Published by Avanti Publishers

International Journal of Architectural Engineering Technology

ISSN (online): 2409-9821

Comparative Analysis of Space Efficiency in Contemporary Tall Buildings: Residential, Office, Hotel and Mixed-Use Functions

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

[1]School of Architecture, Faculty of Built Environment, Tampere University, P.O. Box 600, FI–33014 Tampere, Finland

[2]Department of Interior Architecture and Environmental Design, Faculty of Art, Design and Architecture, Atılım University, Ankara 06830, Turkey

ARTICLE INFO

Article Type: Research Article

Academic Editor: Kashan Khan

Keywords:
Hotel
Office
Tower
Mixed-use
Residential
Space efficiency

Timeline:
Received: August 21, 2024
Accepted: October 11, 2024
Published: October 17, 2024

Citation: Ilgın HE, Aslantamer ÖN. Comparative analysis of space efficiency in contemporary tall buildings: Residential, office, hotel and mixed-use functions. Int J Archit Eng Technol. 2024; 11: 60-79.

DOI: https://doi.org/10.15377/2409-9821.2024.11.4

ABSTRACT

This paper offers an in-depth comparative analysis of space efficiency in contemporary tall towers, specifically focusing on residential, office, hotel and mixed-use functions (166 cases in total). To the best of current knowledge, no study in the existing literature has focused on this critical and topical subject. The findings underscore the pivotal importance of central core planning and prismatic building forms, which emerge as crucial design elements for optimizing space efficiency across all building types. Central core planning ensures the strategic placement of essential elements like elevators and stairwells, thereby minimizing wasted space and maximizing usable floor area. Meanwhile, prismatic building forms, characterized by their straightforward geometric shapes, facilitate more efficient construction processes and space usage. Average space efficiencies of residential, office, hotel and mixed towers were 76%, 71%, 81%, and 71%, whereas core area to GFA ratio were 19%, 26%, 16% and 26%, respectively. Values fluctuated from the lowest of 55% and 4% to the highest of 94% and 38%. By exploring these dimensions, this research offers valuable insights for the architects and developers, guiding them in the creation of tall buildings that are not only architecturally impressive but also economically viable and highly efficient. This comprehensive analysis serves as a critical resource, emphasizing the need for a balanced approach that considers core planning, structural integrity, and material choice in the design and construction of tall edifices. This holistic perspective is essential for professionals aiming to achieve the highest standards of efficiency and practicality in their architectural endeavors.

*Corresponding Author
Email: emre.ilgin@tuni.fi
Tel: +(358) 505738397

1. Introduction

1.1. Historical Context and Evolution of Tall Buildings

The construction of tall buildings began in the late 19th century, driven by pivotal advancements in elevator technology and the development of metal rigid frames [1-3]. These innovations heralded the advent of skyscrapers as a unique American building type, revolutionizing urban architecture and paving the way for future developments. Over the decades, the quest for greater heights transcended national borders, propelled by socio-technical advancements and the growing demand for urban space efficiency. Iconic early examples, such as Empire State Building and the Chrysler Building from New York, epitomized this architectural revolution, demonstrating that skyscrapers could be both functional and iconic [4-6]. These pioneering structures not only transformed city skylines but also showcased the immense potential for vertical expansion in urban settings. As technology advanced, the complexity of constructing these towering edifices increased, necessitating innovations in materials such as high-strength steel and reinforced concrete [7]. Alongside these material advancements, new construction techniques and evolving design philosophies emerged, enabling the creation of buildings that reach unprecedented heights. Modern tall buildings are meticulously designed to maximize usable space while enhancing energy efficiency and sustainability [8]. They incorporate cutting-edge technologies like smart building systems and green construction practices, ensuring they meet the multifaceted demands of contemporary urban living while minimizing their environmental footprint [9-11]. Today's tall buildings stand as testaments to the continuous evolution of architectural and engineering practices, representing a progression from simply tall structures to sophisticated, efficient, and sustainable urban landmarks [12-14]. These advancements not only support the functional and economic viability of these buildings but also align with broader environmental goals, making contemporary skyscrapers integral to the future of sustainable urban development.

1.2. Background and Significance

Tall buildings have emerged as iconic symbols of modernity and economic prowess, reshaping the skylines of cities such as New York, Dubai, and Shanghai and becoming integral to their urban identities [15-17]. These towering structures epitomize the advancements in architectural design and engineering capabilities, reflecting the ambitions and growth of the cities they inhabit. However, the process of designing and constructing buildings that soar to such heights while maintaining space efficiency presents significant challenges that demand innovative solutions and meticulous planning [18, 19]. The economic implications of space efficiency in tall buildings are substantial, as optimizing the usable or rentable space within these structures directly enhances their financial viability [20]. High space efficiency means that more floor area can be allocated for productive use, which can lead to increased revenue from leasing or sales, thereby justifying the substantial investments required for such ambitious projects. Achieving this efficiency involves a careful balance of architectural creativity, structural integrity, and the integration of advanced technologies. Architects and engineers must consider a myriad of factors, from core planning and structural systems to the selection of materials and building forms, to ensure that every square meter of the building contributes to its overall functionality and profitability. As cities continue to grow vertically, the emphasis on space efficiency will play a crucial role in the sustainable development of urban environments, ensuring that tall buildings remain not only feats of engineering but also practical, economically sound investments.

1.3. Key Factors Influencing Space Efficiency

Space efficiency in tall towers is shaped by a complex interplay of several interrelated factors, including core planning, form, structural systems, and the choice of structural materials [21-24]. Extensive research has delved into these elements across various building types, uncovering trends and best practices that significantly enhance space utilization. Among these factors, core planning emerges as a critical component, with central core designs being identified as the most prevalent typology [25-27]. This preference is largely due to the structural advantages that central cores offer, such as improved stability and load distribution, which are essential for the integrity of tall buildings. Moreover, central core designs are highly effective in maximizing usable floor area, allowing for more flexible and efficient interior layouts. The building form also plays a crucial role [28-30], with prismatic forms often being favored for their simplicity and ease of construction, further contributing to space efficiency. Additionally, the selection of structural systems [31-33] and materials is pivotal [34-36]; for instance, the use of high-strength steel and reinforced concrete can reduce the footprint of structural elements, thereby freeing up more floor space for functional use. By integrating these various design considerations, architects and engineers can develop tall buildings that not only reach impressive heights but also optimize the available space, ensuring economic viability and enhancing the overall functionality of the building. This holistic approach to design is vital in addressing the challenges posed by urban density and the need for sustainable development, making space efficiency a key priority in the construction of modern tall structures.

1.4. Objectives

The primary objectives of this study are to:

1. Analyze the space efficiency of tall buildings across different functions: residential [37], office [38], hotel [39], and mixed-use [40].
2. Identify key architectural and structural design considerations that impact space efficiency.
3. Compare the effectiveness of various design strategies in optimizing space efficiency.
4. Provide insights and recommendations for architects and developers to enhance space efficiency in future tall building projects.

Overall, the rise of tall buildings has profoundly reshaped urban skylines around the world, symbolizing advancements in engineering and architectural design [41, 42]. These towering structures serve diverse functions, encompassing office spaces, residential units, hotel accommodations, and mixed-use complexes, each presenting unique challenges and opportunities in their design and construction. Central to the success and viability of these immense edifices is the concept of space efficiency, which engages in maximizing the usable floor area relative to the building's gross floor area. Achieving optimal space efficiency is crucial not only for ensuring the financial viability of these ambitious projects but also for enhancing their functional effectiveness and sustainability. This study seeks to offer a comprehensive comparison of space efficiency across different types of tall buildings, delving into the intricacies of how various architectural and structural design choices—such as core planning, form, and material selection—impact this vital parameter. By systematically analyzing these design elements, the research aims to uncover the best practices and innovative solutions that can lead to more efficient, cost-effective, and user-friendly tall buildings. The insights gained from this comparative analysis are intended to inform architects, engineers, and developers, guiding them in creating tall structures that not only stand as iconic landmarks but also meet the highest standards of practicality and economic viability.

2. Literature Survey

In the realm of building space efficiency, many influential works studied numerous dimensions and contexts, offering valuable methodologies and findings. Investigating non-conventional designs, Okbaz *et al*. [43] identified trends in spatial efficiency in unorthodox office towers, demonstrating that architectural design profoundly affects spatial performance, with conical configurations being the most competent. This underscores the importance of creative architectural solutions in enhancing space utilization. Ibrahimy *et al*. [44] examined spatial utilization in residential developments in Kabul, revealing significant deviations from regulatory norms due to insufficient focus on architectural design and building codes. Höjer *et al*. [45] delved into identifying ways to optimize office space utilization, examining strategies to minimize overall space requirements and exploring methods for quantifying the potential energy savings. The impact of emerging technologies on dense urban living spaces was explored by Goessler *et al*. [46], who suggested that these innovations could increase spatial efficiency by two to three times compared to conventional approaches. This highlights the significant potential of technological advancements in the design of urban housing. Hamid *et al*. [47] demonstrated that corner placement of buildings enhances land use efficiency in Sudanese homes, stressing the relevance of intentional placement strategies in architectural planning. Similarly, Suga [48] analyzed space utilization in hotel structures, noting the benefits of efficient space use in the hospitality industry. Arslan [49] studied the factors affecting load-bearing structures in prismatic high-rise buildings, offering insights into the structural considerations that impact spatial efficiency. von Both [50] introduced a collaborative method involving stakeholders during the design phase to optimize space utilization, advocating for a participatory design process. Höjer *et al*. [51] provided guidelines on how digital technologies affect interior space configuration, reflecting the increasing importance of digitalization in architectural design. Nam *et al*. [52] assessed the effects of corner designs and lease durations on spatial efficiency, concluding that corner cuts had minimal impact, but lease durations significantly influenced efficiency. Zhang *et al*. [53] created a model to maximize solar radiation capture in cold environments in relation to spatial efficiency, illustrating the connection of sustainable design and spatial optimization. Sev *et al*. [54] evaluated space utilization in office high-rises, highlighting the critical role of load-bearing arrangements and core design in achieving space efficiency. Saari *et al*. [55] investigated the link between space optimization and overall project costs in office towers, emphasizing the financial advantages of efficient spatial design. Kim *et al*. [56] reviewed spatial efficiency ratios in multi-functional skyscrapers, stressing the necessity of integrating optimal structural systems and configurations. Collectively, these studies highlight the multifaceted nature of space efficiency in architecture, pointing out the importance of innovative design, technological integration, regulatory compliance, and strategic structural planning. Each study contributes to the broader understanding of how to maximize space utilization across different contexts.

