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Space Efficiency in North American Skyscrapers

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

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

Abstract: Space efficiency in North American skyscrapers is crucial due to financial, societal, and ecological reasons. High land prices in major cities require maximizing every square foot for financial viability. Skyscrapers must accommodate growing populations within limited spaces, reducing urban sprawl and its associated issues. Efficient designs also support environmental sustainability and enhance city aesthetics, while optimizing infrastructure and services. However, no comprehensive study has examined the key architectural and structural features impacting the space efficiency of these towers in North America. This paper fills this gap by analyzing data from 31 case study skyscrapers. Findings indicated that (1) central core was frequently employed in the organization of service core; (2) most common forms were setback, prismatic, and tapered configurations; (3) outriggered frame and shear walled frame systems were mostly used; (4) concrete was the material in most cases; and (5) average space efficiency was 76%, and the percentage of core area to gross floor area (GFA) averaged 21%, from the lowest of 62% and 13% to the highest of 84% and 31%. It is expected that this paper will aid architectural and structural designers, and builders involved in shaping skyscrapers in North America.

Keywords: North America; skyscrapers; space efficiency; form; core type; structural system and material

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1. Introduction

Evolution of skyscrapers in North America, starting in the late 19th century, is a narrative of relentless innovation and architectural ambition, driven by advancements in steel-frame construction and elevator technology [1,2]. The reconstruction of Chicago after the Great Fire of 1871 catalyzed early skyscraper development [3], led by visionary architects of the 'Chicago School' like William Le Baron Jenney, who embraced steel frameworks to achieve unprecedented heights [4]. The Home Insurance Building in Chicago, completed in 1885, is often heralded as the world's first skyscraper, setting a precedent for future constructions [5]. New York City soon emerged as a rival with landmark buildings such as the Woolworth, Chrysler, and Empire State Buildings, which not only embodied corporate prestige but also showcased the Art Deco style's bold geometric designs and luxurious ornamentation, reflecting the optimism and modernity of the era [6–8]. The mid-20th century introduced the minimalist International Style, epitomized by the Seagram Building, which influenced skyscraper aesthetics globally through its emphasis on glass, steel, and functional design [9].

Structural engineering breakthroughs have revolutionized the construction of mega towers like Willis Tower and World Trade Center, demonstrating innovative approaches such as tubular systems [10,11]. These advancements not only enabled unprecedented heights but also highlighted a sophisticated understanding of aerodynamics and materials science, crucial for the stability and resilience of these towering giants. In the 21st century, the evolution of skyscraper development has continued apace, driven by a commitment to integrating sustainable design practices and cutting-edge technologies [12]. This modern approach addresses pressing environmental concerns and enhances structural resilience. Towers like One World Trade Center exemplify this trend with their incorporation of state-of-the-art security measures, energy-efficient systems, and a strong emphasis on sustainability [13]. This paradigm shift continually reshapes urban skylines and pushes the boundaries of architectural possibility, reflecting a proactive response to the challenges pretended by rapid urbanization and climate change. As skyscrapers become increasingly integral to urban landscapes, they symbolize the dynamic interplay between engineering innovation, environmental stewardship, and the ever-evolving aspirations of human societies [14].

Today, metropolises across North America are increasingly erecting skyscrapers around transit centers, fueling vertical growth driven by factors such as rising land values [15,16]. This trend reflects a strategic urban planning approach that maximizes land use efficiency and enhances accessibility, promoting sustainable and integrated urban development [17]. The United States, which has the peak count of tall structures in North America, features over 890 buildings exceeding 150 m in height, 244 buildings surpassing 200 m and 31 towering over 300 m [18]. Among American cities, New York City has been rapidly building supertall skyscrapers, showing significant growth in the number of high-rise buildings. Between 1930 and 2015, it completed 56 buildings taller than 200 m. By the third quarter of 2015, 25 more such buildings were under construction, nearly half of what was built in the previous 85 years. Currently, this city boasts 316 structures exceeding 150 m in height, with 98 surpassing the 200 m mark, and 17 towering over 300 m [18].

