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# Toward Context-Aware Vertical Urbanism: A Multidimensional Synthesis of Space Efficiency in Functionally and Formally Diverse Tall and Supertall Buildings

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**ABSTRACT**

This study examines spatial efficiency in high-rise buildings, a critical yet underexplored dimension of their design that directly affects economic viability, environmental performance, and user experience. As urban density intensifies and land values soar, understanding how usable floor area is maximized across varying forms, functions, and regions becomes increasingly significant for architects, engineers, and city planners. The objective of this research is to identify how architectural form, programmatic function, structural system, and regional context interact to influence net-to-gross floor area ratios. This study introduces a novel, data-driven comparative framework by analyzing 166 globally distributed case study towers—one of the most extensive empirical evaluations in this field to date. Drawing on peer-reviewed sources and CTBUH (Council on Tall Buildings and Urban Habitat) classification standards, the methodology combines cross-sectional typological categorization with quantitative spatial performance metrics. Key findings include: (1) Hotel towers exhibit the highest spatial efficiency, averaging 81.2%, due to vertically repetitive room layouts and centralized service cores; (2) Rigid frame structures outperform other systems, achieving net-to-gross ratios 85% through compact core design and minimal lateral intrusion; and (3) Building height correlates negatively with space efficiency, indicating that extreme verticality incurs spatial penalties. These results offer practical guidance for stakeholders by revealing the typologies and structural-logical combinations that deliver the most efficient spatial outcomes. This research contributes to both theoretical discourse and professional practice by framing vertical usability as a product of coordinated design decisions, rather than isolated architectural features.

**KEYWORDS**: space efficiency; architectural design considerations; structural design considerations; (super)tall buildings; multidimensional synthesis

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## INTRODUCTION

The emergence of high-rise buildings has redefined the spatial and economic logic of urban development in the 21st century. Originally conceived as expressions of engineering achievement and commercial dominance, these vertical structures have become integral to the spatial strategies of megacities facing challenges of land scarcity, urban density, and climate adaptation [1,2]. In this context, the efficiency with which interior space is planned, used, and distributed has emerged as a critical factor in the viability and performance of tall buildings.

Space efficiency in high-rise edifices is commonly evaluated through metrics such as net-to-gross floor area ratio, core-to-floorplate percentage, or rentable versus service area ratios [3,4]. These parameters influence construction economics, real estate yield, environmental sustainability, and user experience. They are also directly affected by architectural form, functional program, structural system, and regional planning conditions. In practice, the optimization of internal space is not only a question of design aesthetics but also a matter of long-term operational and financial viability.

Despite its central importance, the concept of space efficiency in the design of high-rise towers has been explored in a fragmented manner across the literature—often addressed through isolated lenses such as structural form, building function, or geographic context [5,6]. While these studies offer valuable insights, they fall short of constructing a comprehensive, comparative understanding that integrates multiple variables and design forces within a consistent analytical framework.

Recent studies have contributed to the field by examining typology-specific outcomes. Residential towers, for example, tend to achieve higher space efficiency due to compact core systems and simplified vertical zoning [7,8]. Office and hotel towers, by contrast, often require complex service cores, and higher circulation ratios, limiting their net efficiency [9]. At the same time, buildings with prismatic geometries have been shown to perform better in terms of spatial logic and structural regularity than tapered or free-form designs [10].

Geographic and cultural context adds another critical dimension to spatial planning. In cities like Singapore, Hong Kong, and Dubai—where land is scarce and regulations strict—developers employ centralized cores, narrow floorplates, and high slenderness ratios to maximize usable space [11,12]. Conversely, cities such as New York and Chicago often favor broader floorplates, decentralized core strategies, and zoning-driven setback regulations, which produce different efficiency profiles [13].

Emerging technological and structural innovations further enrich the discourse on space efficiency. Machine learning techniques are now being used to predict wind loads and optimize structural form [14], while new materials and systems—such as concrete-filled steel tube and outriggered frame systems—allow for slimmer structural footprints without compromising stability [15]. These advancements enable higher degrees of spatial flexibility and have the potential to significantly influence vertical planning outcomes.

Despite these contributions, there remains a clear absence of a large-scale, cross-regional, and multi-variable study that synthesizes data from a representative sample of supertall buildings. Most studies are limited to small case selections or focus narrowly on a single factor such as core layout, height, or structural type. A comprehensive framework that connects building form, function, regional context, and structural logic to actual space-efficiency outcomes is currently lacking.

This study addresses the above gap by analyzing a dataset of 166 verified tall and supertall towers sourced from peer-reviewed publications and enriched with CTBUH classifications. By comparing towers across continents and typologies—residential, office, hotel—this research provides a foundational platform for understanding how space efficiency emerges at the intersection of form, function, and geography. It also introduces standardized comparative metrics for net-to-gross ratios and vertical spatial composition.

The investigation is structured around four core research questions: (i) How does building function (such as residential, office, and hotel) influence space efficiency in tall buildings? (ii) What is the relationship between architectural form (such as prismatic, tapered, and free form) and spatial efficiency outcomes? (iii) Are specific structural systems more conducive to efficient floorplate planning? (iv) Does building height have a quantifiable impact on spatial efficiency, and if so, what is the nature and magnitude of that relationship?

The primary objectives of this study are as follows: (a) to compile and validate a robust dataset of case study buildings across functions, regions, and forms; (b) to categorize spatial performance using standardized metrics (net/gross ratio, core area percentage, etc.); (c) to identify and evaluate cross-regional spatial planning strategies; and (d) to inform future practice through evidence-based design principles for maximizing usable vertical space.

By adopting a comparative, data-driven methodology, this study bridges the gap between theory and practice in the evolving field of tall building design. It provides both academic researchers and practicing professionals with a comprehensive view of how spatial efficiency is constructed, optimized, and constrained across global contexts. Ultimately, it aims to shape the discourse around future high-rise development in an era defined by complexity, urban intensification, and performance-driven design. Based on these aims, the following hypothesis is proposed: “As building height increases, space efficiency (net-to-gross ratio) decreases.”

## MATERIALS AND METHODS

This study adopts a comparative and empirical research design grounded in a cross-sectional analytical framework to investigate space efficiency in supertall buildings. The comparative case method was chosen due to the complex, multi-variable nature of tall building design, where architectural form, structural system, programmatic function, and urban context interact in ways that defy isolated analysis. Recent architectural research highlights the value of comparative case synthesis in identifying typological and spatial patterns, particularly in studies with broad geographic and functional scope [16,17].

The dataset comprises 166 verified cases collected from eight peer-reviewed studies by [7,9–11,13]. The case study buildings represent a wide functional spectrum, including residential, office, and hotel towers, and are distributed across several regions: North America, the Middle East, Southeast Asia, and Europe (Figure 1). The selection of case studies was based on the availability of verifiable attributes such as total height, dominant functional program, architectural form, structural system, and—crucially—either published net-to-gross floor area ratios or floorplans that allowed these values to be reasonably approximated (Appendix A Tables A1 and A2). Each of the 166 buildings was cross verified using the CTBUH online database [1], which is considered the most authoritative global reference for tall building classification, dimensional accuracy, and typological metadata. Only buildings whose data could be traced to peer-reviewed publications or established technical sources were included, ensuring the credibility and consistency of the sample. This combined approach of academic sourcing and database validation enhances the dataset's transparency and reliability.

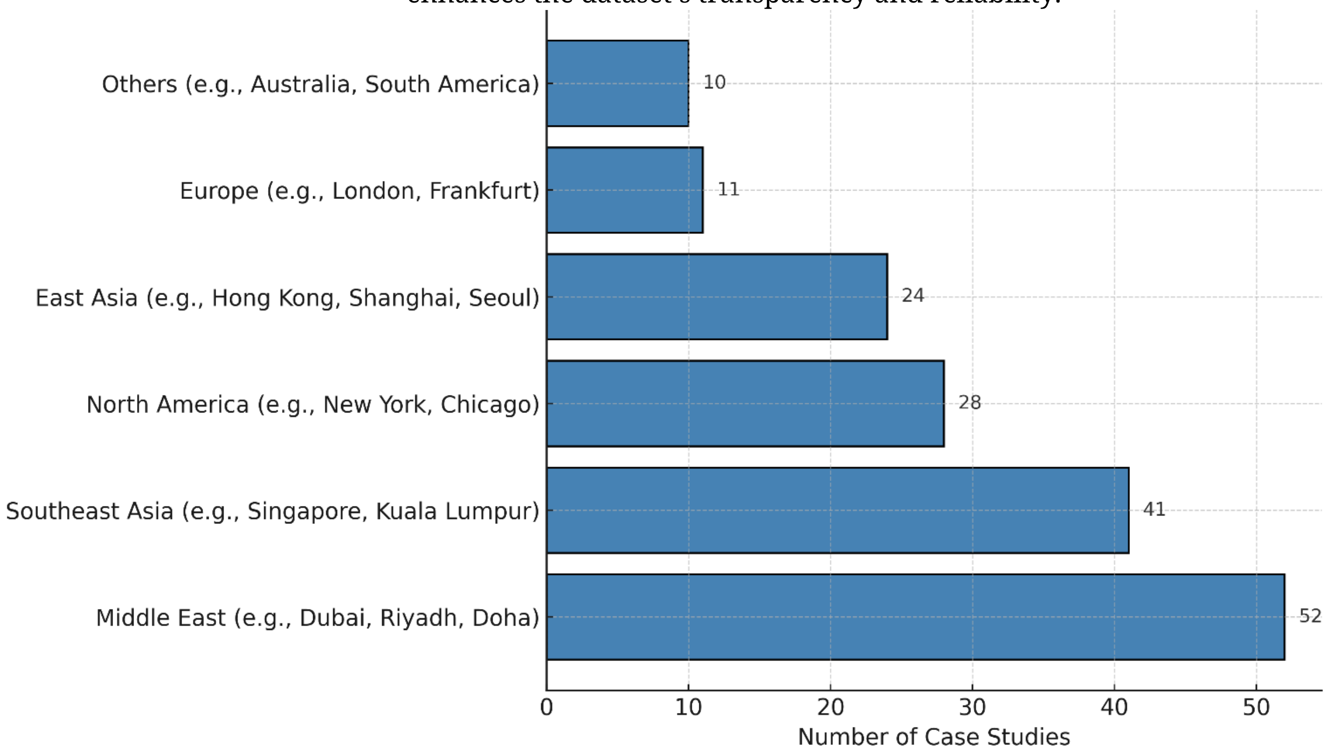


**Figure 1.** Regional distribution of tall and supertall buildings in the dataset ($n$ = 166).

Buildings were classified according to four categorical variables: (i) function, based on dominant program use; (ii) architectural form, defined as prismatic, tapered, or free form based on visual massing and vertical profile; (iii) structural system, where available, identified as shear walled frame, outriggered frame or tube systems; and (iv) regional context, categorized by geographic zone. The classification logic aligns with contemporary high-rise design research practices that emphasize visual-formal morphology and dominant-use hierarchy [18].

To enable consistent evaluation across the sample, two standardized spatial efficiency metrics were used:

1. Net-to-Gross Floor Area Ratio (N/G):

$$N/G = \frac{\text{Net (Usable) Floor Area}}{\text{Gross Floor Area}} \times 100\% \quad (1)$$

This ratio expresses the proportion of usable interior space relative to the total constructed area.