A comprehensive examination of the existing literature reveals a notable research gap regarding comparative analysis of space efficiency in contemporary tall buildings with various functions. To bridge this gap and deepen the understanding of emerging trends, this paper seeks to systematically gather and evaluate data on spatial efficiency in these structures. Through an in-depth investigation of 166 case studies, this research will explore critical architectural and structural characteristics, with the aim of identifying patterns and offering valuable insights into this relatively underexamined subject.

3. Methods

Case study approach was utilized to organize and gather data from 166 high-rise towers, as depicted in Fig. (**1**). This approach is commonly applied in research to capture both qualitative and quantitative information and to conduct thorough literature reviews [57-61]. It facilitates a thorough assessment of the architectural and structural components of these projects, allowing for a comprehensive exploration of real-world cases. This approach enables a deep examination of each individual case, offering valuable insights into the unique design features and structural attributes of each development. By concentrating on specific examples, researchers can discern commonalities and distinctions in modern skyscraper designs, revealing emerging trends and patterns. The flexibility of this approach allows for the integration of various data sources, like architectural plans and other relevant documents, to create a holistic insight.

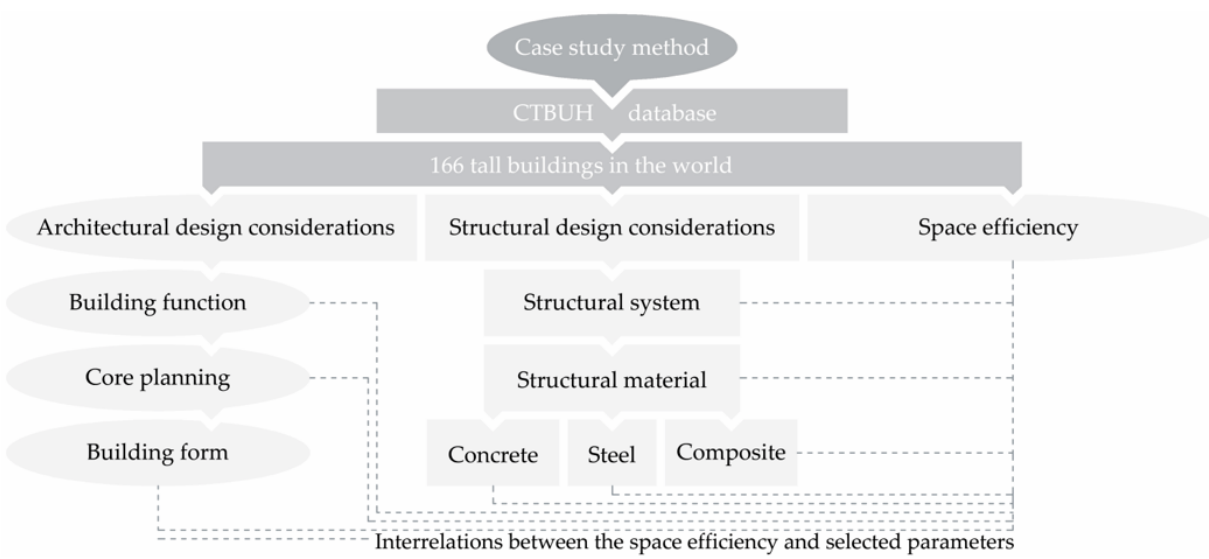


Figure 1: Overview of the research methodology employed in the current study.

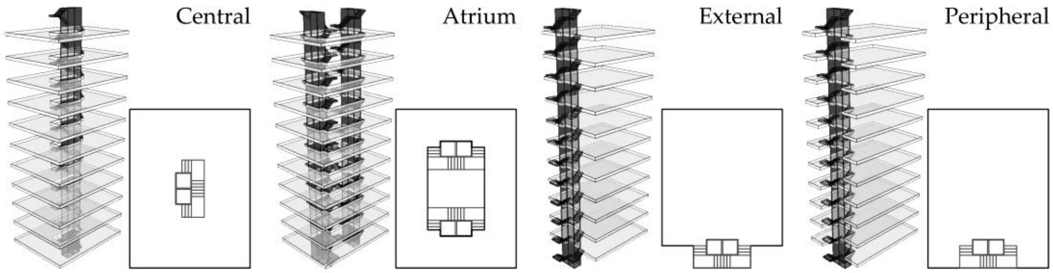
166 skyscrapers analyzed in this paper were selected from the comprehensive Council on Tall Buildings and Urban Habitat (CTBUH) database, representing a strategically chosen global sample of high-rise buildings [62]. CTBUH, a highly regarded nonprofit organization, advocates for the development of sustainable and resilient urban spaces, addressing the challenges of urban expansion and climate change. The organization not only establishes the criteria for classifying tall buildings, awarding prominent titles such as 'The World's Tallest Building,' but also recognizes architectural innovation through initiatives like 'Buildings of Distinction.' Utilizing the CTBUH database, this research defines structures exceeding 50 meters or 14-story in height as 'tall building' and 300 meters in height as 'supertall,' highlighting their significance and the advanced technical and architectural expertise required for their construction.

The selection of 166 towers for this study represents a deliberate and strategic effort to guarantee the strength and representativeness of the findings in analyzing skyscrapers with varying functions worldwide. While the availability of cases is constrained by geographical limitations and access, this sample size has been carefully curated to provide a well-rounded and comprehensive perspective on spatial efficiency and architectural features in tall buildings. The sample includes a diverse range of skyscrapers, as depicted in Fig. (**2**). The varied selection is crucial in capturing a wide array of design methodologies and spatial optimization techniques, thus increasing the generalizability of the findings. By rigorously examining these cases, the study aims to identify recurring patterns and trends, offering valuable insights into how spatial efficiency is achieved and maximized in contemporary skyscrapers. This holistic approach enables a more profound comprehension of the architectural and structural strategies utilized in these buildings, significantly enriching the broader discussion on skyscraper design and urban planning. The insights derived from this research are anticipated to be both dependable and broadly applicable, offering a valuable contribution to the field and guiding future design practices and scholarly investigations.

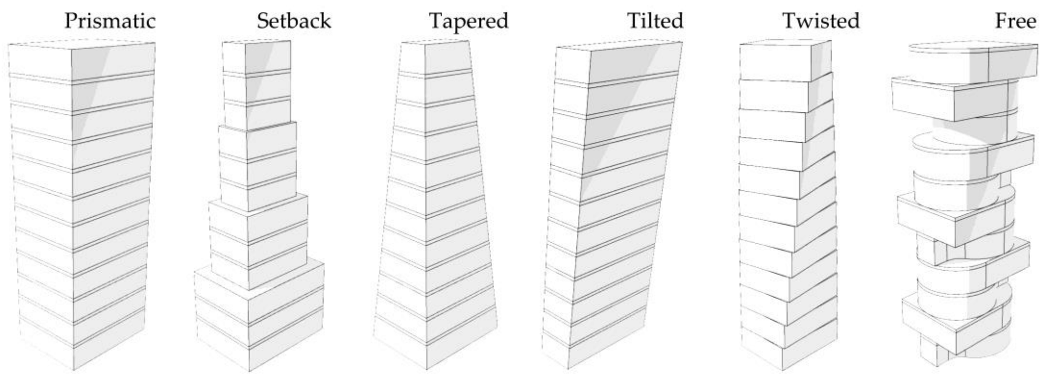
The design of skyscrapers is influenced by both architectural and structural limitations. Key considerations include the organization of core, form, and the choice of structural system and materials.

Figure 2: Selected case studies on the world map.

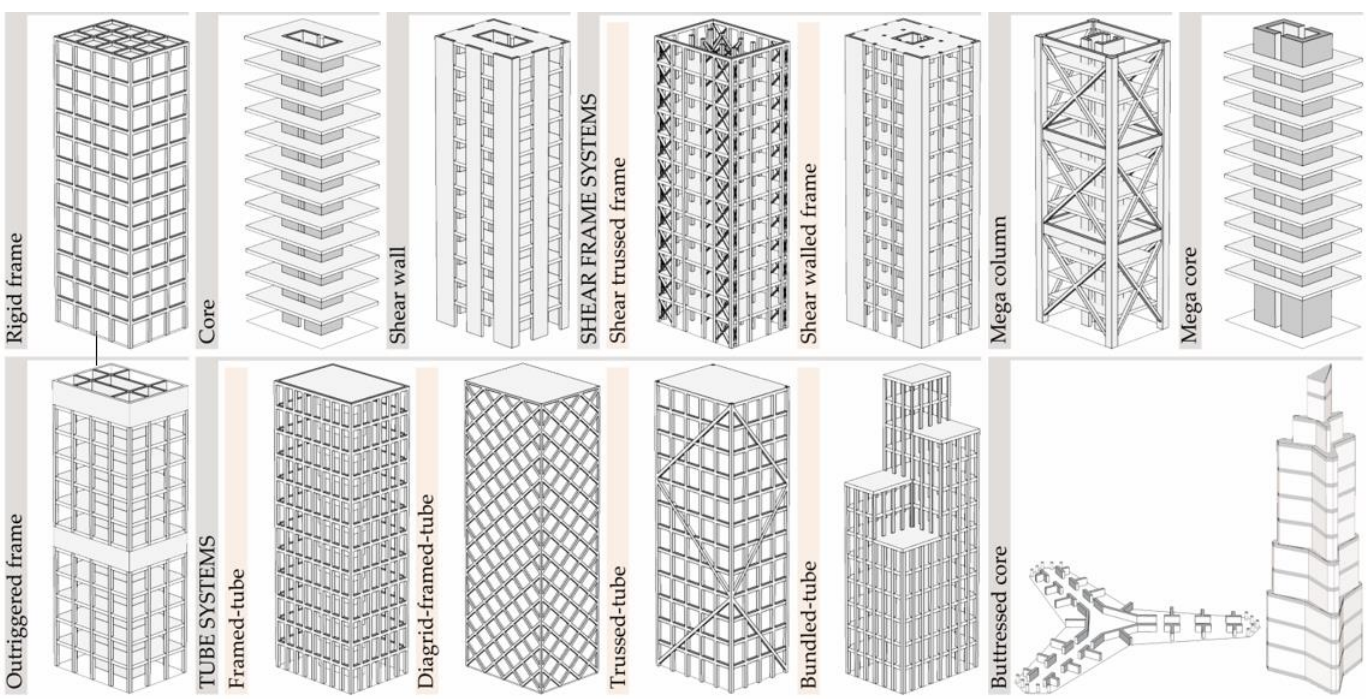
For architectural parameters, the core layout model proposed by [37] was adopted, as it offers a comprehensive framework encompassing four main categories: central, atrium, external, and peripheral, as shown in Fig. (**3a**). Additionally, building forms are classified into the following types: prismatic, setback, tapered, tilted, twisted, and freeform, as depicted in Fig. (**3b**).