Manhattan is expected to see a sharp increase in buildings taller than 200 m, with projections suggesting over 30 such structures in the next decade, compared to just four since 2010 [19]. Chicago, despite population declines in the broader region, has experienced growth in its downtown area, marked by the construction of new skyscrapers. Miami has also seen a surge in tall building construction, with remarkable skyscrapers like Panorama Tower becoming landmarks. San Francisco, particularly near the Transbay Transit Center, has seen the construction of significant high-rises like the Oceanwide Center and the Waldorf Astoria Hotel. Overall, these cities are experiencing substantial growth in skyscraper construction, with significant increases in both the number and height of tall buildings, reinforcing existing clusters and contributing to iconic skylines.

Therefore, North American skyscrapers, particularly those in cities like New York, was chosen as a focal point in this study on skyscraper development due to their pivotal role in the architectural and engineering advancements of high-rise towers. These skyscrapers exemplified the use of new materials, like steel and concrete, which enabled constructions to reach unprecedented heights. Additionally, the architectural ingenuity of these towers, including the development of the skeletal frame structure, profoundly influenced global building practices. Studying North American skyscrapers offers insights into the socio-economic forces that spurred vertical growth and the technological breakthroughs that have shaped modern cityscapes, making them a rich case study for understanding the broader evolution of skyscrapers worldwide.

Space efficiency is paramount in North American skyscrapers due to financial, societal, and ecological considerations. Land prices in major cities are exorbitant, necessitating the maximization of every square foot to ensure financial viability [20]. Additionally, with urbanization leading to increased population density, skyscrapers must accommodate more people within limited areas, reducing urban sprawl and associated issues like congestion and environmental degradation. Efficient use of space also contributes to environmental issues by reducing land and energy usage for space heating, and cooling. Furthermore, aesthetically pleasing skylines are preserved when skyscrapers are efficiently designed, enhancing the city's characteristics, and potentially boosting its financial and cultural significance. Thus, space efficiency in North American towers is critical for revenue, growing populations, environment, and effective building operations.

In North America, there is a notable deficiency in comprehensive research concerning space utilization within skyscrapers. This paper bridges this gap through an in-depth analysis of 31 towers. Drawing on data from these case studies, this study critically assesses space efficiency by analyzing essential design parameters in modern North American skyscraper architecture, delving into the impact of various design considerations on space utilization with three fundamental aspects: (1) Architectural elements, including the design of service cores, and building form. (2) Structural elements, focusing on the selection of materials and structural frameworks. (3) Relationship between space efficiency and the aforementioned considerations. Through this examination, this paper provides valuable insights to influence future architectural strategies for skyscrapers in North America. By elucidating trends and identifying best practices, it is aimed to advance architectural and structural design paradigms, enhancing space efficiency in these giant towers.

Space efficiency is defined as the effective use of net floor area (NFA) in relation to GFA, aiming to maximize financial returns by optimizing the use of available floor space. Space efficiency is impacted by various considerations, including the choice of structural frameworks and architectural design parameters. This research assessed space efficiency by calculating the NFA-to-GFA ratio, which offers a numeric measure of how well the floor area is operated for practical drives, and the core-to-GFA ratio, which indicates the percentage of GFA dedicated to essential structural and service components. NFA is derived by subtracting the service core area and the area of structural elements from the GFA, thereby isolating the functional spaces used for activities from the total area. NFA-to-GFA ratio highlights the effectiveness of space distribution for practical use. Meanwhile, the core-to-GFA ratio determines the proportion of GFA used by critical infrastructure such as elevators and stairwells, offering insights into how much of the building's space is used for essential services versus usable floor area. Both ratios are crucial for understanding overall space efficiency and optimizing building design.