2. Core-to-Gross Area Percentage (C/G):

$$C/G = \left(\frac{\text{Core Area}}{\text{Gross Floor Area}}\right) \times 100\% \quad (2)$$

Where published sources or project documentation included these values explicitly, they were directly adopted. For cases lacking explicit data, a visual estimation method was applied using architectural floorplans obtained from peer-reviewed publications or official databases. Scaled diagrams were imported into CAD-based digital environments such as AutoCAD or Rhino, where both the gross floorplate and core zones were manually traced based on recognizable spatial elements. Software-integrated tools were then used to compute area values, enabling the derivation of spatial ratios. For raster-only floorplans (e.g., scans or PDFs), pixel-based proportional estimation was employed using image analysis software such as Adobe Illustrator or ImageJ, following best-practice methods used in recent spatial research [9–11]. In all estimation cases, conservative interpretation was prioritized to avoid overstatement. Spatial ratio outputs were triangulated by comparing each derived value to similar towers—based on region, function, and structural typology—also included in the dataset. This hybrid approach, blending direct numerical use with plan-based estimation and typological benchmarking, aligns with current methodological standards in empirical high-rise analysis and strengthens the transparency and replicability of the findings.

This research adopts a descriptive, pattern-based approach to extract meaningful spatial tendencies across typologies and regions. This choice aligns with recent high-rise performance studies that prioritize architectural synthesis over probabilistic generalization when full data uniformity is not achievable [19–21]. The focus here is on observing empirical configurations and interpreting form-function-space relationships across a broad set of real-world cases.

Validation of extracted metrics was conducted through triangulation across multiple sources: peer-reviewed case documents, CTBUH data, and plan interpretations. In cases where numeric core areas were unavailable, core-to-gross ratios were visually approximated using proportional scaling of published floorplates, supported by comparisons to similar buildings in the same functional or regional category. This technique is increasingly used in contemporary tall building evaluations, especially in the absence of full proprietary documentation [16].

By utilizing a structured and transparent classification and analysis method, this study achieves both breadth and replicability. It offers a scientifically valid methodology that acknowledges the real-world constraints of tall building documentation and prioritizes architectural realism over abstraction. The integration of up-to-date academic frameworks and validated spatial metrics ensures that the findings contribute meaningfully to the body of knowledge in vertical urbanism and spatial optimization.

To examine the relationship between building height and spatial efficiency, a simple linear regression analysis was performed. The analysis utilized:

- Independent Variable (X): Total building height (measured in meters)
- Dependent Variable (Y): Net-to-Gross Floor Area Ratio (N/G)

While the model involved only two continuous variables, linear regression was selected over Pearson's correlation for several reasons. First, regression enables not only the assessment of the direction and strength of association between the variables but also provides a slope coefficient that quantifies the expected change in spatial efficiency for each unit increase in building height. This was essential for capturing the rate of spatial efficiency decline as verticality increases—a central analytical goal of this study. Additionally, regression offers a visual representation through a fitted trendline, making the general tendency across the dataset more interpretable.

The regression model was applied to the entire sample of 166 buildings. All values of the net-to-gross ratio used in this analysis were either directly obtained from published sources or conservatively estimated from floorplans as described earlier. The results were visualized using a scatter plot (Figure 7), where each data point represents a unique tower and is color-coded by function to aid interpretation. It is important to note that this was a strictly bivariate regression, and no higher-order or multivariate statistical inferences were attempted.

**RESULTS**

This study provides a cross-sectional evaluation of more than 160 case study buildings, integrating quantitative metrics with qualitative design analysis. Through variables such as function, architectural form, structural system, geographic context, and core configuration, this research identifies multidimensional trends in spatial efficiency—measured primarily via net-to-gross and core-to-gross floor area ratios. The results substantiate and extend findings across a series of typology- and region-specific investigations [7,9–11].

**Spatial Efficiency by Function**

Function emerges as the dominant variable in determining space efficiency. As illustrated in Figure 2, hotel towers yield the highest average net-to-gross floor area ratio (81.2%). The high spatial efficiency observed in hotel-type case study towers can be scientifically attributed to several interrelated design and programmatic factors. Firstly, hotels typically employ centralized core configurations that minimize horizontal circulation space, allowing for compact floorplates with repetitive room modules arranged along double-loaded corridors. This repetition enables efficient stacking of services such as plumbing, HVAC, and vertical risers, reducing the need for redundant shafts. Secondly, unlike office buildings, hotels do not require large open-plan spaces or high-capacity elevator zoning, which lowers core area demands. Furthermore, hotels often have functionally integrated amenity zones (e.g., restaurants, spas, meeting rooms) confined to podium levels, while upper floors are dedicated almost exclusively to guest rooms. This vertical program stratification allows for high spatial yield across the majority of the tower. Finally, recent hotel designs in dense urban environments increasingly prioritize real estate efficiency due to economic pressures, leading to optimized structural grids, minimized structural transitions, and space-saving innovations in service integration.

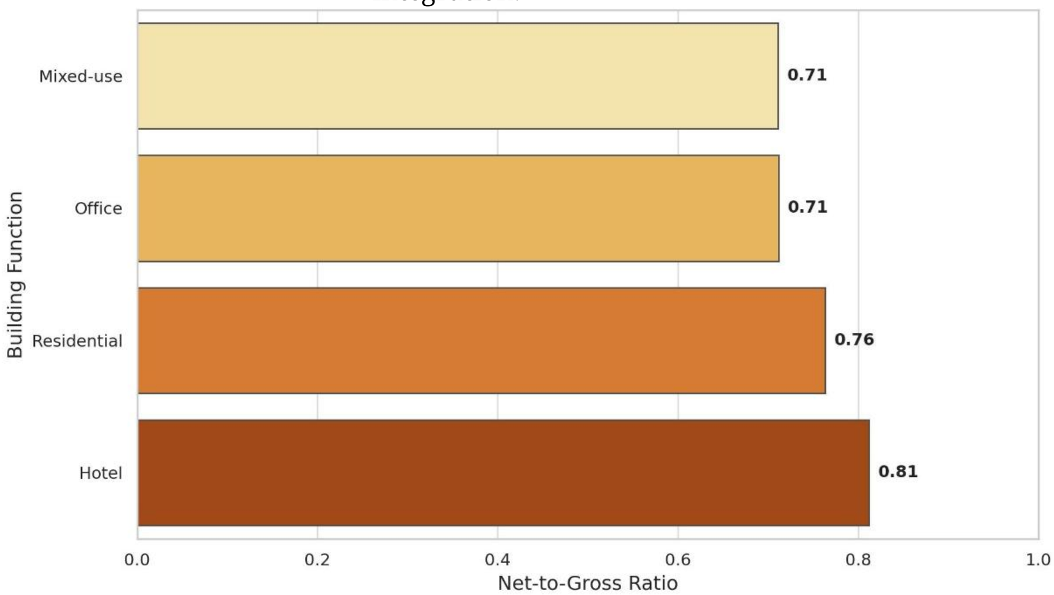


**Figure 2.** Average space efficiency by function.

The relatively low spatial efficiency in office and mixed-use supertall buildings—typically averaging below 72% net-to-gross ratio—stems from their complex core requirements, programmatic diversity, and structural constraints. Office towers demand extensive vertical circulation systems, including multiple elevator banks (for low, mid, and high zones), fire escape stairwells, mechanical shafts, and refuge areas to meet stringent safety and redundancy codes. These core components occupy a significant portion of the floorplate, especially in high-rise typologies. Additionally, office layouts often necessitate deeper floorplates to accommodate open-plan workspaces, which in turn require more sophisticated structural spans and HVAC distribution systems. In mixed-use towers, spatial efficiency is further reduced due to vertical program fragmentation—such as the inclusion of retail, hotel, residential, and office functions within a single building. This leads to duplicated services (e.g., separate lobbies, mechanical floors, and elevator shafts) and inefficient stacking, particularly at transition zones between uses. These compounded spatial interruptions result in larger gross areas without proportional increases in usable space, thus lowering overall efficiency.

Across all functions, core design configuration is a silent yet decisive factor. Buildings with centralized core layouts demonstrate the most efficient floorplate integration, particularly in residential and office towers. By contrast, dual-core or offset-core strategies, often used in hotel towers to separate front-of-house from service circulation, lead to spatial discontinuities. As noted in Ilgın and Aslantamer [7], dual-core hotels may incur an 8–12% penalty in net floor area due to duplicated circulation space and intermediate elevator zones. The vertical zoning strategy adds another layer of complexity. Particularly in hotel and mixed-use towers, functional stacking (e.g., ground-floor lobbies, mid-tower amenities, upper guest rooms) demands sky lobbies, mechanical floors, and elevator transfers. These vertical transitions—while essential for user experience and operational flow—introduce spatial inefficiencies. Ilgın and Aslantamer [9] observed that in hotel towers with two or more sky lobbies, the loss of usable floor area can exceed 15%, even when the core remains centralized.

**Spatial Efficiency by Building Form**

Building form plays a pivotal role in determining spatial efficiency, second only to building function. As shown in Figure 3, prismatic towers continue to exhibit the highest average net-to-gross floor area ratios among form types, averaging approximately 75.1%, followed closely by setback and free-form designs. While these values are slightly lower than earlier studies, prismatic towers still outperform twisted and tapered configurations, which tend to suffer from geometric complexity and inefficient vertical transitions. The efficiency of prismatic forms is primarily attributed to their regular floorplates, centralized core systems, and repetitive spatial logic—features that facilitate vertical modularity and high space yield. Within the 166-building dataset, prismatic towers frequently demonstrate consistent planning discipline and minimal spatial interruption, reinforcing their superior performance in space optimization.

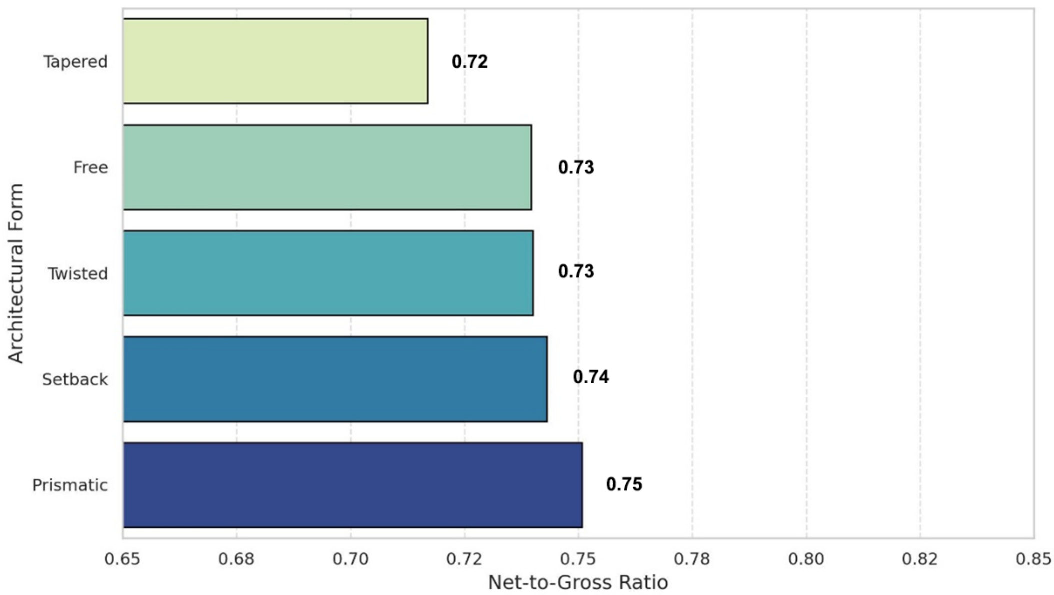


**Figure 3.** Average space efficiency by building form.

Tapered towers, by contrast, exhibit the lowest average spatial efficiency among all form types in the 166-building dataset, with a net-to-gross ratio of approximately 72%. These buildings often require expanded or non-uniform cores due to their narrowing floorplates, leading to vertically inconsistent core zones and structural transitions. Such conditions complicate elevator zoning, increase the frequency of mechanical floors, and introduce inefficiencies in vertical circulation. This geometric tapering also restricts modular planning, often resulting in underutilized upper floor areas.