(**a**)



(**b**)



(**c**)

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

Within the architectural parameters, the selection of an appropriate structural framework is crucial for optimizing space utilization in towers, as it directly influences the layout and dimensions of structural components. This study adopts the broader classification proposed by [38] for skyscraper structures, which includes shear frames (shear-walled and shear-trussed), mega cores, mega columns, outriggered frames, tube systems, and buttressed core systems, as depicted in Fig. (**3c**). Since structural materials affect the size and configuration of these elements, their selection plays a pivotal role in determining spatial efficiency. These materials are categorized as steel, concrete, and composite. In this study, with a focus on vertical load-bearing elements such as shear walls and columns, the term 'composite' is used to refer to buildings where load-bearing components are a combination of concrete, steel, or both.

4. Results

4.1. Main Design Parameters

Fig. (**4**) shows the functional distribution of the cases selected in this study. According to the data, mixed-use buildings constitute the largest proportion, representing 39% of the total sample. This is likely due to the growing trend in urban development toward mixed-use projects that integrate various functions such as residential, commercial, and public spaces within a single building, optimizing land use in dense urban areas. Office buildings account for 26% of the sample, reflecting the high demand for commercial spaces in urban centers. Hotels make up 19% of the sample, indicative of the hospitality industry's contribution to high-rise construction, particularly in tourism-driven cities. Residential buildings, which account for 16%, represent the smallest share in the study. This distribution highlights the varying levels of focus on different building functions in contemporary high-rise architecture and provides insight into how space efficiency is approached across these typologies. The prominence of mixed-use buildings suggests that they may offer more complex challenges and opportunities in optimizing space efficiency due to their multi-functional nature.

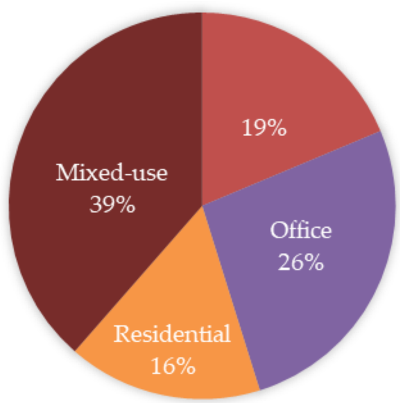


Figure 4: Case studies by function.

In residential buildings [37], achieving space efficiency is crucial for maximizing rentable areas and enhancing market appeal. Prismatic forms and outriggered frame systems are frequently employed in these structures due to their ability to support tall buildings while minimizing the footprint of structural elements, thereby freeing up more space for living areas. Residential towers are typically designed with layouts that prioritize expansive living spaces and a range of amenities, ensuring that every square foot of available floor area is used effectively. By incorporating features such as generous living spaces, private balconies, and communal amenities like gyms and lounges, developers can significantly increase the attractiveness of the property, thereby drawing in more tenants and boosting the overall profitability of the building. This strategic design approach not only enhances the quality of life for residents but also ensures that the building remains competitive in a crowded real estate market.

Central core designs are a dominant feature in office buildings [38], often coupled with prismatic forms to enhance interior layouts and maximize natural daylight penetration. Central core facilitates an even distribution of floor space, enabling flexible, open floor plans that are highly sought after in commercial settings [63]. Research consistently demonstrates that office buildings utilizing central cores and prismatic shapes achieve superior space efficiency, resulting in more rentable or leasable area per floor. This efficiency not only optimizes the use of space but also significantly increases the potential for higher returns on investment, making these designs particularly appealing to commercial real estate developers aiming to create adaptable, well-illuminated, and economically viable office environments.

Hotel towers commonly utilize prismatic forms and central cores to achieve a balance between efficient room layouts and accessible service areas [39]. Central core plays a vital role in these buildings, accommodating vertical transportation systems and essential services, thereby ensuring seamless access for both guests and staff. Room layouts are meticulously designed to maximize the number of guest rooms per floor while strategically positioning amenities such as restaurants, spas, and meeting rooms for convenience and accessibility. This thoughtful design approach not only elevates the guest experience by providing spacious, well-organized accommodations but also optimizes the management of operational areas, enhancing the overall functionality and profitability of the hotel. By effectively integrating guest and service areas, hotel towers can deliver a superior level of comfort and efficiency that appeals to both visitors and operators, making these designs highly successful in the competitive hospitality industry.

Mixed-use buildings, which blend residential, commercial, and recreational spaces, often employ flexible forms and composite materials to meet their diverse functional demands [40]. These structures necessitate innovative design solutions that effectively balance and integrate the different functions within a single footprint. The adaptability of flexible forms enables the dynamic allocation of space, allowing residential units to seamlessly coexist with commercial offices and recreational facilities, creating a harmonious and multifunctional environment [64-66]. The incorporation of composite materials not only enhances the structural integrity of the building but also supports more creative and expressive architectural designs. This combination of flexibility and material innovation leads to a more efficient and versatile use of space, making mixed-use buildings highly adaptable to the evolving needs of urban environments while providing aesthetic appeal and functional diversity.

Table **1** and **2** compare the outcomes on architectural and structural design parameters for residential, office, hotel, and mixed-use.

Table 1: Comparison of architectural design parameters.

Findings	Residential	Office	Hotel	Mixed-use
Core type	Central (93%) Peripheral (7%)	Central (95%) External (5%)	Central (65%) Peripheral (35%)	Central (100%)
Form	Prismatic (56%) Setback (11%) Tapered (11%) Twisted (7%) Free (15%)	Prismatic (20%) Setback (16%) Tapered (30%) Twisted (2%) Free (32%)	Prismatic (77%) Free (23%)	Prismatic (17%) Setback (17%) Tapered (38%) Twisted (1%) Free (27%)

Table 2: Comparison of structural design parameters.

Findings	Residential	Office	Hotel	Mixed-use
Material	Concrete (96%) Composite (4%)	Concrete (14%) Composite (80%) Steel (6%)	Concrete (13%) Composite (81%) Steel (6%)	Concrete (27%) Composite (72%) Steel (1%)
System	Outriggered frame (74%) Tube (22%) Buttressed core (4%)	Outriggered frame (59%) Tube (23%) Mega column & core (7%) Shear-frame (11%)	Outriggered frame (74%) Shear walled frame (13%) Rigid frame (13%)	Outriggered frame (73%) Tube (17%) Buttressed core (3%) Mega column & core (6%) Shear-frame (1%)

4.2. Space Efficiency in Towers with Different Functions

The analysis of spatial efficiency across different tower types, as depicted in Fig. (**5**), reveals notable variations in the optimization of usable space relative to GFA. Specifically, the average space efficiencies for residential, office, hotel, and mixed-use towers were calculated to be 76%, 71%, 81%, and 71%, respectively. Fig. (**5**) highlights the degree to which the internal layout of each tower type maximizes usable space for its intended function. Values fluctuated from the lowest of 55% and 4% to the highest of 94% and 38%, respectively. Table **3** compares the findings on average space efficiency and ratio of core to GFA with those of residential, office, hotel, and mixed-use.

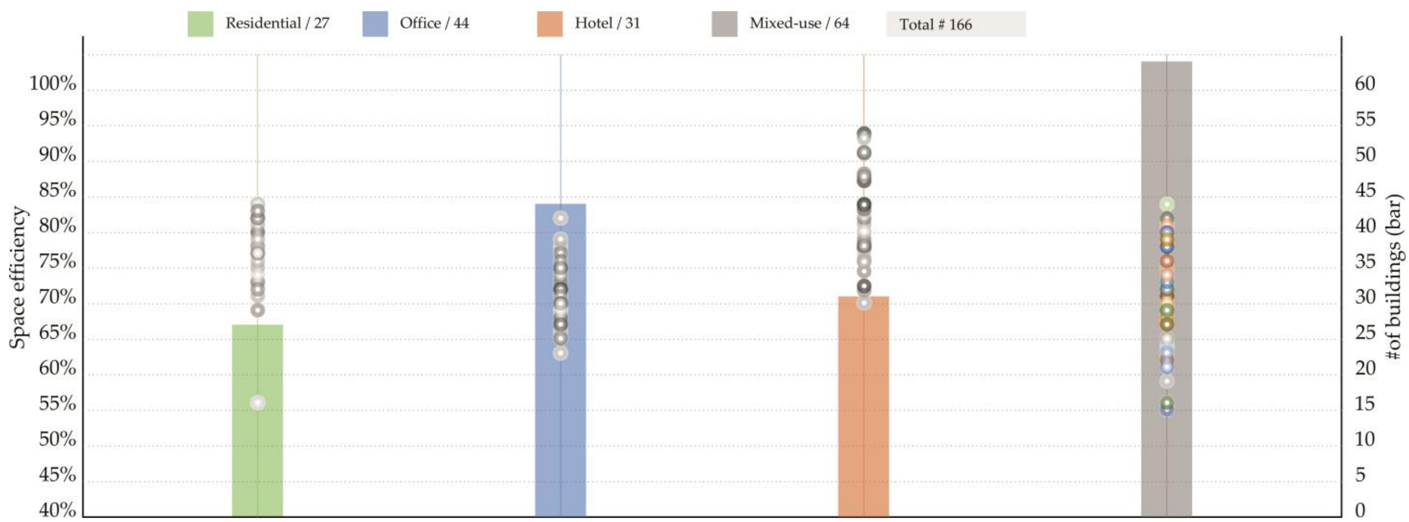


Figure 5: Space efficiencies of different functions.