This research is dedicated exclusively to the analysis of space utilization, deliberately omitting considerations related to sustainable design like energy efficiency, environmental sustainability, and disaster resilience. This exclusion is necessitated by the insufficient and inconsistent data available across the various case studies, which precludes a comprehensive analysis of these sustainability elements. By narrowing the focus to space utilization, the study seeks to provide a more accurate and detailed scrutiny of this feature, thereby circumventing the complexities and potential inaccuracies that would arise from the inclusion of incomplete sustainability data. This approach guarantees that the findings are robust and consistent, providing beneficial insights into space utilization without the confounding effects of inadequate sustainability information.

2. Literature Survey

In the field of buildings' space efficiency, several key studies have explored various aspects and contexts, providing valuable insights and methodologies. Tuure and Ilgın [21] conducted a comprehensive analysis of wooden apartments in Finland, revealing spatial efficiency rates ranging from 78% to 88%. Their study underscored the potential of wooden structures in achieving high efficiency. Ilgın [22–24] extended this examination to supertall edifices of numerous purposes and regions, encompassing office, residential, and multi-use developments. Across these diverse categories, Ilgın consistently found that the use of outriggered frame and central service cores were prevalent, with a clear relationship between building height and spatial efficiency. Focusing on unconventional designs, Okbaz and Sev [25] established a pattern for space efficiency in unconventional office towers, showing that architectural design significantly impacts spatial effectiveness, with conical structures being the most efficient. This highlights the importance of innovative architectural approaches in optimizing space use. Ibrahimy et al. [26] assessed space use in housing developments in Afghanistan's capital, identifying significant deviations from regulations due to a lack of focus on architectural design and legislative guidelines. Their study pointed out the crucial role of regulatory frameworks in ensuring spatial efficiency. The impact of new know-hows on compact urban habitations was explored by Goessler and Kaluarachchi [27], who suggested that these innovations could enhance spatial efficiency by two to three times compared to traditional methods. This indicates the transformative potential of technology in urban housing design. Hamid et al. [28] found that placement of structures in corners boosts land use efficiency in Sudanese dwellings, emphasizing the importance of strategic placement in architectural design. Similarly, Suga [29] examined spatial use in hotel buildings, highlighting the benefits of efficient space utilization in the hospitality sector. Arslan Kılınç [30] investigated factors affecting load-bearing structures in prismatic skyscrapers, contributing to the understanding of structural considerations in spatial efficiency. Von Both [31] introduced a shareholder assessment method to enhance spatial use during the design phase, suggesting a participatory approach to optimizing space. Höjer and Mjörnell [32] offered a building guide to identify the impact of digitalization on internal space, reflecting the growing importance of digital tools in architectural design. Nam and Shim [33] studied lease spans and corner shapes of buildings, finding that corner cuts had an insignificant effect on spatial efficiency, but lease spans had noteworthy impacts. Zhang et al. [34] advanced a model to optimize solar radiation absorption in cold areas in relation to spatial efficiency, demonstrating the intersection of environmental sustainability and space optimization. Sev and Özgen [35] assessed space use in office towers, stressing the influence of load-bearing arrangements and core design on spatial efficiency. Saari et al. [36] scrutinized relationship between space optimization and total costs in office towers, highlighting the financial implications of efficient design. Finally, Kim and Elnimeiri [37] reviewed space efficiency ratios in multi-function skyscrapers, stressing the importance of integrating optimal load-bearing configurations and forms. Overall, these studies collectively underscore the multifaceted nature of space efficiency in buildings, emphasizing the importance of architectural design, technological innovations, regulatory frameworks, and strategic structural considerations. Each contribution provides a piece of the puzzle, advancing the understanding of how to maximize space efficiency in various building types and contexts.

A thorough review of the current literature reveals a significant lack of research on spatial efficiency in North American skyscrapers. To address this gap and enhance understanding of evolving tendencies, this paper aims to systematically compile, analyze, and assess data on spatial efficiency in these supertall projects. By closely examining 31 cases from the region, this research investigates key architectural and structural features, aiming to uncover trends and provide insights in this underexplored area.

