher efficiencies, around 70% to 80%. This indicates that buttressed core systems, though less common, can achieve high space efficiency depending on regional design practices and specific structural needs.

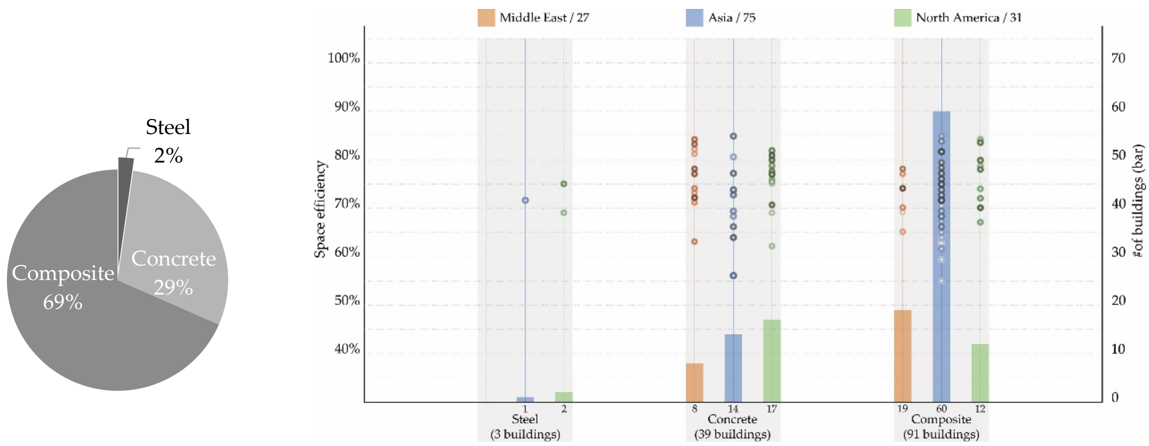

Figure 8 Different locations by material

Figure 8 provides a comprehensive analysis of the relationship between structural materials steel, concrete, and composite and space efficiency in skyscrapers across three regions: the Middle East, Asia, and North America. Space efficiency, depicted on the y-axis as a percentage, measures the proportion of usable floor area relative to the total floor area, serving as a key indicator of how effectively different structural mate-rials contribute to maximizing functional space within tall buildings.

Steel, represented by only three buildings, demonstrates relatively high space efficiencies, with the buildings in Asia and North America both achieving efficiencies around 70%. This suggests that steel, although less commonly used in this dataset, can provide substantial space efficiency. The high efficiency is likely due to steel's excellent strength-to-weight ratio, which allows for larger spans and more open floor plans, thus maximizing usable space. The limited data points for steel may reflect its specialized use in specific regional contexts where structural advantages such as flexibility and high load-bearing capacity are prioritized.

Concrete, a more prevalent material with 39 buildings represented, exhibits a wide range of space efficiencies across all regions. In Asia, concrete buildings have space efficiencies ranging from approximately 40% to 80%, with a notable clustering around 60% to 70%. This variability suggests diverse architectural strategies and potentially varying regulatory environments that influence space utilization. The data indicates that Asian concrete buildings are designed with a broad spectrum of efficiency considerations, from highly efficient designs to those with more modest efficiencies, possibly due to different construction practices and economic factors. Middle Eastern concrete buildings show a similar range, primarily between 60% and 80%, with a significant concentration around 70%. This reflects a consistent approach to optimizing space with concrete, potentially driven by regional design standards or material availability that favors efficient space use. North American concrete buildings dis-play a comparable efficiency range from about 50% to 80%, clustering mostly around 60% to 70%. This suggests a balanced approach in North America, utilizing concrete's structural properties to enhance space efficiency while adhering to local building codes and architectural norms.

Composite materials, which combine different structural elements to optimize strength, flexibility, and material efficiency, are the most common in the dataset, with 91 buildings represented. Buildings using composite materials display a broad range of space efficiencies, especially in Asia, where efficiencies range from 40% to 80%, with a concentration around 60% to 70%. This wide distribution indicates a variety of design practices and the versatility of composite materials in accommodating different architectural and functional requirements. In the Middle East, composite buildings generally show higher efficiencies, clustering between 60% and 80%, suggesting a regional emphasis on maximizing usable space while leveraging the adaptability and strength of composite materials. This efficiency range indicates that the Middle East may prioritize structural systems that provide both flexibility and high space utilization, aligning with regional construction practices and climate considerations. North American buildings using composites also exhibit a broad efficiency range from 50% to 80%, reflecting flexibility in design approaches and a focus on achieving high space efficiency with these materials. The concentration around 60% to 70% in North America high-lights a trend toward optimizing space through the strategic use of composite materials, which can offer tailored structural solutions to meet varied design and regulatory needs.