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

Findings	Residential	Office	Hotel	Mixed-use
Space efficiency	76% (max. 84%, min. 56%)	71% (max. 82%, min. 63%)	81% (max. 94%, min. 70%)	71% (max. 84%, min. 55%)
Core to GFA	19% (max. 36%, min. 11%)	26% (max. 36%, min. 15%)	16% (max. 28%, min. 4%)	26% (max. 38%, min. 16%)

The differences in space efficiency among skyscrapers with varying functions are rooted in the fundamental architectural and engineering principles that guide the design of high-rise buildings. These principles must balance the needs of maximizing usable floor area, ensuring structural integrity, and accommodating the essential services that allow the building to function effectively. The space efficiency of a skyscraper, typically expressed as the percentage of gross floor area that is usable, and the core area to gross floor area ratio, which indicates the proportion of the building dedicated to structural and service cores, are critical metrics in understanding how these different functions influence skyscraper design.

Residential skyscrapers, with an average space efficiency of 76% and a core area ratio of 19%, are primarily designed to provide as much living space as possible. This is achieved by minimizing the footprint of the building's core, which contains vertical circulation elements such as elevators and stairwells, as well as mechanical, electrical, and plumbing systems. The lower core ratio reflects the lower density of occupants compared to office buildings, as well as the simpler service requirements of residential spaces. The relatively high space efficiency in residential towers is also a result of the design emphasis on maximizing private living areas, where the demand for large communal or shared spaces is lower compared to other building types.

Office skyscrapers, by contrast, show a lower average space efficiency of 71% and a higher core area ratio of 26%. The higher core area ratio in office buildings is a consequence of the need to support a high density of occupants and the extensive infrastructure required for modern office environments. This includes not only elevators and stairwells but also larger service shafts for data, electrical, and HVAC systems, which must be robust enough to meet the demands of business operations. Moreover, office buildings often require flexible, open floor plans that can be reconfigured to suit the changing needs of businesses. This flexibility is supported by larger structural cores, which allow for fewer internal columns and more open spaces, albeit at the cost of overall space efficiency.

Hotels, which boast the highest average space efficiency at 81% and the lowest core area ratio of 16%, are designed to maximize the number of guest rooms per floor while minimizing the space allocated to non-revenue-generating areas. The compact core in hotel buildings is made possible by the repetitive, standardized layout of hotel rooms, which reduces the need for extensive circulation spaces and service areas. Additionally, hotels typically have lower occupant densities compared to office buildings, which allows for a more efficient distribution of services within a smaller core. This design approach not only maximizes the usable floor area but also enhances operational efficiency, as more rooms can be accommodated within the same building foot-print.

Mixed-use skyscrapers, which combine residential, office, and often retail or commercial spaces, present unique challenges in terms of space efficiency. With an average space efficiency of 71% and a core area ratio of 26%, mixed-use towers must accommodate the diverse needs of different functions within a single structure. This complexity often results in a larger core, as each function may require its own dedicated vertical circulation system, mechanical services, and fire safety measures. For example, the residential portion of a mixed-use building may have separate elevators and stairwells from the office or retail sections, leading to an increase in the overall core area. The result is a lower space efficiency compared to single-function buildings, as the need to serve multiple functions within the same building envelope necessitates a more substantial infrastructure.

The observed variability in space efficiency (ranging from 55% to 94%) and core area ratios (from 4% to 38%) across different skyscraper functions underscores the influence of design decisions, structural systems, and building technologies on the overall performance of high-rise buildings. For instance, taller buildings may require more robust structural cores to withstand lateral forces such as wind or seismic activity, which can reduce space efficiency. Conversely, advances in construction materials and methods, such as the use of high-strength concrete or steel, can allow for slimmer cores and more efficient use of space. Additionally, innovative design strategies, such as the use of sky lobbies, shared service areas, or integrated building systems, can help reduce the core area while maintaining the functionality of the building, thereby enhancing space efficiency.

It is worth noting that the variation in efficiencies (from 55% to 94%) can largely be attributed to several key design and functional considerations unique to each building typology. For instance, residential buildings often display a broader range of space efficiencies due to the inclusion of non-leasable spaces such as circulation areas, common amenities, balconies, and in some cases, building features that enhance livability (e.g., wider corridors, communal spaces, or larger apartment footprints). These design decisions, while potentially reducing space efficiency, improve the overall quality of life for occupants. Conversely, office buildings, which are often designed with a focus on maximizing leasable area, tend to show higher space efficiency. This is due to their more uniform and streamlined layout, where circulation and service areas are minimized to increase usable office space.

In the case of hotel and mixed-use buildings, the variability could stem from the need to accommodate a variety of functions and user groups, which inherently leads to more complex spatial requirements. Hotels, for example, often include large public areas, such as lobbies, restaurants, and recreational facilities, which do not contribute to room occupancy but are essential to the building's function. Mixed-use buildings, with their combination of residential, commercial, and public spaces, further complicate the spatial efficiency calculation, as the need to balance these diverse functions leads to varying efficiency outcomes depending on the proportion of each use.

In conclusion, the differences in space efficiency among residential, office, hotel, and mixed-use skyscrapers reflect the diverse requirements of each building function, as well as the architectural and engineering solutions employed to meet these needs. By understanding these differences, architects and engineers can better optimize the design of high-rise buildings to maximize usable space while ensuring the safety, comfort, and functionality of the structure. This optimization is particularly important in urban environments, where space is at a premium and the efficient use of available floor area can have significant economic and social impacts.

4.2.1. Relation of Space Efficiency and Function, Core Typology, Form, Structural Material, and System

Figs. (**6**-**9**) provide a comprehensive and scientifically rigorous analysis of the empirical data, illustrating the intricate relationship between spatial efficiency and the multitude of architectural and structural factors that influence it. These figures are designed to communicate both the breadth and depth of the data, with each visual element contributing to a nuanced understanding of how spatial efficiency is affected by specific design choices.

On the right-hand side of each figure, a bar chart succinctly categorizes the total number of towers according to relevant classifications, offering an immediate and clear summary of the data distribution. This method of classification ensures that the comparative analysis of different architectural types is both systematic and accessible, facilitating a deeper understanding of trends across the dataset.

The incorporation of colored dots is a particularly effective tool for illustrating the spatial efficiency of individual towers, with each dot representing a specific tower's performance relative to its functional and structural characteristics. This visual cue not only highlights variation in spatial efficiency across different tower designs but also underscores the interplay between function, form, and design. The color-coding scheme allows for quick identification of efficiency levels, making complex data more intuitive to interpret while enabling cross-comparisons between towers with different functional purposes.

A notable feature of these figures is the inclusion of a gray bar, which draws attention to buildings within the sample that share identical design parameters. By doing so, the figures emphasize recurrent architectural choices and reveal underlying patterns that may influence design trends. This element highlights key aspects of decision-making in architecture, particularly the prevalence of certain design solutions and their impact on overall spatial efficiency.

Fig. (**6**) offers a comprehensive analysis of the relationship between core configurations and space efficiency across various building functions. Central cores, which are predominantly utilized in residential and office buildings, consistently lead to higher space efficiency. In office buildings, for example, space efficiency typically ranges from 70% to as high as 90%, with the central core layout minimizing the space required for circulation and services, thereby maximizing usable floor area. Residential buildings with central cores exhibit a slightly lower but still robust efficiency, generally between 60% and 80%, indicating a well-balanced distribution of private living spaces and shared amenities. Hotel buildings, which employ a mix of core configurations, show a broader and more variable range of space efficiency, from 60% to 85%. Hotels with central cores tend to be more efficient, often achieving space efficiencies in the upper range, around 80% to 85%, due to the compact organization of guest rooms around a central service core. However, when peripheral or external cores are used, hotel space efficiency often drops to the lower end of the spectrum, between 60% and 70%, due to the increased need for circulation and service areas to reach dispersed rooms. Mixed-use buildings, which incorporate a variety of functions within a single structure, display the most variability in space efficiency, ranging from 60% to above 90%. This wide range is largely dependent on the core configuration; mixed-use buildings with central cores typically achieve higher efficiencies, often exceeding 80%, as shared services and circulation spaces are optimized. Conversely, those with peripheral cores tend to have lower efficiencies, often in the 60% to 70% range, as the complexity of serving multiple functions within the same structure increases the need for additional circulation and service space.

Overall, Fig. (**6**) underscores the significant influence of core typology on space efficiency, demonstrating that central cores are generally the most effective in maximizing usable space across different building functions. Peripheral and external cores, while necessary in certain design contexts, often lead to lower space efficiency, particularly in buildings with complex or specialized spatial requirements, such as hotels and mixed-use developments. The data suggests that careful consideration of core configuration during the design phase is crucial to optimizing space efficiency and meeting the functional needs of the building.