Free-form towers, which maintain a moderate average net-to-gross ratio around 74.0%, demonstrate high variability in performance. Their efficiency largely depends on the degree of internal spatial regularity. When external fluid geometries are accompanied by orthogonal internal planning—such as "camouflaged prismatic" layouts—the efficiency loss is minimized. However, in cases where internal layouts follow the expressive exterior, spatial fragmentation increases significantly. These findings reaffirm that while sculptural design offers aesthetic and branding value, it frequently imposes trade-offs in functional efficiency.

**Spatial Efficiency by Structural System**

Structural systems have a profound impact on the spatial efficiency of supertall buildings, as demonstrated by clear differences in net-to-gross ratios across structural typologies. As shown in Figure 4, the Rigid Frame System leads with the highest average efficiency at 85%, significantly outperforming all other systems. This exceptional performance is attributed to its structural simplicity, which enables compact core layouts, minimized lateral structural demands, and consistent floorplate geometry—conditions ideal for modular, repetitive planning in tall towers.

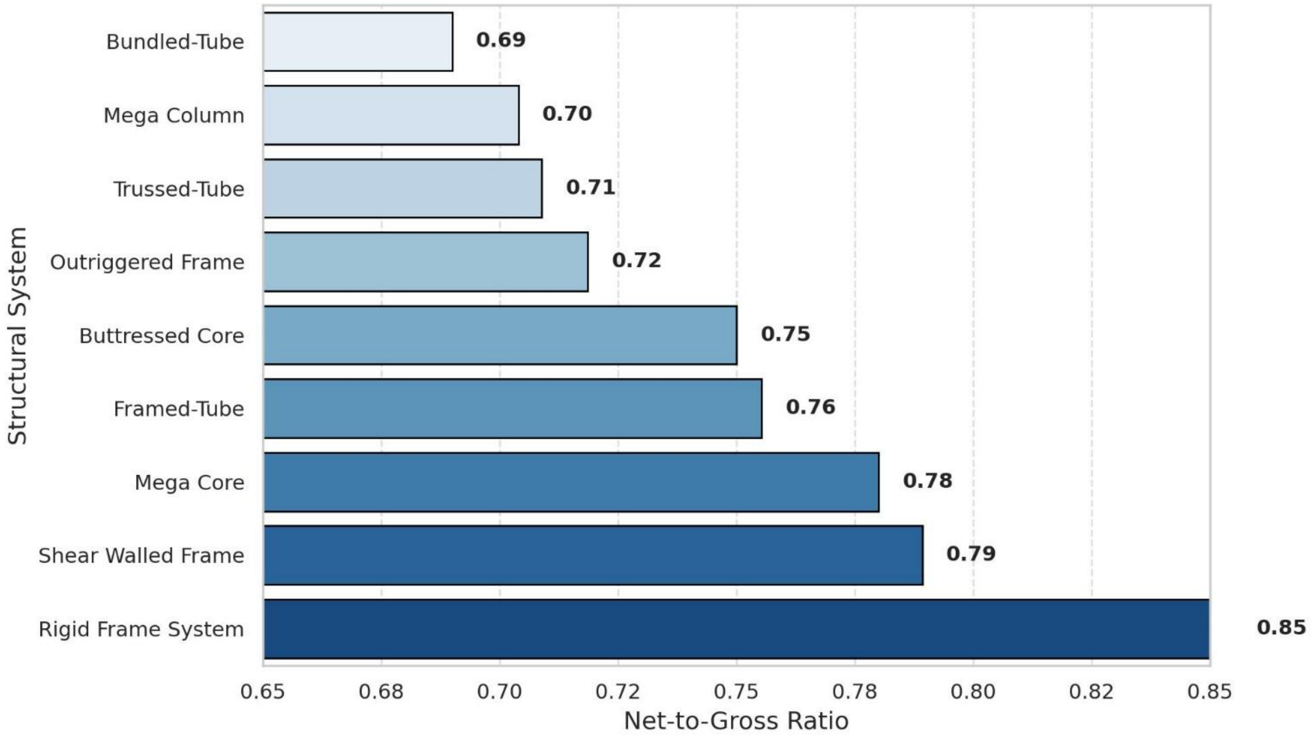


**Figure 4.** Average space efficiency by structural system.

Following closely are Shear Walled Frame (79%), Mega Core (78%), and Framed-Tube (76%) systems, all of which achieve relatively high efficiency through centralized bracing, uniform massing, and vertical core alignment. These systems support rational vertical zoning and deliver greater usable areas across floors with limited internal disruption.

In contrast, systems like the Outriggered Frame (72%), Trussed-Tube (71%), Mega Column (70%), and Bundled-Tube (69%) register noticeably lower spatial performance. These typologies, while structurally effective at resisting lateral loads and enabling landmark heights, often introduce spatial fragmentation due to intermediate mechanical zones, transfer structures, and multi-core schemes. These elements reduce the efficiency of interior layouts and complicate circulation patterns.

The analysis clearly underscores that structural robustness does not necessarily equate to spatial efficiency. The outstanding performance of the Rigid Frame System—often underutilized in high-rise applications—shows that, when paired with regular massing and single-function programs, it can deliver optimal floor area returns. For developers aiming to maximize rentable or sellable space, these insights offer crucial guidance in selecting structural systems that align with both engineering and commercial objectives.

### Regional Distribution and Planning Influences

Regional planning conditions clearly influence the relationship between architectural form and spatial efficiency, though not always in expected ways. In the 166-building dataset, towers located in Dubai, Doha, and Riyadh exhibit the highest average space efficiency, with a mean net-to-gross ratio of 76.7%. This finding may reflect the prevalence of prismatic geometries and relatively uniform vertical zoning strategies, despite the presence of monumental lobbies and internal atria in some mixed-use towers. Contrary to common assumptions, towers in Singapore and Kuala Lumpur, while operating under strict FAR constraints and vertical zoning codes, achieve slightly lower average efficiency at 74.2%, likely due to complex program stacking and integrated service cores in dense high-rise clusters.

In North America, particularly New York and Chicago, towers demonstrate a moderate average net-to-gross ratio of 75.8%. While older buildings often include generous core footprints and service corridors due to legacy code constraints, newer towers—especially Class-A office buildings constructed after 2010—show improved efficiency through slimmer cores and modular planning systems. However, their efficiency still lags slightly behind that of their Middle Eastern counterparts, likely due to stricter egress and fire-safety requirements mandated by U.S. codes.

These regional patterns underscore the influence of urban policy, land value, and regulatory culture in shaping spatial performance. While high land premiums encourage vertical efficiency, the translation into actual spatial gains depends on how local codes shape core sizing, mechanical distribution, and circulation logic. The data confirms that high efficiency is not merely a function of density, but of how structure, program, and code are resolved in tandem.

This analysis suggests that no single spatial typology universally dominates, but instead, that efficiency arises from the integration of three key factors: structural rationality, regional regulation, and functional clarity. Buildings that combine a simple, centralized structural system (e.g., Rigid Frame), with regular geometry and contextually efficient core planning, consistently outperform others—regardless of external appearance. Rather than imposing an idealized global model, design strategies should prioritize local building codes, economic pressures, and programmatic logic to shape spatially efficient high-rise buildings.

**Form–Function Matrix Patterns**

When space efficiency is mapped across form–function matrices, three dominant patterns emerge, as seen in Figure 5:

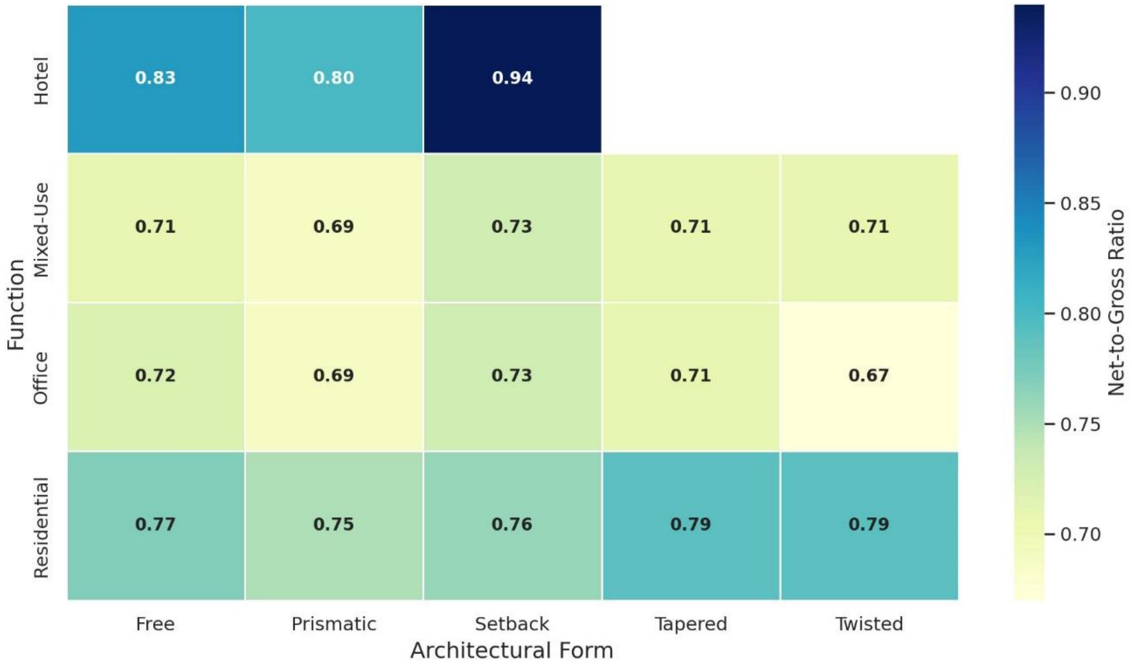


**Figure 5.** Space efficiency mapped across form–function matrices.

The matrix visualization reveals nuanced relationships between architectural form, building function, and spatial efficiency in supertall buildings. Among the observed typologies, setback hotel towers stand out with the highest average net-to-gross ratio of 0.94, indicating minimal circulation loss and high layout regularity. This is likely a result of centralized vertical cores, efficient floorplate stacking, and the vertically zoned repetition inherent to hotel programs. Residential buildings in tapered and twisted forms also demonstrate high efficiency values (0.79), suggesting that when residential unit modules are consistently stacked, even geometrically complex forms can maintain spatial performance.

In contrast, office towers, particularly those with twisted (0.67) and prismatic (0.69) geometries, show comparatively lower net-to-gross ratios. This can be attributed to the increased service core demands, deeper floorplates, and diverse circulation systems required by office functions, which reduce usable floor area. Similarly, mixed-use configurations across all forms underperform relative to single-function counterparts, reinforcing the spatial cost of vertical programmatic mixing and duplicated service elements.