5. Discussion

The comparative analysis of space efficiency in skyscrapers from the Middle East, Asia, and North America provides valuable insights into regional architectural practices, structural engineering approaches, and the economic drivers influencing the design of supertall buildings. By examining the space utilization strategies and design philosophies across these diverse regions, this study uncovers both commonalities and unique aspects that shape skyscraper development globally.

Space efficiency in Asian skyscrapers averages around 67.5%, with a range from 55% to 82%. This relatively wide range reflects the diversity of design approaches and building functions in Asia, where rapid urbanization and high population densities necessitate innovative architectural solutions. The lower average space efficiency compared to other regions may be attributed to the complex mixed-use designs prevalent in Asia, which integrate residential, commercial, and public spaces within a single structure. These multifunctional layouts, while beneficial for urban density, can lead to compromises in spatial efficiency due to the need for larger core areas and diverse circulation spaces.

Skyscrapers in the Middle East exhibit a slightly higher average space efficiency of 75.5%, ranging from 63% to 84%. This efficiency can be linked to the region's emphasis on luxurious and spacious designs that cater to the socio-economic expectations of the market. The use of advanced structural systems and materials, combined with the relatively recent development of skyscrapers in the region, allows for more optimized space planning. In the Middle East, iconic designs and large-scale mixed-use functions often prioritize aesthetic appeal and symbolic value, which sometimes leads to larger service cores and structural elements, reducing available usable space.

In North America, skyscrapers demonstrate an average space efficiency of 76%, with values ranging from 62% to 84%. The consistency in space efficiency can be attributed to the long history of skyscraper development in the region, where optimization techniques have been refined over decades. North American skyscrapers often prioritize office spaces, which generally have more straightforward space requirements than mixed-use or residential buildings. The use of well-established structural systems and an emphasis on maximizing leasable floor space in commercial developments contribute to this relatively high and consistent efficiency.

These variations in space efficiency outcomes highlight how regional differences in economic conditions, cultural expectations, and urban planning strategies influence skyscraper design. While Asia's high-density urban environments push for innovative and multifunctional designs, the Middle East's focus on luxury and iconic architecture results in space-efficient yet grandiose designs. North America's long-standing tradition of skyscraper construction reflects a more refined approach to optimizing office spaces, with a strong focus on financial returns and practical efficiency.

The central core configuration is the predominant choice in skyscrapers across all three regions—Asia, the Middle East, and North America—due to its compact nature, structural efficiency, and its ability to support flexible facade design and enhance fire safety. This choice is particularly pronounced in Asian skyscrapers, where central cores are crucial for supporting the varied requirements of mixed-use and office buildings. In North America, central cores are favored for their role in maximizing usable space along the building's perimeter, improving natural light access and fire safety. The efficiency of central cores is well-documented in the literature, as they consolidate vertical circulation elements (such as elevators and stairwells) and essential services (such as utilities and HVAC systems) into a single, centralized area. This design frees up the perimeter for leasable space, thereby enhancing the building's overall space efficiency.

The choice of building form also significantly impacts space efficiency and is influenced by local climatic conditions, aesthetic preferences, and structural considerations. In Asia, tapered forms are most common, offering aerodynamic advantages essential for regions with high wind loads. This form reduces wind forces acting on the structure, minimizing sway and increasing overall stability—critical factors for supertall buildings in wind-prone cities. In contrast, the Middle East and North America predominantly feature prismatic and setback forms. Prismatic forms provide straightforward solutions for maximizing interior space, while setback forms offer tiered designs that enhance structural stability and reduce wind loads at higher levels.

In terms of structural systems, Asia primarily uses outrigger frame systems, which balance strength and flexibility. Outrigger systems enhance lateral stiffness by linking the central core to external columns, effectively distributing wind and seismic loads. This system is particularly suited to high-rise, mixed-use buildings typical in Asian metropolises, where both structural integrity and spatial efficiency are essential. Middle Eastern skyscrapers also favor outrigger systems, often in combination with concrete shear walls, which provide additional support against lateral forces. North American skyscrapers commonly use a mix of outrigger and shear wall frame systems, emphasizing both structural robustness and cost-effectiveness.

Regarding materials, composite materials—combining steel and concrete—are widely used in Asian skyscrapers due to their synergistic benefits. Steel provides tensile strength, while concrete offers compressive strength and fire resistance, making this combination ideal for the tall, slender profiles of many Asian skyscrapers. In the Middle East, reinforced concrete remains the material of choice, largely due to its durability and thermal mass, which helps regulate indoor temperatures in hot climates. North American skyscrapers typically employ steel or composite materials, reflecting a balance between strength, flexibility, and cost considerations, which are crucial in a market where both structural performance and financial feasibility are prioritized.