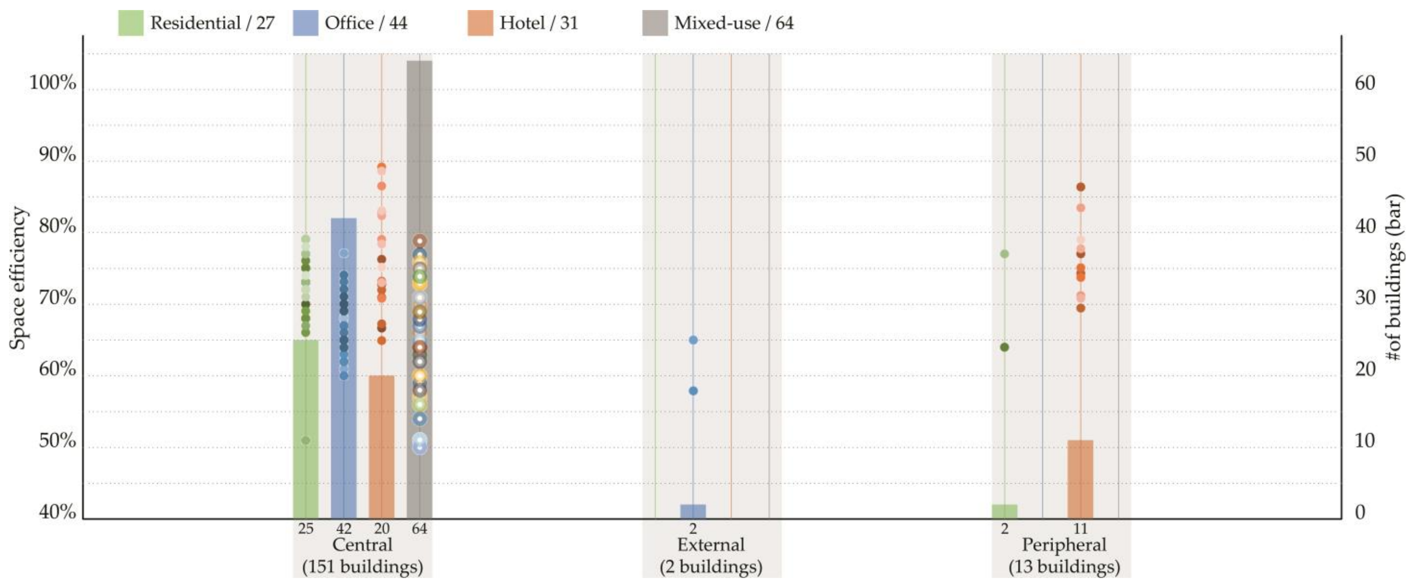


Figure 6: Different functions by core type.

Fig. (**7**) presents a detailed analysis of how building form influences space efficiency across various function. Prismatic form, characterized by its straightforward, rectilinear geometry, exhibits space efficiency ranging from approximately 60% to 80% across different building types. Residential and hotel buildings within this category show a relatively consistent efficiency, with most achieving around 70%, benefiting from the simplicity and regularity of the prismatic form, which allows for optimal use of floor space and straightforward service integration. Office towers with prismatic forms generally fall in the mid to high efficiency range, closer to 70%, reflecting the form's suitability for maximizing usable space while accommodating large open-plan layouts. In contrast, setback forms, which introduce a terraced or stepped geometry, show a broader range of space efficiency, particularly in office and mixed-use buildings. These forms have efficiency levels ranging from 50% to 85%, with office buildings typically on the lower end of this spectrum due to the complex structural and mechanical systems needed to support the varying floor plates. Mixed-use edifices in the setback category tend to perform better, with some exceeding 80%, likely due to shared services and circulation areas that optimize space usage despite the form's inherent complexities. Tapered forms, which are often employed in tall buildings to reduce wind loads and improve stability, show a space efficiency range from 60% to 90%. Office and mixed-use buildings within this form category generally achieve higher efficiencies, often around 80% to 90%, thanks to a well-optimized core-to-perimeter ratio that allows for efficient space distribution even as the floor plates reduce in size at higher levels. Twisted forms, which are architecturally dynamic and visually distinctive, demonstrate more constrained space efficiency, particularly in office buildings, where efficiencies hover around 60% to 70%. The complexity of organizing functional spaces around a twisting core often results in reduced usable floor area, making this form less efficient compared to more traditional geometries. Lastly, free forms, which are characterized by their non-conventional and fluid geometries, exhibit the widest variability in space efficiency, ranging from 50% to 85%. These forms are often used in mixed-use developments where the flexibility and aesthetic appeal of the building outweigh strict efficiency considerations. While some mixed-use buildings with free forms manage to achieve efficiencies up to 85%, the average tends to be lower, around 60% to 70%, due to the challenges of integrating complex structural and service systems within irregularly shaped floor plates.

Overall, Fig. (**7**) highlights the critical trade-offs between architectural innovation and functional efficiency, illustrating that while complex and unconventional forms like twisted or free forms can offer significant aesthetic and symbolic value, they often come at the expense of space efficiency. Consequently, the choice of building form must be carefully aligned with the functional requirements and intended use of the structure, ensuring that design ambition does not compromise the building's operational performance.

Fig. (**8**) provides a comprehensive analysis of the relationship between various structural systems and their impact on space efficiency across different building functions. Rigid frame systems, which are used in a limited

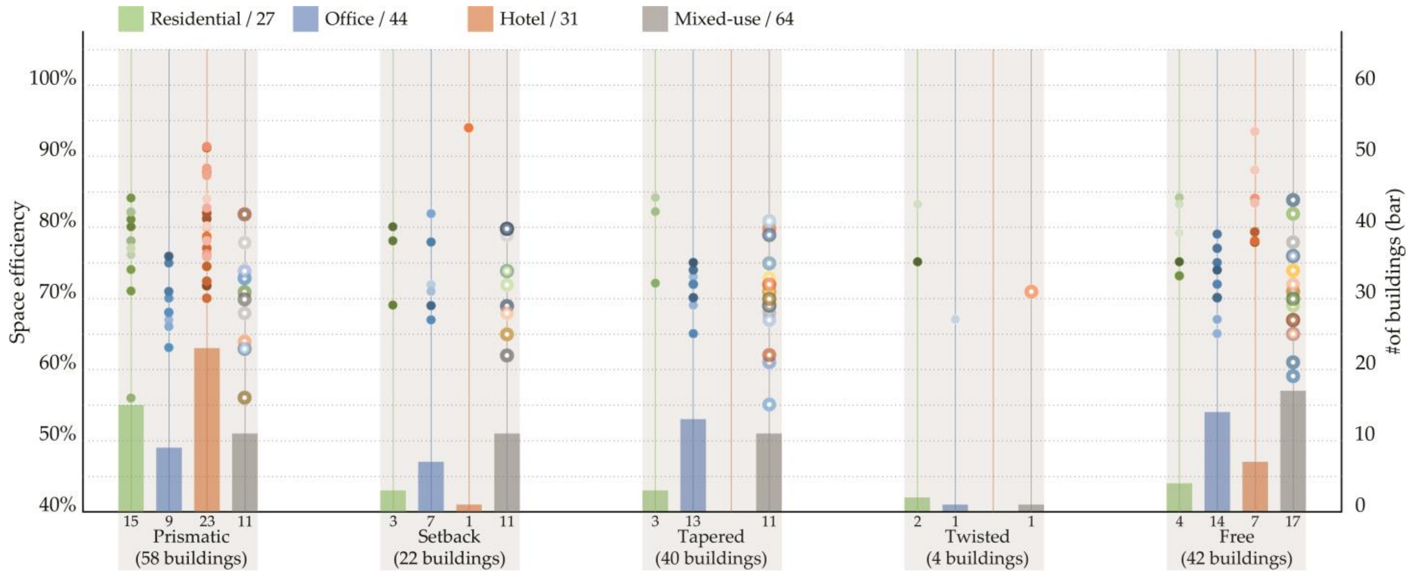


Figure 7: Different functions by form.

number of buildings, generally exhibit lower space efficiency, typically ranging from 60% to 70%. This lower efficiency is particularly evident in hotel buildings, where the need for additional structural elements to support the frame reduces the amount of usable space. In contrast, shear-walled frame systems, which are more widely utilized, offer a broader and higher range of space efficiency, typically between 60% and 85%. Office buildings using shear-walled frames often achieve efficiencies in the 70% to 80% range, capitalizing on the system's ability to effectively manage lateral loads while maintaining large, open floor areas that enhance usable space. Hotels employing shear-walled frames can reach even higher efficiencies, up to 85%, due to the reduction in internal columns, which maximizes space for guest accommodations. Mega column and mega core systems, though less commonly employed, display similar efficiency levels, generally ranging from 65% to 80%. These systems are particularly effective in high-rise office buildings, where concentrating structural support in mega elements minimizes the impact on usable floor space, thereby enhancing overall efficiency. This is especially beneficial in buildings where maximizing floor area is crucial for functionality and profitability. Outriggered frame systems, which are the most frequently used among the structural systems analyzed, demonstrate the widest range of space efficiencies, from 60% to 90%. Mixed-use buildings utilizing outriggered frames often reach the upper end of this spectrum, with efficiencies frequently exceeding 80%. This high efficiency is largely due to the system's ability to link the central core with the perimeter structure, allowing for more flexible and open floor layouts, which is particularly advantageous in multifunctional buildings where space adaptability is key. Tube structures, commonly implemented in both office and mixed-use buildings, show space efficiencies ranging from 60% to 85%. The efficiency in these structures stems from the tube system's capacity to provide significant structural support through the building's perimeter, which minimizes the need for internal columns and thereby maximizes the usable interior space. This makes tube systems especially effective in tall buildings, where structural efficiency directly translates into higher space utilization. Finally, the buttressed core system, though used in only a few buildings, demonstrates space efficiencies ranging from 60% to 80%, particularly in residential and mixed-use buildings. The central core in this system supports open floor plans with minimal structural intrusion, which is essential for creating spacious, flexible living areas and commercial spaces.

Overall, Fig. (**8**) underscores the critical role of structural system selection in determining space efficiency across different building functions. Systems like outriggered frames and tube structures offer the highest space efficiencies, often exceeding 80%, making them ideal for complex, multifunctional buildings. In contrast, more traditional systems like rigid frames tend to offer lower efficiencies, particularly in buildings with intricate spatial requirements, such as hotels. The data highlights the importance of strategically choosing a structural system during the design phase to optimize space efficiency while meeting the specific functional and design needs of the building.