Overall, the data confirms that form alone does not determine efficiency—it is the interaction between programmatic regularity, vertical layout logic, and structural clarity that governs spatial outcomes. Efficient typologies emerge not only from symmetrical geometry but also from program-form compatibility, highlighting the importance of integrated architectural and structural planning in high-rise design.

### Overall Distribution of Spatial Efficiency

The histogram in Figure 6 illustrates the overall distribution of spatial efficiency (measured by net-to-gross floor area ratio) across the 166 cases in the dataset. The distribution is approximately normal but slightly right skewed, with most buildings achieving efficiency values between 0.70 and 0.80. This clustering suggests a general industry standard or design consensus around this efficiency range for high-rise buildings, where circulation cores and service zones are optimized relative to rentable or usable space.

Notably, there is a tail of buildings exhibiting very high efficiency levels (above 0.85), likely corresponding to optimized residential or hotel towers with single-use programming and vertically repetitive cores. Conversely, a smaller proportion of buildings fall below 0.65, indicating either early-generation high-rises with oversized cores or complex mixed-use programs with redundant vertical services.

This distribution supports the interpretation that while architectural ambition and program diversity may drive variance at the extremes, the typical supertall building converges around a 75% net-to-gross benchmark. Such convergence reflects a balance between regulatory constraints, structural logic, and commercial efficiency in high-rise design.

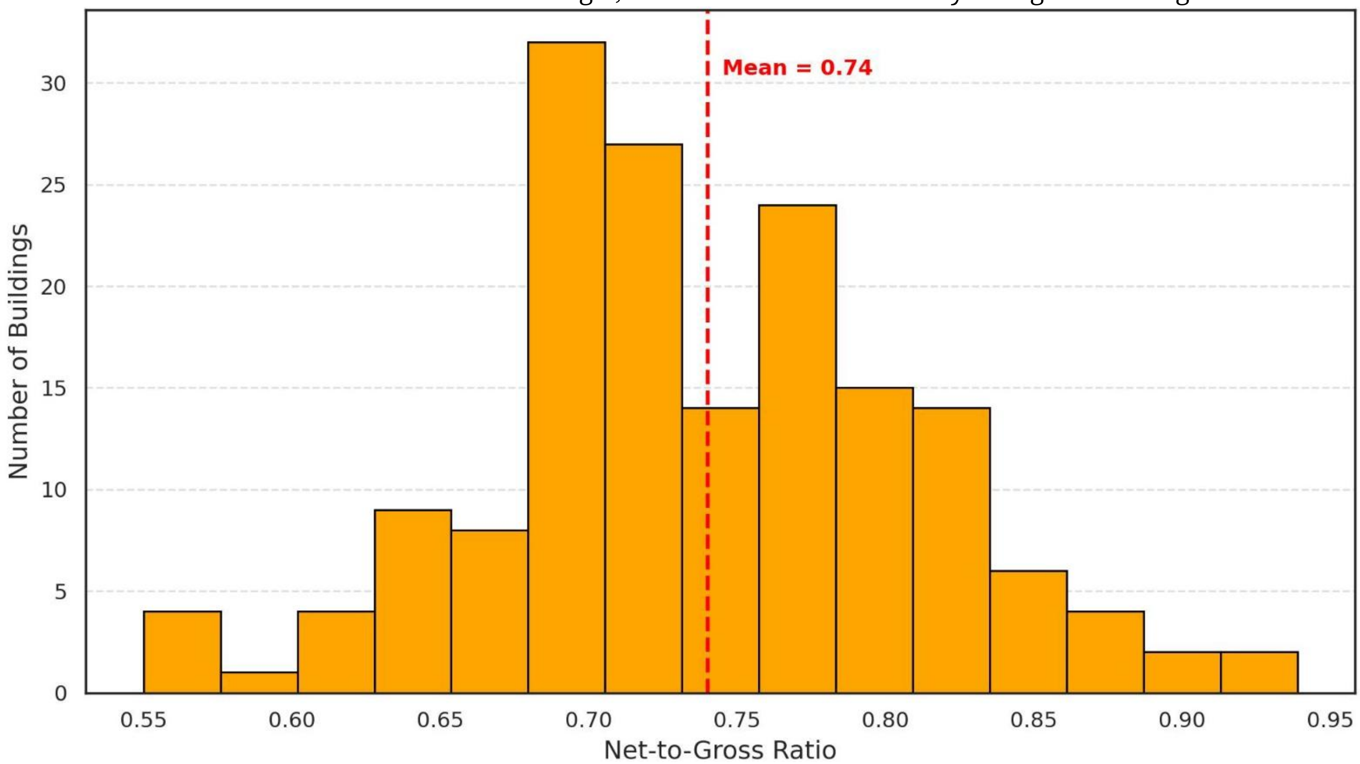


**Figure 6.** Distribution of space efficiency (all buildings).

### Interrelationship between Building Height and Space Efficiency

This section directly addresses the fourth research question by empirically testing the hypothesized negative association between building height and spatial efficiency.

A bivariate linear regression was conducted to evaluate the relationship between building height (independent variable) and net-to-gross floor area ratio (dependent variable) across 166 towers. The resulting model is expressed as:

$$\text{Net-to-Gross Ratio (Y)} = 0.831 - 0.00078 \times \text{Building Height (X)} \quad (3)$$

The slope coefficient (β = –0.00078) indicates that each 1-meter increase in building height is associated with an approximate 0.078% decrease in spatial efficiency. This negative relationship confirms the anticipated trend that spatial efficiency tends to decline as verticality increases.

The regression produced an $R^2$ value of 0.240, indicating that 24% of the variation in spatial efficiency can be explained by building height alone. The model was found to be statistically significant ($p < 0.001$), based on the F-test for overall fit.

The relationship is visualized in Figure 7, which displays a scatter plot of the 166 data points, overlaid with the fitted trendline. Data points are color-coded by building function (e.g., residential, hotel, office, mixed-use) to enhance interpretability. While the strength of the association is moderate, the consistent downward trend illustrates a clear spatial trade-off associated with increasing height in tall building design.

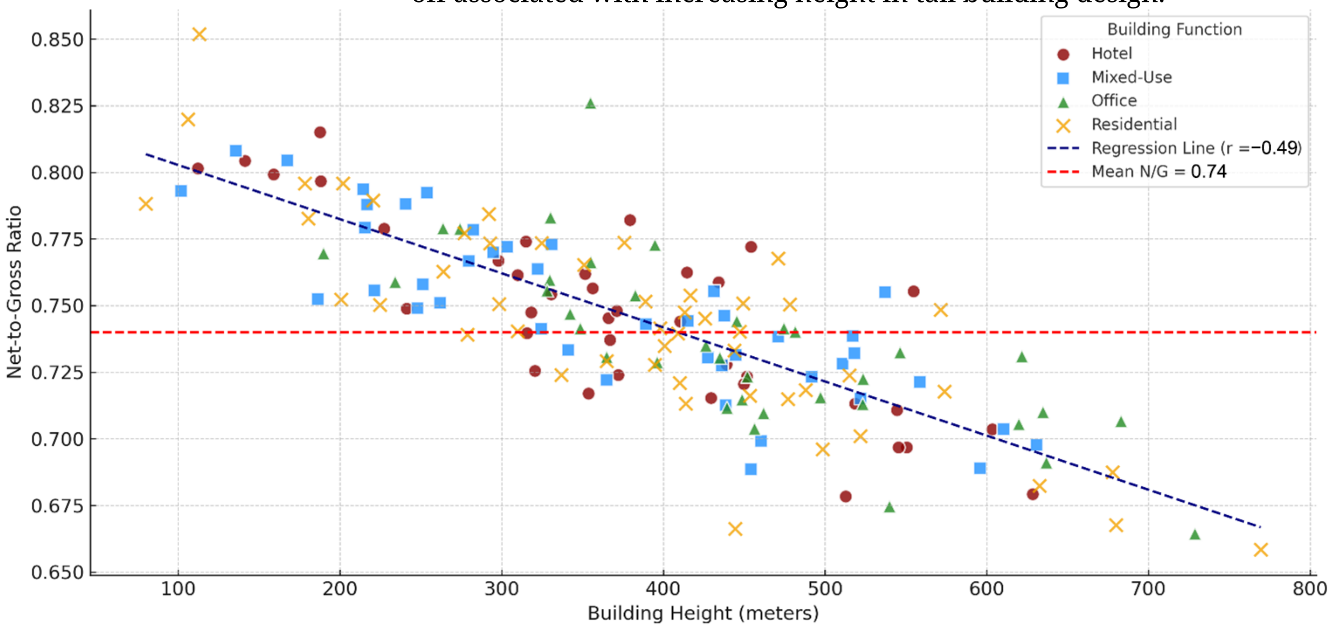


**Figure 7.** Building height vs. space efficiency.

## DISCUSSION

The spatial configuration of supertall buildings is shaped by an intricate confluence of architectural form, functional intent, structural strategy, and regional regulation. This study, based on a detailed analysis of 166 built tall and supertall towers worldwide, affirms that spatial efficiency—defined by the net-to-gross floor area ratio—is not a product of any singular design parameter. Rather, it emerges from the alignment of multiple interdependent factors. This discussion synthesizes the empirical results across five dimensions: function, form, structural system, geographic context, and vertical scale, drawing theoretical and practical implications for high-rise design.

**Functional Clarity and Vertical Efficiency**

The most influential variable in determining space efficiency was building function. Hotel towers consistently demonstrated the highest spatial performance, achieving an average net-to-gross ratio of 81.2%. This finding aligns with the nature of hotel programs, which typically exhibit vertical regularity, repetitive room modules, and compact core strategies. In most cases, amenity spaces are limited to lower levels or podiums, while upper floors remain dedicated to tightly planned guest rooms. The vertical circulation in hotel towers often employs single or dual elevator banks with centralized service shafts, minimizing horizontal travel and maximizing net area.

By contrast, mixed-use and office towers tend to underperform spatially, with average net-to-gross ratios falling below 72%. This is due to their inherently fragmented vertical zoning. Mixed-use buildings require duplicated service cores, transfer lobbies, intermediate mechanical zones, and separate vertical circulation systems for different functions, e.g., hotel, residential, office, or retail. These transitions introduce floor area inefficiencies that significantly reduce usable space. Offices, while monofunctional, demand flexible and open floorplates, deeper service zones, and larger cores to accommodate lift zoning, which adds to the non-net area burden.

**Building Form and Internal Planning Logic**

Building form strongly conditions floorplate efficiency, though its influence is often misunderstood. The results show that prismatic towers remain the most reliably efficient form, with an average net-to-gross ratio of 75.1%. Their orthogonal geometry allows for standardized structural grids, compact core integration, and high repetition—conditions that enable minimal service loss across floors. These forms are most frequently deployed in residential and hotel towers, where stacked modularity and symmetry offer architectural and spatial clarity.

Interestingly, tapered and twisted residential towers also demonstrated high efficiency—averaging 0.79 and 0.76, respectively—when internal planning coherence was preserved. In these cases, external massing complexity did not necessarily compromise interior logic. When the geometry of the tower’s exterior envelope remains decoupled from its structural and spatial core, efficiency can be maintained. This is particularly evident in towers with elliptical plans or rotated volumes, where internal cores and units remain regular while facades serve purely expressive functions.