3. The Research Method

The case study method was employed to organize and collect data from 31 North American skyscrapers, as illustrated in Figure 1. The case study method is widely used in research to record both qualitative and quantitative data, and to conduct extensive literature surveys [38,39]. It enables an in-depth assessment of architectural and structural faces of these developments, facilitating a thorough inquiry of real-world examples. This method provides a comprehensive examination of individual cases, yielding valuable understandings into the unique design components and structural features of each project. By focusing on particular instances, scholars can recognize cohesions and variations across modern skyscraper designs in North America, thereby recognizing emerging patterns and trends. This method's inherent flexibility allows for the incorporation of different data sources, such as blueprints, and other appropriate files, to develop a thorough grasp.

A total of 31 examined skyscrapers in this study, drawn from the extensive the Council on Tall Buildings and Urban Habitat (CTBUH) database, represent a strategically selected cross-section of skyscrapers located across various North American regions. The CTBUH, an esteemed non-profit organization, champions the advancement of urban environments globally, placing a significant emphasis on sustainability and resilience in city planning amid escalating urban sprawl and the exigencies of climate change. This organization not only sets the standards for categorizing tall buildings, conferring prestigious recognitions like 'The World's Tallest Building', but also celebrates architectural excellence through initiatives such as 'Buildings of Distinction'. Moreover, leveraging the CTBUH database, this study categorizes structures that buildings over 300 m as 'supertall', a term that accentuates their prominence and the technical and design prowess required in their construction.

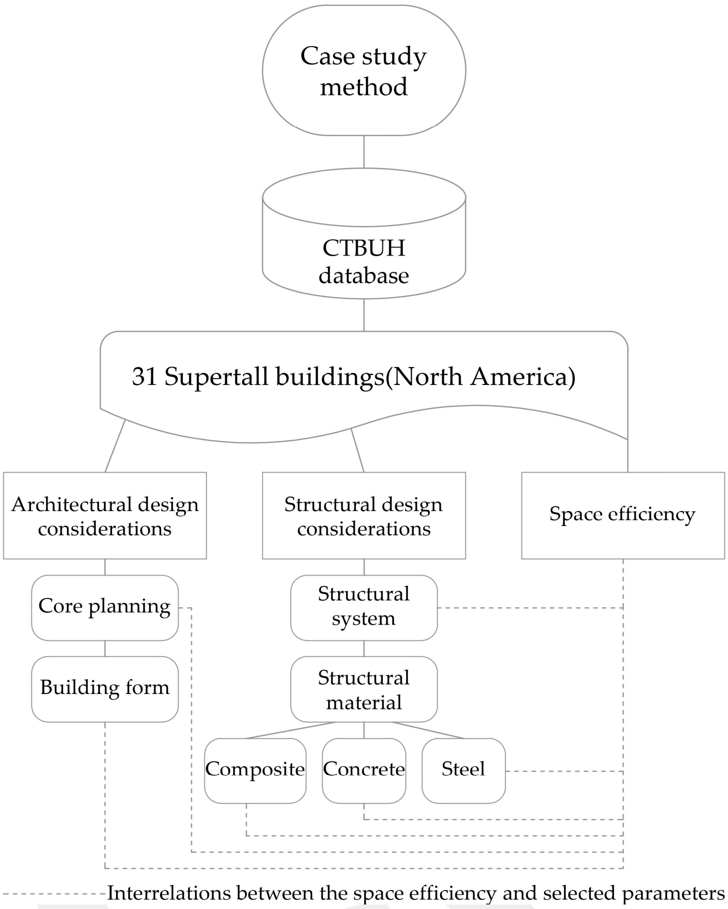

Figure 1. Research method flowchart (by authors).