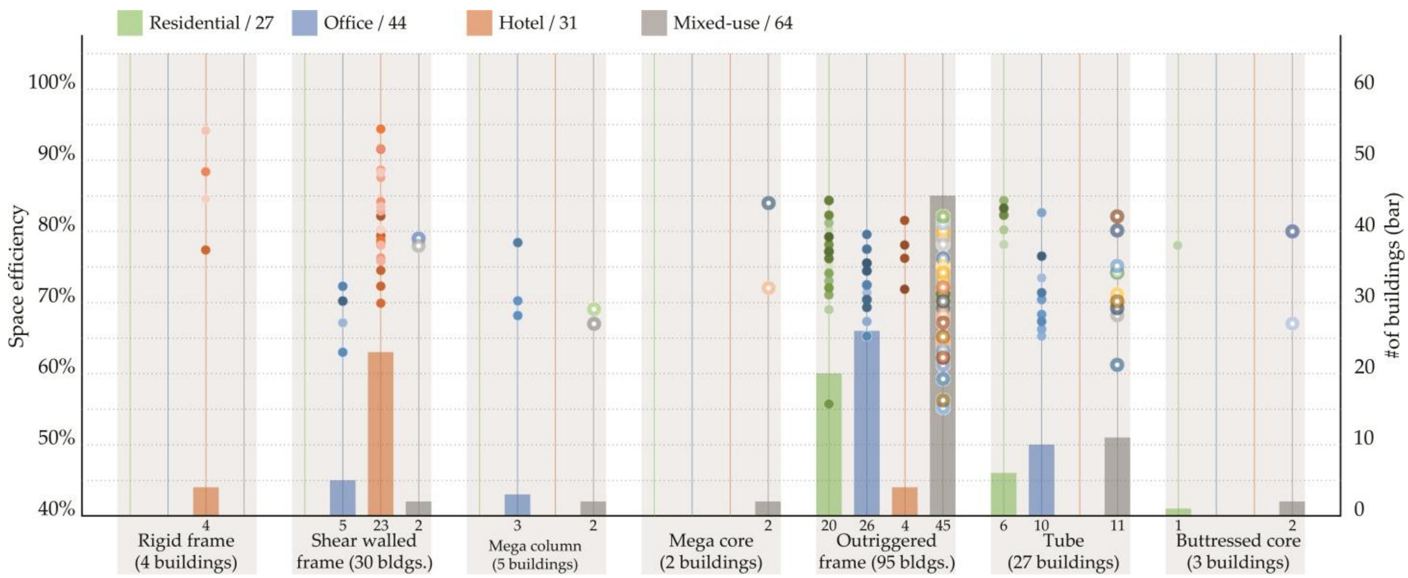


Figure 8: Different functions by system.

Fig. (**9**) provides an in-depth analysis of the relationship between structural materials and space efficiency across various building functions. Steel structures, which are represented by a smaller sample of buildings, generally exhibit a space efficiency range from approximately 60% to 80%. In office buildings utilizing steel, the efficiency tends to be higher, typically around 70% to 80%. This higher efficiency can be attributed to steel's inherent strength and flexibility, which allow for longer spans and fewer internal columns, maximizing the usable floor area. However, in hotel buildings, steel structures show a lower efficiency, around 60% to 70%, due to the need for additional structural supports and more complex service layouts that reduce the overall usable space. Concrete, as a more widely used material across all building types, shows a broader range of space efficiency. Residential buildings constructed with concrete demonstrate efficiencies ranging from 60% to 80%, which reflects concrete's ability to effectively balance load-bearing capacity with space optimization, particularly in high-density residential layouts. Office buildings with concrete structures exhibit even higher efficiency, typically between 65% and 85%, with some reaching as high as 90%. This is due to concrete's adaptability in supporting various core configurations and its capacity for high-rise construction with minimal intrusion into the usable space. Hotels built with concrete structures, however, display a more variable efficiency range from 55% to 80%, often dictated by the need for thicker structural elements and additional service areas, which can reduce the space available for

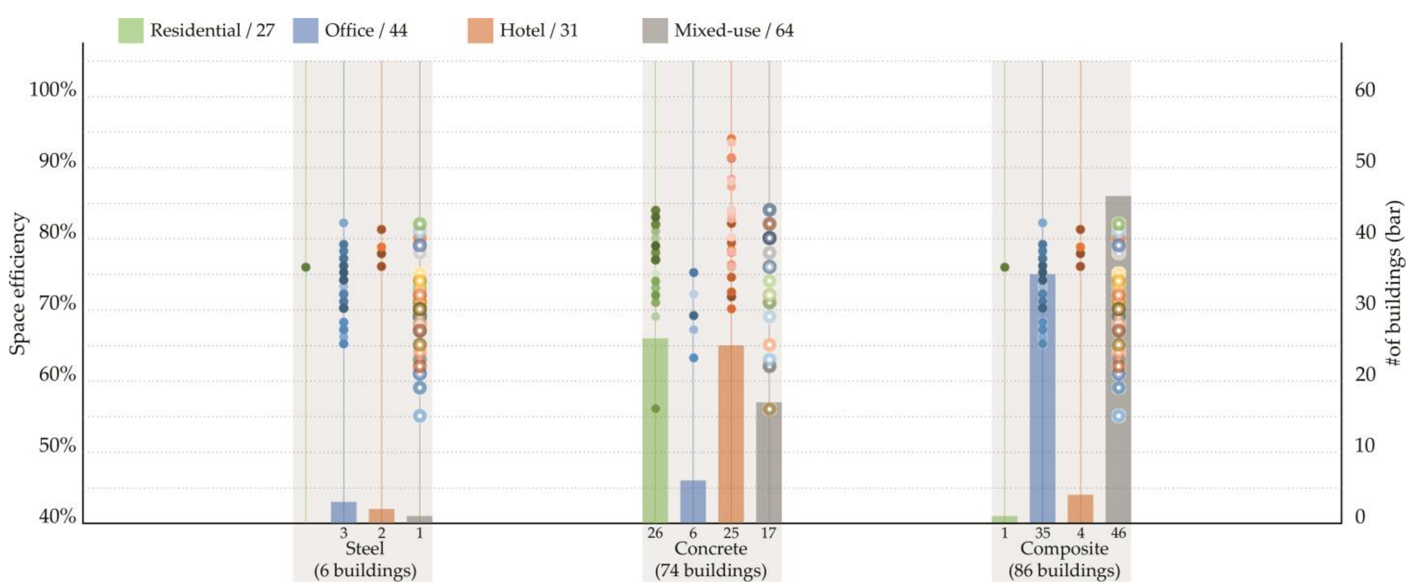


Figure 9: Different functions by material.

guest rooms and amenities. Composite structures, which integrate the strengths of both steel and concrete, offer the widest range of space efficiency, from 60% to 90%, and are most used in office and mixed-use buildings. Office buildings that employ composite structures generally achieve high space efficiencies, often exceeding 80% and sometimes approaching 90%. This high efficiency is due to the composite material's ability to provide strong structural support with minimal space consumption, allowing for open and flexible floor plans. Mixed-use buildings with composite structures also perform well, with space efficiencies typically ranging from 70% to 85%. This performance is driven by the material's versatility in accommodating the diverse and often complex structural and service requirements needed to support multiple functions within a single building.

Overall, Fig. (**9**) underscores the critical impact of structural material selection on space efficiency, demonstrating that while steel provides high efficiency in simpler layouts like office buildings, concrete and composite materials offer greater versatility and higher efficiency across a broader range of building functions. The choice of structural material is therefore a key factor in optimizing space efficiency, requiring careful consideration to align with the building's functional requirements and design objectives to maximize operational performance.

5. Discussion

This article makes a substantial contribution to the fields of architecture and urban planning by providing the first comprehensive and comparative analysis of the architectural and structural parameters that impact space efficiency in towers serving various functions. This research highlights the critical role of central core planning and prismatic building forms in optimizing space efficiency across various building types. Central core planning strategically places essential elements like elevators and stairwells, reducing wasted space, while prismatic forms simplify construction and improve space usage. Efficiency rates were 76% for residential, 71% for office and mixed-use, and 81% for hotel towers. The study also explores how building height and functional use affect efficiency, offering architects and developers insights for creating tall buildings that balance architectural appeal, economic viability, and structural efficiency.

Central core designs are predominant across all building types due to their numerous structural advantages and efficiency in space utilization. These cores are particularly effective in tall buildings, as they provide essential structural stability while maximizing usable floor area. The central core's ability to house vertical transportation elements such as elevators and stairwells, along with service shafts, consolidates these functions into a single, efficient space, leaving the surrounding floor area open for flexible use. In residential buildings, central cores support efficient layouts that prioritize living spaces and amenities, such as common areas and recreational facilities, which are essential for creating comfortable and desirable living environments. In office buildings, central cores facilitate adaptable floor plans that can be customized to meet the diverse needs of various tenants, enhancing the building's attractiveness and functionality for commercial purposes. In hotel towers, central cores are crucial for optimizing guest room layouts and ensuring that service areas are easily accessible for staff, which enhances operational efficiency and maintenance. For mixed-use buildings, central cores provide a robust structural backbone that can support a variety of functions, from residential and commercial spaces to recreational and retail areas, allowing for seamless integration and efficient use of space. Overall, the implementation of central core designs across different building types demonstrates their versatility and effectiveness in promoting structural stability, space efficiency, and functional adaptability, making them a cornerstone of modern high-rise architecture.

Prismatic forms are widely favored for their straightforward geometry and efficient use of interior space. These forms are especially prevalent in residential and office towers, where optimizing floor layouts is critical. Residential buildings use prismatic forms to provide consistent living spaces and optimize daylight access. Office buildings often feature prismatic forms to maximize leasable office space and ensure uniformity in floor layouts. Hotel towers use prismatic forms to create efficient room layouts and streamline guest services. Mixed-use buildings, while incorporating more varied forms to accommodate different functions, still benefit from prismatic elements for efficiency.

The choice of structural system significantly impacts space efficiency. Outriggered frame systems are common in residential and mixed-use buildings, while shear-walled frame systems are typical in hotel towers. The flexibility and height potential of these systems make them suitable for tall buildings. In residential buildings, outriggered frames offer stability and efficiency, supporting the building's height while maximizing usable space [67-70]. In office buildings, outriggered frame systems provide flexibility in column placement, allowing for open and adaptable floor plans. Hotel towers, with their focus on guest comfort and services, use shear-walled frames to ensure structural integrity and space efficiency, providing stable and quiet environments for guests. Mixed-use buildings benefit from the versatility of outriggered frames, which can support varied functions within the same structure.

Reinforced concrete is the most used material across all building types, valued for its cost-effectiveness, ease of use, and fire resistance. Composite materials are also popular in mixed-use buildings due to their versatility. Residential buildings benefit from reinforced concrete's fire resistance and cost-effectiveness, making it an ideal choice for constructing tall residential towers. In office buildings, the use of reinforced concrete allows for robust and flexible design options, accommodating different tenant needs and structural requirements. Hotel towers primarily use reinforced concrete to ensure safety, stability, and efficient space utilization. Mixed-use buildings often incorporate composite materials, combining the benefits of steel and concrete to support diverse functional spaces.