In contrast, free-form and twisted office towers often exhibited the lowest spatial performance, with some falling to 0.67. The irregularity of their plans disrupted core placement required nonstandard service runs, and generated excess circulation space. Beedle et al. [22] emphasized the same challenge in mixed-function towers, noting that expressive form often undermines rational space usage unless clearly decoupled from structural systems.

**Structural Strategy and Spatial Yield**

Structural system choice was another decisive determinant of spatial performance. This study revealed that the Rigid Frame System is the most efficient structural typology, boasting a remarkable 85% average net-to-gross ratio. Its dominance lies in its minimal lateral interference, compatibility with centralized cores, and structural alignment with repetitive plan logic. Such systems are especially suited to hotel and residential typologies, where structural simplicity and plan regularity are synergistic.

Following closely were the Shear Walled Frame (79%), Mega Core (78%), and Framed-Tube (76%) systems. These maintain efficient space allocation through centralized bracing and a focus on regularized stacking. They allow for reduced transfer structures and support high plan continuity.

Conversely, structurally ambitious systems such as the Bundled-Tube (69%), Mega Column (70%), Trussed-Tube (71%), and Outriggered Frame (72%) displayed significantly lower net-to-gross performance. These systems are often employed in landmark towers requiring high stiffness-to-height ratios. However, they tend to introduce deep cores, perimeter stiffening, transfer decks, and belt trusses—all of which compromise net space. Ali and Moon [2] similarly concluded that structurally expressive but spatially disruptive systems—such as mega-columns or outrigger cores—impose a spatial penalty not always justified by performance. These spatial trade-offs, while sometimes necessary for structural or iconic reasons, emphasize the disconnect between engineering optimization and space economy.

**Regional Policy and Efficiency Outcomes**

Geographic context plays a major role in mediating space efficiency. The highest-performing towers by region were found in the Middle East, particularly in Dubai, Doha, and Riyadh, where average net-to-gross ratios reached 76.7%. This finding challenges the perception that iconic forms in these regions come at the cost of efficiency. On the contrary, many towers combined prismatic geometries with centralized cores and minimized service overlaps, demonstrating a strategic alignment between aesthetic ambition and space discipline.

In Southeast Asia, including cities like Singapore and Kuala Lumpur, average efficiency was slightly lower (74.2%), likely due to a prevalence of mixed-use stacking, smaller floorplates, and tighter service integration. Despite stricter FAR regulations, the complexity of vertical programmatic transitions appeared to compromise internal yield.

North American cities, especially New York and Chicago, averaged 75.8%—a reflection of both legacy zoning typologies and recent design innovations. Older towers typically exhibited deep floorplates and oversized cores, whereas post-2010 Class-A office towers achieved higher performance through thinner profiles, more modular planning, and core rationalization.

These regional outcomes align with research by Ford [23], who found regional policy to be a critical force shaping spatial yield in East Asian skyscrapers. Crawford et al. [24] similarly argued that local building codes and market expectations often determine whether vertical form prioritizes usable space or architectural symbolism.

**Height-Driven Spatial Penalties**

A particularly significant and quantitatively validated insight from this study is the inverse relationship between building height and spatial efficiency. With a Pearson correlation of –0.49 ($p < 0.001$), the data shows that as buildings exceed 400 m, their net-to-gross ratios decline, sometimes precipitously. This is due to several interconnected factors: taller towers require more mechanical systems, increased structural stiffness, and elaborate vertical circulation strategies (e.g., express elevators, sky lobbies, and refuge floors).

As height increases, core areas tend to expand disproportionately relative to floor area, reducing usable space even as total gross volume grows. These penalties are structural, regulatory, and operational—not merely architectural. The efficiency loss is particularly acute in towers that combine multiple programs and structural systems over large vertical spans.

This is supported by Moon [6] and recent work by Huang et al. [25], both of whom found that as vertical height increases, non-net components like structure and services multiply, offsetting floor area gains. Thus, while vertical densification remains a vital urban strategy, this study reveals a diminishing spatial return on extreme height. For developers, this finding suggests that the economic rationale for height must be critically evaluated considering net usable space delivered—not simply gross built area.

**Design and Planning Implications**

This discussion reaffirms that spatial efficiency in tall buildings is a compound outcome of architectural clarity, structural discipline, functional simplicity, and contextual responsiveness. The most successful towers—regardless of height—are those that align geometric regularity, programmatic logic, and engineering rationality in service of usable space.

For stakeholders, including designers, developers, and policymakers, this study offers practical guidance:

(i) Favor single-function programs for optimal yield. (ii) Choose structural systems that minimize internal interference. (iii) Avoid vertical hybridity unless justified by site or zoning. (iv) Match form to function, not merely to visual intent.

## CONCLUSIONS

This study examined 166 tall and supertall buildings to evaluate how spatial efficiency—measured through net-to-gross floor area ratio—is shaped by form, function, structural system, and building height. The analysis revealed that hotel towers exhibit the highest spatial efficiency (avg. 81.2%), while rigid frame systems outperform other structures (avg. 85%). A clear inverse relationship between height and efficiency was identified, quantified via linear regression ($\beta = -0.00078$, $R^2 = 0.24$, $p < 0.001$), confirming the spatial penalties of extreme verticality.

These findings underscore that space efficiency is not the result of any single design decision but rather emerges from a coherent alignment of programmatic clarity, geometric regularity, and structural discipline. Efficient high-rise design is therefore a multidimensional task requiring both technical precision and contextual awareness.

This study is limited by the availability of detailed architectural floorplans and the heterogeneity of regional code data, which constrained deeper multivariate modeling. Future research should explore dynamic simulations of spatial efficiency over building life cycles, incorporate post-occupancy evaluations, and expand regional datasets to include underrepresented geographies such as South America and Africa.

## DATA AVAILABILITY

All data generated from the study are available in the manuscript.

## CONFLICTS OF INTEREST

The author declares that there is no conflicts of interest.

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This research received no external funding.

## APPENDIX A

**Table A1.** 166 tall and supertall case study buildings.

| # | Building Name | Country | City | Height (Meters) | # of Stories | Completion Date |
|---|---|---|---|---|---|---|
| 1 | Nakheel Tower | UAE | Dubai | 1000 | 200 | NC |
| 2 | Burj Khalifa | UAE | Dubai | 828 | 163 | 2010 |
| 3 | Suzhou Zhongnan Center | China | Suzhou | 729 | 137 | OH |
| 4 | Merdeka PNB118 | Malaysia | Kuala Lumpur | 644 | 118 | UC |
| 5 | Shanghai Tower | China | Shanghai | 632 | 128 | 2015 |
| 6 | Chicago Spire | USA | Chicago | 609 | 150 | NC |
| 7 | Ping An Finance Center | China | Shenzhen | 599 | 115 | 2017 |
| 8 | Goldin Finance 117 | China | Tianjin | 596 | 128 | OH |
| 9 | Entisar Tower | UAE | Dubai | 577 | 122 | OH |
| 10 | Lotte World Tower | South Korea | Seoul | 554 | 123 | 2017 |
| 11 | One World Trade Center | USA | New York | 541 | 94 | 2014 |
| 12 | Tianjin CTF Finance Centre | China | Tianjin | 530 | 97 | 2019 |
| 13 | Guangzhou CTF Finance Centre | China | Guangzhou | 530 | 111 | 2016 |
| 14 | CITIC Tower | China | Beijing | 528 | 108 | 2018 |
| 15 | Evergrande Hefei Center 1 | China | Hefei | 518 | 112 | OH |
| 16 | Pentominium Tower | UAE | Dubai | 515 | 122 | OH |
| 17 | Busan Lotte Town Tower | South Korea | Busan | 510 | 107 | NC |
| 18 | TAIPEI 101 | Taiwan | Taipei | 508 | 101 | 2004 |
| 19 | Greenland Jinmao International Financial Center | China | Nanjing | 499 | 102 | UC |
| 20 | Shanghai World Financial Center | China | Shanghai | 492 | 101 | 2008 |
| 21 | International Commerce Centre | China | Hong Kong | 484 | 108 | 2010 |
| 22 | Wuhan Greenland Center | China | Wuhan | 475 | 97 | NC |
| 23 | Central Park Tower | USA | New York | 472 | 98 | 2020 |
| 24 | Chengdu Greenland Tower | China | Chengdu | 468 | 101 | OH |
| 25 | R&F Guangdong Building | China | Tianjin | 468 | 91 | OH |
| 26 | Lakhta Center | Russia | St. Petersburg | 462 | 87 | 2019 |
| 27 | Vincom Landmark 81 | Vietnam | Ho Chi Minh City | 461 | 81 | 2018 |
| 28 | Changsha IFS Tower T1 | China | Changsha | 452 | 94 | 2018 |
| 29 | Petronas Twin Tower 1 | Malaysia | Kuala Lumpur | 452 | 88 | 1998 |
| 30 | Petronas Twin Tower 2 | Malaysia | Kuala Lumpur | 452 | 88 | 1998 |
| 31 | Zifeng Tower | China | Nanjing | 450 | 66 | 2010 |
| 32 | The Exchange 106 | Malaysia | Kuala Lumpur | 446 | 95 | 2019 |
| 33 | Marina 106 | UAE | Dubai | 445 | 104 | OH |
| 34 | World One | Mumbai | India | 442 | 117 | NC |
| 35 | KK 100 | China | Shenzhen | 441 | 98 | 2011 |
| 36 | Guangzhou International Finance Center | China | Guangzhou | 438 | 103 | 2010 |
| 37 | Multifunctional Highrise Complex - Akhmat Tower | Russia | Grozny | 435 | 102 | OH |
| 38 | 111 West 57th Street | USA | New York | 435 | 84 | 2021 |
| 39 | Chongqing Tall Tower | China | Chongqing | 431 | 101 | OH |
| 40 | Haikou Tower 1 | China | Haikou | 428 | 94 | UC |
| 41 | One Vanderbilt Avenue | USA | New York | 427 | 62 | 2020 |
| 42 | Marina 101 | UAE | Dubai | 425 | 101 | 2017 |
| 43 | 432 Park Avenue | USA | New York | 425 | 85 | 2015 |
| 44 | Trump International Hotel & Tower | USA | Chicago | 423 | 98 | 2009 |
| 45 | Al Hamra Tower | Kuwait | Kuwait City | 413 | 80 | 2011 |
| 46 | Princess Tower | UAE | Dubai | 413 | 101 | 2012 |
| 47 | Two International Finance Center | China | Hong Kong | 412 | 88 | 2003 |
| 48 | LCT The Sharp Landmark Tower | South Korea | Busan | 411 | 101 | 2019 |
| 49 | Guangxi China Resources Tower | China | Nanning | 402 | 86 | 2020 |
| 50 | China Resources Tower | China | Shenzhen | 393 | 68 | 2018 |
| 51 | 23 Marina | UAE | Dubai | 392 | 88 | 2012 |
| 52 | CITIC Plaza | China | Guangzhou | 390 | 80 | 1996 |
| 53 | Shum Yip Upperhills Tower 1 | China | Shenzhen | 388 | 80 | 2020 |
| 54 | Dynamic Tower | UAE | Dubai | 388 | 80 | NC |