An inverse relationship between building height and space efficiency is observed across all regions, highlighting the challenges of maintaining high space efficiency ratios as buildings increase in height. Taller buildings require larger cores and more substantial structural elements to withstand wind and seismic forces, reducing the proportion of usable floor area. This relationship is particularly pronounced in supertall buildings, where structural demands significantly impact design choices and space allocation.

Each region's unique socio-economic context, climate, and cultural values significantly influence skyscraper design trends and space efficiency. In Asia, rapid urbanization, high population densities, and economic growth drive skyscraper development. The focus is on high-density, mixed-use developments that integrate residential, commercial, and public spaces to accommodate diverse needs within limited urban footprints. This approach reflects a pragmatic response to land scarcity and the demand for multifunctional urban spaces. In the Middle East, skyscraper development is driven by economic diversification and the desire to create iconic structures that enhance global competitiveness. The emphasis on luxury and spaciousness in skyscraper design reflects the region's socio-economic status and cultural expectations, often resulting in higher space efficiency metrics compared to Asia. North American skyscrapers reflect a balance between maximizing floor area and ensuring structural and environmental sustainability in densely populated urban areas. The region’s long history of skyscraper development has led to a mature understanding of space optimization techniques, integrating advanced materials and systems to enhance building performance.

Future research could further explore these variations by examining additional factors such as environmental impact, cultural influences, and economic contexts, providing a more comprehensive understanding of global skyscraper design trends. Expanding the study to include other regions, such as Europe or South America, could also offer new insights into how different contexts shape skyscraper design and space efficiency.

This synthesis of findings from Asia, the Middle East, and North America serves as a valuable resource for architects, engineers, and urban planners aiming to optimize space efficiency in skyscrapers. Adapting strategies to fit the unique demands and opportunities of different regions will be essential. As the global skyline continues to evolve, understanding these regional nuances will be crucial for developing innovative, efficient, and sustainable skyscrapers.

6. Conclusion

This comparative analysis of space efficiency in skyscrapers across the Middle East, Asia, and North America highlights significant regional differences and similarities in architectural strategies and structural innovations.

In the Middle East, Asia, and North America, skyscrapers are designed with both regional characteristics and shared strategies. Middle Eastern skyscrapers typically use prismatic forms with central cores, focusing on residential and mixed-use functions, and often employ concrete and outrigger frame systems to balance structural stability with space efficiency. However, as building height increases, space efficiency tends to decrease due to the need for larger core areas and more robust structural elements. Similarly, in Asia, supertall towers frequently feature tapered forms and central cores, aiming to balance aesthetics with practical considerations such as wind resistance. Here too, space efficiency decreases with height for the same reasons. In North America, skyscrapers often employ setback, prismatic, and tapered configurations, combined with advanced core planning and structural systems like outrigger and shear-walled frames. This approach balances space utilization with structural integrity, reflecting a focus on financial viability and efficient land use, particularly in cities with high land costs. Overall, these regions exhibit a mature approach to skyscraper construction that emphasizes both economic and ecological considerations.

There is a need for further research focusing on integrating sustainability measures with space efficiency strategies. This could help create buildings that are both spatially optimized and environmentally friendly. Exploring the impact of emerging construction technologies and materials, such as 3D printing and advanced composites, could provide insights into how to reduce the size of structural elements and core areas without compromising safety. Detailed cross-regional comparisons of skyscrapers, including those in emerging markets, could reveal how different cultural, economic, and environmental contexts influence design decisions and efficiency outcomes. Additionally, examining how space efficiency affects the comfort, productivity, and satisfaction of building occupants would be valuable in balancing space utilization with high-quality indoor environments.

Based on the findings of this study, architects and engineers involved in skyscraper design should prioritize optimizing the size and layout of service cores. This could involve exploring new configurations that minimize the space taken up by elevators, stairwells, and mechanical systems, thereby increasing usable floor space. Incorporating innovative structural systems, such as hybrid or advanced composite materials, can also allow for slimmer structural elements, reducing the overall footprint and improving space efficiency. It is important to tailor skyscraper designs to local environmental conditions and building codes, considering factors like wind loads and seismic activity. Emphasizing mixed-use developments can maximize space efficiency while meeting diverse urban needs. Additionally, integrating sustainable practices, such as green roofs and energy-efficient facades, can enhance a building's overall performance and appeal.

By continuing to explore the complex interplay of factors influencing skyscraper design and implementing these recommendations, architects and engineers can enhance both the efficiency and sustainability of high-rise buildings, better meeting the evolving needs of urban environments worldwide.

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Resume

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