Residential buildings achieve average space efficiency ratios of 76%, with core area ratios averaging 19%. Prismatic forms and outriggered frame systems are common, providing stability and efficient layouts for living spaces. The space efficiency of residential towers tends to decrease with height, but effective core planning and structural design can help maintain optimal space utilization. In residential buildings, the design of living spaces and amenities plays a crucial role in achieving high space efficiency. By incorporating compact and efficient layouts, architects can maximize the usable floor area while providing comfortable living environments. Additionally, the use of advanced construction techniques and materials can enhance the overall efficiency and sustainability of residential towers.

Office buildings with central cores and prismatic forms demonstrate high space efficiency, with average space efficiency ratios ranging from 63% to 82%. The core area ratio typically varies between 15% and 36%, highlighting the importance of core design in maximizing usable office space. As buildings become taller, maintaining high space efficiency requires careful planning and innovative structural solutions. In addition to central cores, the use of advanced structural systems such as outriggered frames and tube systems can enhance space efficiency in office buildings. These systems provide the necessary lateral stability while minimizing the need for interior columns, allowing for more open and adaptable floor plans. The integration of sustainable design practices, such as energy-efficient systems and green building certifications, can further enhance the space efficiency and overall performance of office buildings.

Hotel towers demonstrate high space efficiency, averaging 81.2%, with core area-to-GFA ratios averaging 16%. Prismatic forms and central core designs are predominant, providing efficient room layouts and service areas. The space efficiency of hotel towers is influenced by their operational requirements, necessitating effective design strategies to optimize guest room space and service facilities. In hotel towers, the design of guest rooms and service areas is critical to achieving high space efficiency. By optimizing room layouts and minimizing wasted space, architects can enhance the overall efficiency and profitability of hotel operations. The use of advanced construction materials and techniques can further improve the performance and sustainability of hotel towers.

Mixed-use buildings exhibit varied space efficiency ratios due to their diverse functional requirements. The average space efficiency aligns with other building types, around 75%. The use of composite materials and flexible forms allows for efficient layouts that balance residential, commercial, and recreational spaces. Core planning and structural systems play crucial roles in optimizing space efficiency in mixed-use buildings. In mixed-use buildings, the integration of different functions requires careful planning and coordination. By designing flexible and adaptable spaces, architects can accommodate changing market demands and ensure the long-term viability of these structures. The use of advanced building management systems can further enhance the efficiency and performance of mixed-use buildings.

6. Conclusions

The comparative analysis of space efficiency in contemporary tall towers with various functions presented in this study underscores the intricate interplay between architectural design, structural considerations, and functional use. The findings emphasize that central core planning and prismatic building forms are critical to optimizing space efficiency across various building types, including residential, office, hotel, and mixed-use towers. These elements not only streamline construction processes but also enhance the overall usability of floor space, which is vital for the economic viability of these structures.

Given the substantial variation in space efficiency observed across different building types and heights, architects and engineers must prioritize the strategic placement of core elements such as elevators and stairwells. This approach minimizes wasted space and ensures maximum usable floor area. Furthermore, the adoption of prismatic building forms, with their straightforward geometric shapes, should be encouraged to facilitate more efficient construction processes and space utilization.

Concrete suggestions for practitioners include: 1. Core Planning Optimization: Architects should consider innovative core planning strategies that minimize the footprint of essential services while maintaining functionality. Engineers can explore advanced technologies in elevator systems and structural cores to reduce core sizes without compromising on safety or service efficiency. 2. Form and Geometry Selection: The preference for prismatic forms should be a guiding principle in the design of tall towers. These forms not only contribute to space efficiency but also simplify structural design and material usage. Collaboration between architects and structural engineers is essential to refine these forms for specific project needs. 3. Material Innovation: The choice of materials plays a significant role in both structural integrity and space efficiency. Engineers should continue to investigate and incorporate new materials that allow for slimmer structures without sacrificing strength. Architects, in turn, should focus on materials that align with both aesthetic and efficiency goals. 4. Tailored Solutions for Mixed-Use Developments: Given the diverse functional requirements of mixed-use towers, a tailored approach that balances the needs of each function (residential, office, hotel) is crucial. This may involve flexible core planning, modular structural systems, and adaptable building forms that can respond to different spatial demands. 5. Continuous Performance Monitoring: To maintain high standards of efficiency, it is recommended that buildings undergo regular performance assessments post-construction. These evaluations should consider both spatial efficiency and operational performance, providing data that can inform future designs.

By implementing these strategies, architects and engineers can achieve a balanced approach that maximizes space efficiency while ensuring that tall towers remain functional, aesthetically pleasing, and economically viable. The insights gained from this research provide a foundation for future innovations in the design and construction of tall buildings, fostering the development of structures that are not only monumental in scale but also exemplary in efficiency and practicality.

Conflict of Interest

The authors declare no conflict of interest.

Funding

This research received no external funding.

References

[1] Peters T. The development of the tall building. Struct Eng Int. 1992; 2(3): 161-4. https://doi.org/10.2749/101686692780628433

[2] Ray P, Roy S. Skyscrapers: origin, history, evolution and future. J Today's Ideas-Tomorrow's Technol. 2018; 6(1): 9-20. https://doi.org/10.15415/jotitt.2018.61001

[3] Memon S, Zain M, Zhang D, Rehman S, Usman M, Lee D. Emerging trends in the growth of structural systems for tall buildings. J Struct Integrity Maint. 2020; 5(3): 155-70. https://doi.org/10.1080/24705314.2020.1765270

[4] Weingardt R. Homer gage balcom and the empire state building. Leadersh Manag Eng. 2011; 11(2): 209-18. https://doi.org/10.1061/(ASCE)LM.1943-5630.0000122

[5] Jacobsson M, Wilson T. Revisiting the construction of the Empire State Building: Have we z something? Bus Horiz. 2018; 61(1): 47-57. https://doi.org/10.1016/j.bushor.2017.09.004

[6] Sharma M, Sain H. A review on seismic analysis of connected and high rise buildings. Int J Eng Trends Appl. 2024; 11(1): 18-21.

[7] Hassan W, Elmorsy M. Database trends and critical review of seismic performance tests on high strength steel reinforced concrete components. Eng Struct. 2021; 239: 112092. https://doi.org/10.1016/j.engstruct.2021.112092

[8] Fernando D, Navaratnam S, Rajeev P, Sanjayan J. Study of technological advancement and challenges of façade system for sustainable building: Current design practice. Sustainability. 2023; 15(19): 14319. https://doi.org/10.3390/su151914319

[9] Chen L, Hu Y, Wang R, Li X, Chen Z, Hua J, *et al.* Dong L. Green building practices to integrate renewable energy in the construction sector: a review. Environ Chem Lett. 2024; 22(2): 751-84. https://doi.org/10.1007/s10311-023-01675-2

[10] Heidari M, Thangavel S, Al Naamani E, Khashehchi M. Emerging trends in smart green building technologies. Sustain Technol Energy Efficient Buildings. 2024; 24: 313. https://doi.org/10.1201/9781003496656-15

[11] Wang C, Che Y, Xia M, Lin C, Chen Y, Li X, *et al.* Fan G. The evolution and future directions of green buildings research: a scientometric analysis. Buildings. 2024; 14(2): 345. https://doi.org/10.3390/buildings14020345

[12] Pietrzak J. Opportunities of building tall and green-an overview from a European perspective. Acta Sci Pol, Architectura. 2024; 23: 167-88. https://doi.org/10.22630/ASPA.2024.23.13

[13] Alkhatib F, Daris A, Almasaudi A, Alawag A, Baarimah A, Alakhali A. Review and conceptual workflow for enhancing wind loads design of sustainable asymmetrical tall buildings. In: 2024 ASU International Conference in Emerging Technologies for Sustainability and Intelligent Systems (ICETSIS); 2024 Jan 28; IEEE. p. 812-6. https://doi.org/10.1109/ICETSIS61505.2024.10459521

[14] Erkoç Y, Torunbalcı N. Design of inclined-form buildings: architectural and structural considerations. J Architect Eng. 2024; 30(3): 03124003. https://doi.org/10.1061/JAEIED.AEENG-1777

[15] Al-Kodmany K, Ali M, Zhang T. Importing urban giants: re-imaging Shanghai and Dubai with skyscrapers. ArchNet-IJAR. 2013; 7(2): 22.

[16] Roche Cárcel J. The spatialization of time and history in the skyscrapers of the twenty-first century in Shanghai. City, Territory and Architecture. 2021; 8(1): 7. https://doi.org/10.1186/s40410-021-00136-z

[17] Botti G. The Skyscraper: Go East, Go High, Go Hybrid. In: Designing Emerging Markets: A Quantitative History of Architectural Globalisation; 2023 May 23. Singapore: Springer Nature; p. 163-248. https://doi.org/10.1007/978-981-99-1552-1_5

[18] Thai H, Ngo T, Uy B. A review on modular construction for high-rise buildings. Structures. 2020; 28: 1265-90. https://doi.org/10.1016/j.istruc.2020.09.070

[19] Vosloo C. Early sustainable architecture in hanging skyscrapers: A comparison of two financial office buildings. Acta Structilia. 2020; 27(1): 144-77. https://doi.org/10.18820/24150487/as27i1.6

[20] Scaramozzino D, Lacidogna G, Carpinteri A. New trends towards enhanced structural efficiency and aesthetic potential in tall buildings: The case of diagrids. Appl Sci. 2020; 10(11): 3917. https://doi.org/10.3390/app10113917

[21] Alotaibi F, Sinclair B. Tall buildings, high expectations, towering responsibilities: Critically considering skyscrapers, urbanism and sustainability. In: Couceiro da Costa MJR, Roseta F, Couceiro da Costa S, Lages JP, Eds. Architectural Research Addressing Societal Challenges. CRC Press; 2017, pp. 535-42.

[22] Watts S, Kalita N, Maclean M. The economics of super-tall towers. The Struct Des Tall Spec Buildings. 2007; 16(4): 457-70. https://doi.org/10.1002/tal.424

[23] Barton J, Watts S. Office vs. residential: the economics of building tall. CTBUH J. 2013; 2: 38-43.