Selecting 31 cases for this research represents a meticulous and strategic effort to ensure both the robustness and representativeness of the findings in the study of North American skyscrapers. Although the number of available cases is limited by geographical constraints and accessibility, this sample size is carefully chosen to offer a balanced and comprehensive view of spatial efficiency and architectural characteristics in skyscrapers. The sample encompasses a range of skyscrapers: 26 from the United States, including 18 specifically from New York City, 3 from Canada, and 2 from Mexico. This diversity, as illustrated in Figure 2 and outlined in Appendix A, allows for an inclusive examination of current skyscraper practices across different regions and urban contexts within North America. This varied selection is instrumental in capturing a broad spectrum of design approaches and spatial solutions, thus enhancing the generalizability of the findings. Research traditions suggest that a sample of approximately 30 case studies is generally sufficient to derive meaningful insights and identify significant trends, as demonstrated by previous research [23,40,41]. The choice of 31 cases not only aligns with these established guidelines but also provides a robust foundation for analyzing various aspects of skyscraper design, including core configurations, building forms, structural systems, and material choices. By thoroughly examining these cases, this research aims to uncover recurrent themes and trends, thereby offering valuable insights into how spatial efficiency is achieved and optimized in modern North American skyscrapers. This comprehensive approach facilitates a deeper understanding of architectural and structural strategies employed in these buildings, contributing to the broader discourse on skyscraper design and North American urban development. The resulting insights are expected to be both reliable and broadly applicable, providing a significant contribution to the field and informing future design practices and research. However, it is essential to emphasize that in certain regions analyzed, such as Mexico, there is a paucity of building data and limited availability of comprehensive datasets, which impedes the formulation of scientifically robust conclusions. Consequently, it is more appropriate to conduct evaluations on an individual case basis rather than applying broad generalizations to this region. This approach ensures a more accurate and nuanced understanding of the architectural landscape, given the constraints in data availability and regional specificity.

Figure 2. Case studies on the map of North America (by authors).

Similar to skyscrapers in Asia [42] and the Middle East [43], the planning of North American skyscrapers is driven by both architectural and structural constraints. These critical issues include core arrangement, form, and structural system and material.

Within the architectural parameters, core planning model suggested by [44] was used due to its all-encompassing architecture, which incorporates four primary categories: central, atrium, external, and peripheral, as shown Figure 3a. Moreover, forms are divided as follows: prismatic, setback, tapered, tilted, twisted, and free, as illustrated in Figure 3b and Appendix B.

Within architectural parameters, selecting appropriate structural framework is pivotal for enhancing space utilization in skyscrapers, as it affects the arrangement and size of structural elements. This study embraces a broader categorization introduced by [45] for skyscrapers, encompassing shear frame including shear-walled frame and shear-trussed frame; mega core; mega column; outriggered frame; tube; and buttressed core systems, as portrayed in Figure 3c. Given that structural materials play a role in shaping the dimensions of structural elements, their choice is a critical dynamic influencing space efficiency. These materials can be grouped as follows: steel, concrete, and composite. In this paper, concentrating on vertical load-bearing components like shear walls and columns as principal structural parts, 'composite' was utilized to denote buildings where load-bearing members consist of a blend of concrete, steel, or both.