| | | | | | | |
|---|---|---|---|---|---|---|
| 55 | 30 Hudson Yards | USA | New York | 387 | 73 | 2019 |
| 56 | PIF Tower | Saudi Arabia | Riyadh | 385 | 72 | 2021 |
| 57 | Shun Hing Square | China | Shenzhen | 384 | 69 | 1996 |
| 58 | Autograph Tower | Indonesia | Jakarta | 382 | 75 | 2022 |
| 59 | Burj Mohammed Bin Rashid | UAE | Abu Dhabi | 381 | 88 | 2014 |
| 60 | Guiyang World Trade Center Landmark Tower | China | Guiyang | 380 | 92 | OH |
| 61 | Elite Residence | UAE | Dubai | 380 | 87 | 2012 |
| 62 | Central Plaza | China | Hong Kong | 374 | 78 | 1992 |
| 63 | Federation Tower | Russia | Moscow | 373 | 93 | 2016 |
| 64 | Golden Eagle Tiandi Tower A | China | Nanjing | 368 | 77 | 2019 |
| 65 | Bank of China Tower | China | Hong Kong | 367 | 72 | 1990 |
| 66 | Ciel Tower | UAE | Dubai | 365 | 81 | UC |
| 67 | St. Regis Chicago | USA | Chicago | 362 | 101 | 2020 |
| 68 | Almas Tower | UAE | Dubai | 360 | 68 | 2008 |
| 69 | Hanking Center Tower | China | Shenzhen | 359 | 65 | 2018 |
| 70 | Greenland Group Suzhou Center | China | Suzhou | 358 | 77 | UC |
| 71 | Sino Steel International Plaza T2 | China | Tianjin | 358 | 83 | OH |
| 72 | II Primo Tower 1 | UAE | Dubai | 356 | 79 | UC |
| 73 | Emirates Tower One | UAE | Dubai | 355 | 54 | 2000 |
| 74 | OKO - Residential Tower | Russia | Moscow | 354 | 90 | 2015 |
| 75 | The Torch | UAE | Dubai | 352 | 86 | 2011 |
| 76 | Spring City 66 | China | Kunming | 349 | 61 | 2019 |
| 77 | The Center | China | Hong Kong | 346 | 73 | 1998 |
| 78 | NEVA TOWERS 2 | Russia | Moscow | 345 | 79 | 2020 |
| 79 | ADNOC Headquarters | UAE | Abu Dhabi | 342 | 65 | 2015 |
| 80 | One Shenzhen Bay Tower 7 | China | Shenzhen | 341 | 78 | 2018 |
| 81 | Comcast Technology Center | USA | Philadelphia | 339 | 59 | 2018 |
| 82 | LCT The Sharp Residential Tower A | Korea | Busan | 339 | 85 | 2019 |
| 83 | Mercury City Tower | Russia | Moscow | 338 | 75 | 2013 |
| 84 | Hengqin International Finance Center | China | Zhuhai | 337 | 69 | 2020 |
| 85 | Tianjin World Financial Center | China | Tianjin | 337 | 75 | 2011 |
| 86 | Wilshire Grand Center | USA | Los Angeles | 335 | 62 | 2017 |
| 87 | DAMAC Heights | UAE | Dubai | 335 | 88 | 2018 |
| 88 | Shimao International Plaza | China | Shanghai | 333 | 60 | 2006 |
| 89 | LCT The Sharp Residential Tower B | Korea | Busan | 333 | 85 | 2019 |
| 90 | China World Tower | China | Beijing | 330 | 74 | 2010 |
| 91 | Hon Kwok City Center | China | Shenzhen | 329 | 80 | 2017 |
| 92 | 3 World Trade Center | USA | New York | 329 | 69 | 2018 |
| 93 | Keangnam Hanoi Landmark Tower | Vietnam | Hanoi | 328 | 72 | 2012 |
| 94 | Golden Eagle Tiandi Tower B | China | Nanjing | 328 | 68 | 2019 |
| 95 | Salesforce Tower | USA | San Francisco | 326 | 61 | 2018 |
| 96 | Deji Plaza | China | Nanjing | 324 | 62 | 2013 |
| 97 | Q1 Tower | Australia | Gold Coast | 322 | 78 | 2005 |
| 98 | Nina Tower | China | Hong Kong | 320 | 80 | 2006 |
| 99 | Sinar Mas Center 1 | China | Shanghai | 320 | 65 | 2017 |
| 100 | 53 West 53 | USA | New York | 320 | 77 | 2019 |
| 101 | Palace Royale | Mumbai | India | 320 | 88 | OH |
| 102 | New York Times Tower | USA | New York | 319 | 52 | 2007 |
| 103 | Chongqing IFS T1 | China | Chongqing | 316 | 63 | 2016 |
| 104 | Australia 108 | Australia | Melbourne | 316 | 100 | 2020 |
| 105 | MahaNakhon | China | Bangkok | 314 | 79 | 2016 |
| 106 | CITIC Financial Center Tower 1 | China | Shenzhen | 312 | - | UC |
| 107 | Bank of America Plaza | USA | Atlanta | 312 | 55 | 1992 |
| 108 | Shenzhen Bay Innovation and Technology Centre Tower 1 | China | Shenzhen | 311 | 69 | 2020 |
| 109 | Menara TM | Malaysia | Kuala Lumpur | 310 | 55 | 2001 |
| 110 | Ocean Heights | UAE | Dubai | 310 | 83 | 2010 |
| 111 | Pearl River Tower | China | Guangzhou | 309 | 71 | 2013 |
| 112 | Fortune Center | China | Guangzhou | 309 | 68 | 2015 |
| 113 | Guangfa Securities Headquarters | China | Guangzhou | 308 | 60 | 2018 |
| 114 | The One | Canada | Toronto | 308 | 85 | UC |
| 115 | Burj Rafal | Saudi Arabia | Riyadh | 307 | 68 | 2014 |

| | | | | | | |
|---|---|---|---|---|---|---|
| 116 | Amna Tower | UAE | Dubai | 307 | 75 | 2020 |
| 117 | Noora Tower | UAE | Dubai | 307 | 75 | 2019 |
| 118 | The Shard | UK | London | 306 | 73 | 2013 |
| 119 | Cayan Tower | UAE | Dubai | 306 | 73 | 2013 |
| 120 | Northeast Asia Trade Tower | South Korea | Incheon | 305 | 68 | 2011 |
| 121 | 35 Hudson Yards | USA | New York City | 304 | 72 | 2019 |
| 122 | Jiangxi Nanchang Greenland Central Plaza, Parcel A | China | Nanchang | 303 | 59 | 2015 |
| 123 | Jiangxi Nanchang Greenland Central Plaza, Parcel B | China | Nanchang | 303 | 59 | 2015 |
| 124 | Two Prudential Plaza | USA | Chicago | 303 | 64 | 1990 |
| 125 | One Manhattan West | USA | New York | 303 | 67 | 2019 |
| 126 | Leatop Plaza | China | Guangzhou | 303 | 64 | 2012 |
| 127 | Kingdom Centre | Saudi Arabia | Riyadh | 302 | 41 | 2002 |
| 128 | Capital City Moscow Tower | Russia | Moscow | 301 | 76 | 2010 |
| 129 | Aspire Tower | Qatar | Doha | 300 | 36 | 2007 |
| 130 | Abeno Harukas | Japan | Osaka | 300 | 60 | 2014 |
| 131 | Shimao Riverside Block D2b | China | Wuhan | 300 | 53 | UC |
| 132 | Torre Costanera | Chile | Santiago | 300 | 62 | 2014 |
| 133 | Supernova Spira | India | Noida | 300 | 80 | OH |
| 134 | Al Wasl Tower | UAE | Dubai | 300 | 64 | UC |
| 135 | NBK Tower | Kuwait | Kuwait City | 300 | 61 | 2019 |
| 136 | Golden Eagle Tiandi Tower C | China | Nanjing | 300 | 60 | 2019 |
| 137 | Grand Parkray Hangzhou Hotel Tower 1 | China | Hangzhou | 258 | 50 | 2013 |
| 138 | Yunda Central Plaza–St. Regis Hotel | China | Changsha | 248 | 63 | 2016 |
| 139 | Shangri-La by the Gardens | Australia | Melbourne | 231 | 59 | 2023 |
| 140 | Westin Hotel | China | Changsha | 230 | 46 | 2018 |
| 141 | Oasia Hotel Downtown | Singapore | Singapore | 191 | 27 | 2016 |
| 142 | Jewel Hotel | Australia | Gold Coast | 170 | 48 | 2019 |
| 143 | Hotel Las Americas Golden Tower | Panama | Panama City | 152 | 31 | 2016 |
| 144 | Bulgari Hotel | China | Shanghai | 150 | 37 | 2017 |
| 145 | APA Hotel & Resort Yokohama Bay Tower | Japan | Yokohama | 136 | 37 | 2019 |
| 146 | Kerry Hotel | China | Shanghai | 128 | 30 | 2011 |
| 147 | Hotel Porta Fira (Torres Porta Fira) | Spain | L'Hospitalet de Llobregat | 114 | 27 | 2010 |
| 148 | Costanera Hotel (Torre Costanera 4) | Chile | Santiago | 113 | 28 | 2012 |
| 149 | Moxy Hotel | USA | New York | 111 | 30 | 2018 |
| 150 | AC Hotel NoMad | USA | New York | 109 | 26 | OH |
| 151 | Hilton Hotel at 54th | USA | New York | 104 | 34 | 2013 |
| 152 | J Hotel @ Jervois Street | China | Hong Kong | 102 | 29 | 2011 |
| 153 | T30 Hotel (T30 Tower Hotel) | China | Changsha | 100 | 30 | 2012 |
| 154 | 1 Hotel and Embassy Suites | USA | Nashville | 99 | 26 | 2022 |
| 155 | Next Hotel (80 Collins) | Australia | Melbourne | 98 | 27 | 2020 |
| 156 | Hotel Riu Plaza New York Times Square | USA | New York | 90 | 27 | 2016 |
| 157 | Ramada Hotels and Suítes | Brazil | Recife | 88 | 26 | 2015 |
| 158 | CHAO Hotel | China | Beijing | 85 | 25 | 2017 |
| 159 | Clarion Hotel Helsinki | Finland | Helsinki | 78 | 16 | 2016 |
| 160 | Hôtel Monville | Canada | Montreal | 76 | 20 | 2018 |
| 161 | citizenM Hotel | USA | New York | 75 | 19 | 2019 |
| 162 | QO Hotel | Netherlands | Amsterdam | 70 | 21 | 2017 |
| 163 | Graduate Hotel | USA | New York | 69 | 18 | 2021 |
| 164 | Westin Hotel | USA | Austin | 65 | 19 | 2015 |
| 165 | Hotel Resonance Taipei | Taiwan | Taipei | 61 | 16 | 2020 |
| 166 | Fletcher Hotel Amsterdam | Netherlands | Amsterdam | 60 | 17 | 2013 |

Note on abbreviations: 'UAE' indicates the United Arab Emirates; 'UC' indicates Under construction; 'NC' indicates Never completed; 'OH' indicates on hold.