[24] Moon KS, de Oliveira Miranda MD. Conjoined towers for livable and sustainable vertical urbanism. Int J High-Rise Buildings. 2020; 9(4): 387-96.

[25] Özşahin B. An assessment of the relation between architectural and structural systems in the design of tall buildings in Turkey. Buildings. 2022; 12(10): 1649. https://doi.org/10.3390/buildings12101649

[26] Mamati N, Kuruşcu A, Parsa A. Examination of the core as a rigidity center in high-rise buildings. Eur J Res Dev. 2022; 2(2): 190-212. https://doi.org/10.56038/ejrnd.v2i2.57

[27] Fakıoğlu Gedik B, Ay B. The impact of service core reduction in supertall buildings: a study on structural design, embodied carbon, and leasable floor area. Archit Sci Rev. 2023; 66: 144-53. https://doi.org/10.1080/00038628.2023.2182271

[28] Yung C, Ismail L, Abd Wahab I, Hanapi N. Skyscrapers architectural form effects on airflow. J Design + Build. 2021;14(1): 103-12.

[29] Goncikowski M. Landmarks of the metropolis: the types of forms of Varsovian skyscrapers as compared to global precedence. Buildings. 2022; 12(10): 1507. https://doi.org/10.3390/buildings12101507

[30] Jung C, Awad R, Awad J. A study of optimal design process for complex-shaped skyscrapers' structural systems in the United Arab Emirates. Ain Shams Eng J. 2022;13(5): 101683. https://doi.org/10.1016/j.asej.2021.101683

[31] Elhegazy H, Ebid A, Mahdi I, Haggag S, Rashid I. Selecting optimum structural system for RC multi-story buildings considering direct cost. Structures. 2020; 24: 296-303. https://doi.org/10.1016/j.istruc.2020.01.039

[32] Alhaddad W, Halabi Y, Xu H, Lei H. A comprehensive introduction to outrigger and belt-truss system in skyscrapers. Structures 2020; 27: 989-98. https://doi.org/10.1016/j.istruc.2020.06.028

[33] Chaudhary N. Construction of skyscrapers: boon or bane from an economic perspective. J Tikapur Mult Campus. 2024; 7(1-2): 69-84. https://doi.org/10.3126/jotmc.v7i1-2.63173

[34] Chigozie A. Skyscrapers construction technology: A BIM approach. J Env Design Constr Mgmt. 2020; 20(4): 355-81.

[35] Finnigan S, Gerardy J, Popa N, Trabucco D. Steel and skyscrapers: a productive history and a sustainable future. CTBUH J. 2019; 4: 28-35.

[36] Almusaed A, Almssad A. Sustainable wooden skyscrapers for the future cities. In: Du G, Zhou X, Eds. Wood Industry-Past, Present and Future Outlook. IntechOpen; 2022. https://doi.org/10.5772/intechopen.105809

[37] Ilgın H. Space efficiency in contemporary supertall residential buildings. Architecture. 2021; 1:25-37. https://doi.org/10.3390/architecture1010004

[38] Ilgın H. Space efficiency in contemporary supertall office buildings. J Archit Eng. 2021; 27: 04021024. https://doi.org/10.1061/(ASCE)AE.1943-5568.0000486

[39] Aslantamer Ö, Ilgın H. Space efficiency in tall hotel towers. Buildings. 2024; 14(7): 2051. https://doi.org/10.3390/buildings14072051

[40] Ilgın H. A study on space efficiency in contemporary supertall mixed-use buildings. J Build Eng. 2023; 69: 106223. https://doi.org/10.1016/j.jobe.2023.106223

[41] Dal Molin R, Ragiv S, Giacomello E. Tall buildings and city development: comparison of five case studies. CTBUH J. 2023; 2: 28-35.

[42] Charney I, Drozdz M, Rosen G. Venerated skylines under pressure: a view of three cities. Urban Geography. 2022; 43(7): 1087-107. https://doi.org/10.1080/02723638.2021.1897742

[43] Okbaz F, Sev A. A model for determining the space efficiency in non-orthogonal high-rise office buildings. J Fac Eng Archit Gazi Univ. 2023; 38: 113-25. https://doi.org/10.17341/gazimmfd.831937

[44] Ibrahimy R, Mohmmand M, Elham F. An evaluation of space use efficiency in residential houses, Kabul City. J Res Appl Sci Biotechnol. 2023; 2: 1-6. https://doi.org/10.55544/jrasb.2.3.1

[45] Höjer M, Hongo Y, Francart N, Kishita Y. Measuring space efficiency and estimating the potential for reduced operational and embodied energy use for office spaces. Sustainability. 2023; 16(1): 332. https://doi.org/10.3390/su16010332

[46] Goessler T, Kaluarachchi Y. Smart adaptive homes and their potential to improve space efficiency and personalization. Buildings. 2023; 13(5): 1132. https://doi.org/10.3390/buildings13051132

[47] Hamid G, Elsawi M, Yusra O. The impacts of spatial parameters on space efficiency in hybrid villa-apartments in greater Khartoum. J Archit Plan. 2022; 34: 425-40. https://doi.org/10.33948/JAP-KSU-34-4-4

[48] Suga R. Space efficiency in hotel development [Thesis]. MODUL University Vienna; 2021.

[49] Arslan Kılınç G. Improving a model for determining space efficiency of tall office buildings [Thesis]. Mimar Sinan Fine Art University; 2019.

[50] Von Both P. A stakeholder- and function-based planning method for space-efficient buildings. P Von Both. 2019; IOP Conf Ser: Earth Environ Sci. 2019; 323: 012040. https://doi.org/10.1088/1755-1315/323/1/012040

[51] Höjer M, Mjörnell K. Measures and steps for more efficient use of buildings. Sustainability. 2018; 10(6): 1949. https://doi.org/10.3390/su10061949

[52] Nam H, Shim J. An analysis of the change in space efficiency based on various tall building corner shapes and lease spans. J Archit Inst Korea Plan Des. 2016; 32: 13-20. https://doi.org/10.5659/JAIK_PD.2016.32.11.13

[53] Zhang L, Zhang L, Wang Y. Shape optimization of free-form buildings based on solar radiation gain and space efficiency using a multi-objective genetic algorithm in the severe cold zones of China. Solar Energy. 2016; 132: 38-50. https://doi.org/10.1016/j.solener.2016.02.053

[54] Sev A, Özgen A. Space efficiency in high-rise office buildings. METU J Faculty Archit. 2009; 26: 69-89. https://doi.org/10.4305/METU.JFA.2009.2.4

[55] Saari A, Tissari T, Valkama E, Seppänen O. The effect of a redesigned floor plan, occupant density and the quality of indoor climate on the cost of space, productivity and sick leave in an office building: A case study. Build Environ. 2006; 41: 1961-72. https://doi.org/10.1016/j.buildenv.2005.07.012

[56] Kim H-I, Elnimeiri M. Space efficiency in multi-use tall buildings. In: Tall buildings in historical cities-culture and technology for sustainable cities. Chicago, IL, USA: CTBUH; 2004. p. 748-55.

[57] Opoku A, Ahmed V, Akotia J. Choosing an appropriate research method. In: Ahmed V, Opoku A, Aziz Z, Eds. Research methodology in the built environment. London: Routledge; 2016, PP. 32-49.

[58] Noor K. Case study: A strategic research methodology. Am J Appl Sci. 2008; 5(11): 1602-4. https://doi.org/10.3844/ajassp.2008.1602.1604

[59] Marsh E, Allen S, Hattam L. Tackling uncertainty in life cycle assessments for the built environment: A review. Build Environ. 2023; 231: 109941. https://doi.org/10.1016/j.buildenv.2022.109941

[60] Saka A, Taiwo R, Saka N, Salami B, Ajayi S, Akande K, *et al*. GPT models in construction industry: Opportunities, limitations, and a use case validation. Develop Built Environ. 2023; 12: 100300. https://doi.org/10.1016/j.dibe.2023.100300

[61] Pan Y, Zhu M, Lv Y, Yang Y, Liang Y, Yin R, *et al*. Building energy simulation and its application for building performance optimization: A review of methods, tools, and case studies. Adv Appl Energy. 2023; 10: 100135. https://doi.org/10.1016/j.adapen.2023.100135

[62] 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 02 October 2024).

[63] Oldfield P, Doherty B. Offset cores: Trends, drivers and frequency in tall buildings. CTBUH J. 2019; 1(2): 40-5.

[64] Sung L, Kim Y. The study on the height standard and the slenderness ratio according to location types of mixed-use residential tall buildings. J Korea Academia-Ind Cooperation Soc. 2012; 13(6): 2779-88. https://doi.org/10.5762/KAIS.2012.13.6.2779

[65] Alotaibi F, Sinclair B. Tall buildings, high expectations, towering responsibilities: Critically considering skyscrapers, urbanism and sustainability. In: da Costa MJRC, Roseta F, da Costa SC, Lages JP, Eds. Architectural Research Addressing Societal Challenges. London: CRC Press; 2017. pp. 535-42. https://doi.org/10.1201/9781315226255-82

[66] Oldfield P, Trabucco D, Wood A. Five energy generations of tall buildings: An historical analysis of energy consumption in high-rise buildings. J Architect. 2009; 14(5): 591-613. https://doi.org/10.1080/13602360903119405

[67] Kavyashree B, Patil S, Rao V. Evolution of outrigger structural system: A state-of-the-art review. Arabian J Sci Eng. 2021; 46(11): 10313-31. https://doi.org/10.1007/s13369-021-06074-9

[68] Amoussou C, Lei H, Alhaddad W, Halabi Y. Simplified modeling and analysis method for skyscrapers with outrigger system. Structures. 2021; 33; 1033-50. https://doi.org/10.1016/j.istruc.2021.04.096

[69] Tiwary A. Different types of outrigger system in high-rise buildings: A preliminary comparative seismic analysis in a 40-story RC building. Innov Infrastruct Solut. 2022; 7(6): 347. https://doi.org/10.1007/s41062-022-00946-1

[70] Xing L, Gardoni P, Zhou Y, Aguaguiña M. Optimal outrigger locations and damping parameters for single-outrigger systems considering earthquake and wind excitations. Eng Struct. 2021; 245: 112868. https://doi.org/10.1016/j.engstruct.2021.112868