**Table A2.** 166 tall and supertall case study buildings by building form, function, core type, structural system, structural material, and space efficiency ratio.

| # | Building Name | Building Form | Function | Core Type | Structural System | Structural Material | Space Efficiency |
|---|---|---|---|---|---|---|---|
| 1 | Nakheel Tower | Free | M (H/R/O) | Central | Mega column | Composite | 69% |
| 2 | Burj Khalifa | Setback | M (H/R/O) | Central | Buttressed core | Concrete | 80% |
| 3 | Suzhou Zhongnan Center | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 62% |
| 4 | Merdeka PNB118 | Free | M (H/O) | Central | Outriggered frame | Composite | 65% |
| 5 | Shanghai Tower | Twisted | M (H/O) | Central | Outriggered frame | Composite | 71% |
| 6 | Chicago Spire | Twisted | R | Central | Outriggered frame | Concrete | 75% |
| 7 | Ping An Finance Center | Tapered | O | Central | Outriggered frame | Composite | 70% |
| 8 | Goldin Finance 117 | Tapered | M (H/O) | Central | Trussed-tube | Composite | 68% |
| 9 | Entisar Tower | Setback | M (H/R) | Central | Framed-tube | Concrete | 74% |
| 10 | Lotte World Tower | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 69% |
| 11 | One World Trade Center | Tapered | O | Central | Outriggered frame | Composite | 70% |
| 12 | Tianjin CTF Finance Centre | Tapered | M (H/O) | Central | Framed-tube | Composite | 70% |
| 13 | Guangzhou CTF Finance Centre | Setback | M (H/R/O) | Central | Outriggered Frame | Composite | 65% |
| 14 | CITIC Tower | Free | O | Central | Trussed-tube | Composite | 70% |
| 15 | Evergrande Hefei Center 1 | Free | M (H/R/O) | Central | Outriggered frame | Composite | 59% |
| 16 | Pentominium Tower | Free | R | Central | Outriggered frame | Concrete | 73% |
| 17 | Busan Lotte Town Tower | Free | M (H/R/O) | Central | Outriggered frame | Composite | 70% |
| 18 | TAIPEI 101 | Free | O | Central | Outriggered frame | Composite | 72% |
| 19 | Greenland Jinmao International Financial Center | Tapered | M (H/O) | Central | Outriggered frame | Composite | 55% |
| 20 | Shanghai World Financial Center | Tapered | M (H/O) | Central | Outriggered frame | Composite | 69% |
| 21 | International Commerce Centre | Tapered | M (H/O) | Central | Outriggered frame | Composite | 69% |
| 22 | Wuhan Greenland Center | Tapered | M (H/R/O) | Central | Buttressed core | Composite | 67% |
| 23 | Central Park Tower | Setback | R | Central | Outriggered frame | Concrete | 80% |
| 24 | Chengdu Greenland Tower | Tapered | M (H/O) | Central | Outriggered frame | Composite | 72% |
| 25 | R&F Guangdong Building | Setback | M (H/R/O) | Central | Outriggered frame | Composite | 68% |
| 26 | Lakhta Center | Twisted | O | Central | Outriggered frame | Composite | 67% |
| 27 | Vincom Landmark 81 | Setback | M (H/R) | Central | Bundled-tube | Composite | 69% |
| 28 | Changsha IFS Tower T1 | Prismatic | M (H/O) | Central | Outriggered frame | Composite | 63% |
| 29 | Petronas Twin Tower 1 | Setback | O | Central | Outriggered frame | Concrete | 72% |
| 30 | Petronas Twin Tower 2 | Setback | O | Central | Outriggered frame | Concrete | 72% |
| 31 | Zifeng Tower | Free | M (H/O) | Central | Outriggered frame | Composite | 71% |
| 32 | The Exchange 106 | Tapered | O | Central | Outriggered frame | Composite | 70% |
| 33 | Marina 106 | Prismatic | R | Central | Framed-tube | Concrete | 78% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 34 | World One | Setback | R | Central | Buttressed core | Concrete | 78% |
| 35 | KK 100 | Free | M (H/O) | Central | Framed-tube | Composite | 61% |
| 36 | Guangzhou International Finance Center | Tapered | M (H/O) | Central | Outriggered frame | Composite | 71% |
| 37 | Multifunctional Highrise Complex—Akhmat Tower | Tapered | M (R/O) | Central | Framed-tube | Steel | 75% |
| 38 | 111 West 57th Street | Setback | R | Peripheral | Outriggered frame | Concrete | 69% |
| 39 | Chongqing Tall Tower | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 81% |
| 40 | Haikou Tower 1 | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 75% |
| 41 | One Vanderbilt Avenue | Tapered | O | Central | Outriggered frame | Composite | 72% |
| 42 | Marina 101 | Prismatic | M (H/R) | Central | Framed-tube | Concrete | 82% |
| 43 | 432 Park Avenue | Prismatic | R | Central | Framed-tube | Concrete | 80% |
| 44 | Trump International Hotel & Tower | Setback | M (H/R) | Central | Outriggered frame | Concrete | 62% |
| 45 | Al Hamra Tower | Free | O | Central | Shear walled frame | Composite | 70% |
| 46 | Princess Tower | Prismatic | R | Central | Framed-tube | Concrete | 82% |
| 47 | Two International Finance Center | Setback | O | Central | Outriggered frame | Composite | 71% |
| 48 | LCT The Sharp Landmark Tower | Prismatic | M (H/R) | Central | Outriggered frame | Concrete | 56% |
| 49 | Guangxi China Resources Tower | Tapered | M (H/O) | Central | Outriggered frame | Composite | 61% |
| 50 | China Resources Tower | Tapered | O | Central | Framed-tube | Composite | 73% |
| 51 | 23 Marina | Prismatic | R | Central | Outriggered frame | Concrete | 81% |
| 52 | CITIC Plaza | Prismatic | O | Central | Shear walled frame | Concrete | 67% |
| 53 | Shum Yip Upperhills Tower 1 | Prismatic | M (H/O) | Central | Outriggered frame | Composite | 64% |
| 54 | Dynamic Tower | Free | M (H/R) | Central | Mega core | Concrete | 84% |
| 55 | 30 Hudson Yards | Tapered | O | Central | Outriggered frame | Steel | 69% |
| 56 | PIF Tower | Free | O | Central | Trussed-tube | Composite | 65% |
| 57 | Shun Hing Square | Free | O | Central | Outriggered frame | Composite | 67% |
| 58 | Autograph Tower | Prismatic | M (H/O) | Central | Outriggered frame | Composite | 68% |
| 59 | Burj Mohammed Bin Rashid | Free | R | Central | Outriggered frame | Concrete | 73% |
| 60 | Guiyang World Trade Center Landmark Tower | Tapered | M (H/O) | Central | Framed-tube | Composite | 71% |
| 61 | Elite Residence | Prismatic | R | Central | Framed-tube | Concrete | 84% |
| 62 | Central Plaza | Prismatic | O | Central | Trussed-tube | Composite | 66% |
| 63 | Federation Tower | Free | M (R/O) | Central | Outriggered frame | Composite | 82% |
| 64 | Golden Eagle Tiandi Tower A | Tapered | M (H/O) | Central | Outriggered frame | Composite | 70% |
| 65 | Bank of China Tower | Setback | O | Central (split) | Trussed-tube | Composite | 82% |
| 66 | Ciel Tower | Prismatic | H | Central | Outriggered frame | Concrete | 72% |
| 67 | St. Regis Chicago | Free | M (H/R) | Central | Outriggered frame | Concrete | 76% |
| 68 | Almas Tower | Free | O | Central | Outriggered frame | Composite | 77% |
| 69 | Hanking Center Tower | Tapered | O | External | Trussed-tube | Steel | 70% |
| 70 | Greenland Group Suzhou Center | Free | M (H/O) | Central | Outriggered frame | Composite | 70% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 71 | Sino Steel International Plaza T2 | Prismatic | O | Central | Framed-tube | Composite | 68% |
| 72 | II Primo Tower 1 | Prismatic | R | Central | Outriggered frame | Concrete | 71% |
| 73 | Emirates Tower One | Prismatic | O | Central | Mega column | Composite | 70% |
| 74 | OKO—Residential Tower | Free | M (H/R) | Central | Outriggered frame | Concrete | 76% |
| 75 | The Torch | Prismatic | R | Central | Outriggered frame | Concrete | 74% |
| 76 | Spring City 66 | Free | O | Central | Outriggered frame | Composite | 70% |
| 77 | The Center | Prismatic | O | Central | Mega column | Composite | 68% |
| 78 | NEVA TOWERS 2 | Prismatic | R | Central | Outriggered frame | Concrete | 77% |
| 79 | ADNOC Headquarters | Prismatic | O | External | Shear walled frame | Concrete | 63% |
| 80 | One Shenzhen Bay Tower 7 | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 81% |
| 81 | Comcast Technology Center | Setback | M (H/O) | Central | Trussed-tube | Composite | 74% |
| 82 | LCT The Sharp Residential Tower A | Prismatic | R | Central | Outriggered frame | Concrete | 56% |
| 83 | Mercury City Tower | Setback | M (R/O) | Central | Framed-tube | Concrete | 80% |
| 84 | Hengqin International Finance Center | Free | M (R/O) | Central | Outriggered frame | Composite | 67% |
| 85 | Tianjin World Financial Center | Tapered | O | Central | Outriggered frame | Composite | 72% |
| 86 | Wilshire Grand Center | Tapered | M (H/O) | Central | Outriggered frame | Composite | 80% |
| 87 | DAMAC Heights | Tapered | R | Central | Outriggered frame | Concrete | 72% |
| 88 | Shimao International Plaza | Free | M (H/O) | Central | Mega column | Composite | 67% |
| 89 | LCT The Sharp Residential Tower B | Prismatic | R | Central | Outriggered frame | Concrete | 56% |
| 90 | China World Tower | Tapered | M (H/O) | Central | Outriggered frame | Composite | 79% |
| 91 | Hon Kwok City Center | Prismatic | M (R/O) | Central | Outriggered frame | Composite | 70% |
| 92 | 3 World Trade Center | Setback | O | Central | Trussed-tube | Composite | 67% |
| 93 | Keangnam Hanoi Landmark Tower | Setback | M (H/R/O) | Central | Outriggered frame | Concrete | 72% |
| 94 | Golden Eagle Tiandi Tower B | Tapered | O | Central | Outriggered frame | Composite | 65% |
| 95 | Salesforce Tower | Tapered | O | Central | Shear walled frame | Composite | 72% |
| 96 | Deji Plaza | Prismatic | M (H/O) | Central | Outriggered frame | Composite | 73% |
| 97 | Q1 Tower | Prismatic | R | Central | Outriggered frame | Concrete | 78% |
| 98 | Nina Tower | Prismatic | M (H/O) | Central | Outriggered frame | Concrete | 71% |
| 99 | Sinar Mas Center 1 | Free | O | Central | Outriggered frame | Composite | 72% |
| 100 | 53 West 53 | Tapered | R | Peripheral | Framed-tube | Concrete | 82% |
| 101 | Palace Royale | Prismatic | R | Central | Outriggered frame | Concrete | 82% |
| 102 | New York Times Tower | Prismatic | O | Central | Outriggered frame | Steel | 75% |
| 103 | Chongqing IFS T1 | Prismatic | M (H/O) | Central | Outriggered frame | Composite | 74% |
| 104 | Australia 108 | Free | R | Central | Outriggered frame | Concrete | 84% |
| 105 | MahaNakhon | Free | M (H/R) | Central | Outriggered frame | Concrete | 65% |

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 106 | CITIC Financial Center Tower 1 | Tapered | M (R/O) | Central | Framed-tube | Composite | 70% |
| 107 | Bank of America Plaza | Setback | O | Central | Mega column | Composite | 78% |
| 108 | Shenzhen Bay Innovation and Technology Centre Tower 1 | Prismatic | O | Central | Framed-tube | Composite | 71% |
| 109 | Menara TM | Free | O | Central | Outriggered frame | Concrete | 75% |
| 110 | Ocean Heights | Tapered | R | Central | Outriggered frame | Concrete | 84% |
| 111 | Pearl River Tower | Free | O | Central | Outriggered frame | Composite | 79% |
| 112 | Fortune Center | Free | O | Central | Outriggered frame | Composite | 77% |
| 113 | Guangfa Securities Headquarters | Tapered | O | Central | Outriggered frame | Composite | 74% |
| 114 | The One | Prismatic | R | Central | Outriggered frame | Composite | 76% |
| 115 | Burj Rafal | Prismatic | M (H/R) | Central | Outriggered frame | Composite | 78% |
| 116 | Amna Tower | Prismatic | R | Central | Outriggered frame | Concrete | 77% |
| 117 | Noora Tower | Prismatic | R | Central | Outriggered frame | Concrete | 77% |
| 118 | The Shard | Tapered | M (H/R/O) | Central | Shear walled frame | Composite | 79% |
| 119 | Cayan Tower | Twisted | R | Central | Framed-tube | Concrete | 83% |
| 120 | Northeast Asia Trade Tower | Tapered | M (H/R/O) | Central | Outriggered frame | Composite | 72% |
| 121 | 35 Hudson Yards | Setback | M (H/R) | Central | Outriggered frame | Concrete | 80% |
| 122 | Jiangxi Nanchang Greenland Central Plaza, Parcel A | Free | O | Central | Outriggered frame | Composite | 70% |
| 123 | Jiangxi Nanchang Greenland Central Plaza, Parcel B | Free | O | Central | Outriggered frame | Composite | 70% |
| 124 | Two Prudential Plaza | Setback | O | Central | Outriggered frame | Concrete | 69% |
| 125 | One Manhattan West | Tapered | O | Central | Shear walled frame | Composite | 70% |
| 126 | Leatop Plaza | Prismatic | O | Central | Trussed-tube | Composite | 76% |
| 127 | Kingdom Centre | Free | M (H/R/O) | Central | Shear walled frame | Concrete | 78% |
| 128 | Capital City Moscow Tower | Free | R | Central | Outriggered frame | Concrete | 79% |
| 129 | Aspire Tower | Free | M (H/O) | Central | Mega core | Concrete | 72% |
| 130 | Abeno Harukas | Setback | M (H/O) | Central | Outriggered frame | Composite | 79% |
| 131 | Shimao Riverside Block D2b | Tapered | M (H/O) | Central | Outriggered frame | Composite | 73% |
| 132 | Torre Costanera | Tapered | M (H/O) | Central | Outriggered frame | Concrete | 69% |
| 133 | Supernova Spira | Prismatic | M (H/R) | Central | Outriggered frame | Concrete | 63% |
| 134 | Al Wasl Tower | Free | M (H/R/O) | Central | Outriggered frame | Composite | 74% |
| 135 | NBK Tower | Free | O | Central | Outriggered frame | Composite | 74% |
| 136 | Golden Eagle Tiandi Tower C | Tapered | O | Central | Outriggered frame | Composite | 75% |
| 137 | Grand Parkray Hangzhou Hotel Tower 1 | Free | H | Central | Outriggered frame | Composite | 78% |
| 138 | Yunda Central Plaza –St. Regis Hotel | Prismatic | H | Central | Outriggered frame | Composite | 76% |

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|---|---|---|---|---|---|---|---|
| 139 | Shangri-La by the Gardens | Prismatic | H | Central | Outriggered frame | Composite | 81% |
| 140 | Westin Hotel | Prismatic | H | Peripheral | Shear walled frame | Concrete | 82% |
| 141 | Oasia Hotel Downtown | Prismatic | H | Peripheral | Shear walled frame | Concrete | 91% |
| 142 | Jewel Hotel | Free | H | Peripheral | Shear walled frame | Concrete | 79% |
| 143 | Hotel Las Americas Golden Tower | Prismatic | H | Peripheral | Shear walled frame | Concrete | 74% |
| 144 | Bulgari Hotel | Prismatic | H | Central | Shear walled frame | Concrete | 72% |
| 145 | APA Hotel & Resort Yokohama Bay Tower | Prismatic | H | Central | Rigid frame system | Steel | 77% |
| 146 | Kerry Hotel | Prismatic | H | Central | Shear walled frame | Concrete | 70% |
| 147 | Hotel Porta Fira (Torres Porta Fira) | Free | H | Central | Shear walled frame | Concrete | 78% |
| 148 | Costanera Hotel (Torre Costanera 4) | Prismatic | H | Central | Shear walled frame | Concrete | 78% |
| 149 | Moxy Hotel | Prismatic | H | Peripheral | Shear walled frame | Concrete | 80% |
| 150 | AC Hotel NoMad | Prismatic | H | Peripheral | Shear walled frame | Composite | 79% |
| 151 | Hilton Hotel at 54th | Setback | H | Central | Shear walled frame | Concrete | 94% |
| 152 | J Hotel @ Jervois Street | Prismatic | H | Central | Shear walled frame | Concrete | 76% |
| 153 | T30 Hotel (T30 Tower Hotel) | Prismatic | H | Central | Rigid frame system | Steel | 88% |
| 154 | 1 Hotel and Embassy Suites | Prismatic | H | Central | Shear walled frame | Concrete | 91% |
| 155 | Next Hotel (80 Collins) | Free | H | Central | Shear walled frame | Concrete | 84% |
| 156 | Hotel Riu Plaza New York Times Square | Prismatic | H | Peripheral | Shear walled frame | Concrete | 76% |
| 157 | Ramada Hotels and Suítes | Prismatic | H | Peripheral | Shear walled frame | Concrete | 88% |
| 158 | CHAO Hotel | Prismatic | H | Central | Shear walled frame | Concrete | 87% |
| 159 | Clarion Hotel Helsinki | Prismatic | H | Peripheral | Shear walled frame | Concrete | 83% |
| 160 | Hôtel Monville | Prismatic | H | Peripheral | Shear walled frame | Concrete | 76% |
| 161 | citizenM Hotel | Prismatic | H | Central | Shear walled frame | Concrete | 78% |
| 162 | QO Hotel | Free | H | Central | Shear walled frame | Concrete | 83% |
| 163 | Graduate Hotel | Free | H | Central | Rigid frame system | Concrete | 93% |
| 164 | Westin Hotel | Free | H | Central | Shear walled frame | Concrete | 88% |
| 165 | Hotel Resonance Taipei | Prismatic | H | Peripheral | Rigid frame system | Concrete | 84% |
| 166 | Fletcher Hotel Amsterdam | Prismatic | H | Central | Shear walled frame | Concrete | 80% |

Note on abbreviations: ‘M’ indicates Mixed-use; ‘H’ indicates Hotel; ‘R’ indicates Residential; ‘O’ indicates Office.

## REFERENCES

1. CTBUH Council on Tall Buildings and Urban Habitat. Illinois Institute of Technology, S.R. Crown Hall, 3360 South State Street, Chicago, Illinois, USA. Available from: www.ctbuh.org. Accessed on 7 Aug 2025.
2. Ali MM, Moon K-S. Structural developments in tall buildings: Current trends and future prospects. Architect Sci Rev. 2007;50(3):205-23. doi: 10.3763/asre.2007.5027.
3. Yeang K. The green skyscraper: The basis for designing sustainable intensive buildings. Munich (Germany): Prestel; 1999.
4. Glaeser E. Triumph of the city: How our greatest invention makes us richer, smarter, greener, healthier, and happier. London (UK): Penguin Press; 2011.
5. Willis C. Form follows finance: Skyscrapers and skylines in New York and Chicago. New York (NY, US): Princeton Architect Press; 1995.
6. Moon K-S. Optimal form combinations for tall buildings. CTBUH J. 2008;(1):18-25.
7. Ilgın HE, Aslantamer ÖN. Space efficiency in contemporary supertall residential buildings. Buildings. 2024;14(3):1042. doi: 10.3390/buildings14031042.
8. Al-Kodmany K. The vertical city: A sustainable development model. Southampton (UK): WIT Press; 2015.
9. Ilgın HE, Aslantamer ÖN. Space efficiency in tall hotel towers. Buildings. 2024;14(7):2051. doi: 10.3390/buildings14072051.
10. Ilgın HE, Aslantamer ÖN. Investigating space utilization in skyscrapers designed with prismatic form. Buildings. 2024;14(6):1826. doi: 10.3390/buildings14061826.
11. Ilgın HE, Aslantamer ÖN. Space efficiency of tall buildings in Singapore. Appl Sci. 2024;14(18):8397. doi: 10.3390/app14188397.
12. Wong NH, Lau SSY. Design responses to spatial efficiency in tropical high-rises. J Urban Des. 2020;25(5):630-51. doi: 10.1080/13574809.2020.1747980.
13. Ilgın HE, Aslantamer ÖN. Space efficiency in North American skyscrapers. Buildings. 2024;14(8):2382. doi: 10.3390/buildings14082382.
14. Huang JX, Li QS, Han XL. Prediction of wind pressures on supertall buildings based on proper orthogonal decomposition and machine learning. Struct Des Tall Spec Build. 2024;33(4):e2174. doi: 10.1002/tal.2174.
15. Neelamegam P, Jose YS, Usha S. Optimizing structural performance of short concrete-filled steel tube columns with stiffening methods using Lea-HGCNN technique. Int J High-Rise Build. 2025;14(1):22-36. doi: 10.1142/S0219876225500112.
16. Abedini MH, Gholami H, Sangin H. Multi-objective optimization of window and shading systems for enhanced office building performance. J Daylighting. 2025. Available from: https://solarlits.com/jd/12-91. Accessed on 8 Aug 2025.
17. Yang C, Liu W, Wang W, Xiang C. Risk-aware obstacle avoidance planning near tall buildings. Unmanned Syst. 2025;13(1). doi: 10.1142/S2301385026500196.
18. Li S, Ao Y. Artificial intelligence-aided design (AIAD) for structures. Arch Comput Methods Eng. 2025. doi: 10.1007/s11831-025-10264-1.

19. Felix M, Elsamahy EM. Creating walkability with wayfinding techniques through adaptive reuse. Archit Plan J. 2025;31(1):5.
20. Hågbo TO. Towards realistic and efficient CFD simulations for urban wind and spatial comfort. University of Stavanger; 2025. Available from: https://uis.brage.unit.no/handle/11250/3178687. Accessed on 8 Aug 2025.
21. Cui J, Zhang J, Sun F. Spatial characteristics of land subsidence in architectural heritage sites. Heritage. 2025;8(4):113. Available from: https://www.mdpi.com/2571-9408/8/4/113. Accessed on 8 Aug 2025.
22. Beedle LS, Ali MM, Armstrong PJ. The skyscraper and the city: Design, technology, and innovation. Lewiston (NY, US): Edwin Mellen Press; 2007.
23. Ford LR. Skyscraper competition in Asia: New city images and new city form. In: Imaging the City. Oxfordshire (UK): Routledge; 2021. p. 119-44.
24. Crawford P, Lee E, Beatty M. Aesthetic perception of urban streetscapes and the impact of form-based codes and traditional zoning codes on commercial signage. Curr Urban Stud. 2015;3(03):199.
25. Chen FB, Wang XL, Li X, Shu ZR, Zhou K. Prediction of wind pressures on tall buildings using wavelet neural network. J Build Eng. 2022;46:103674.


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