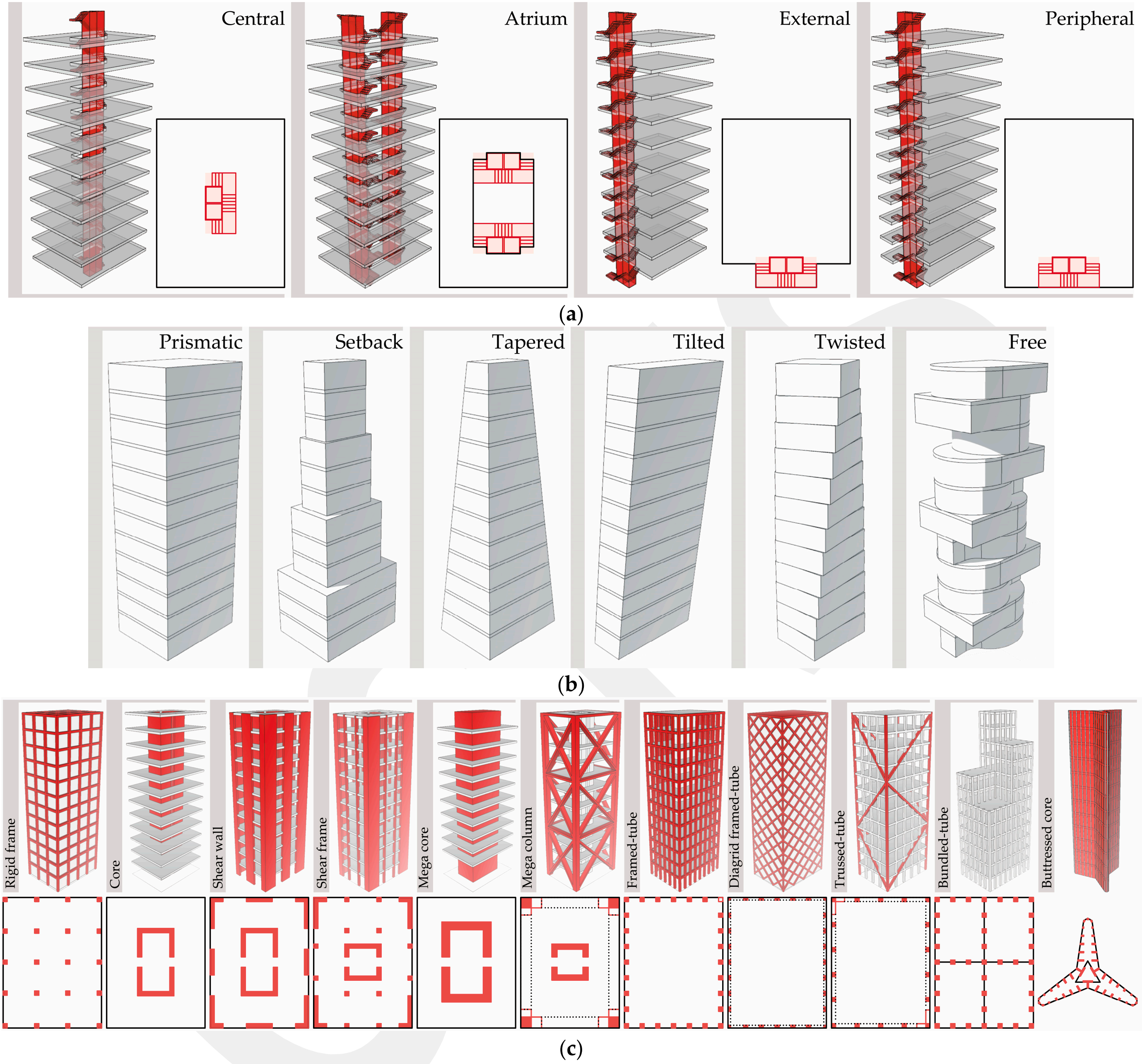

Figure 3. Classifications by (**a**) core planning; (**b**) form; and (**c**) structural system (by authors).

4. Results

In this section, the authors detail the key aspects of architectural parameters, covering core arrangement and form, key structural elements encompassing systems and materials, and space efficiency, along with its relationship with different planning factors.

4.1. Main Architectural Design Parameters: Core Planning and Building Form

Figure 4 demonstrates that in 31 cases, central core design was largely utilized, accounting for 90%. This preference can be attributed to the central core's compact nature, its critical structural role, its potential to increase flexibility in facade design, and its positive impact on fire safety. These considerations collectively make it the most feasible choice among core configurations [46]. Additionally, the deficiency of external cores and the limited use of peripheral core types may be due to their less favorable properties, like extended fire escape routes and less effective circulation [47]. The absence of atrium core arrangements might be related to the need for improved fire safety procedures [48].

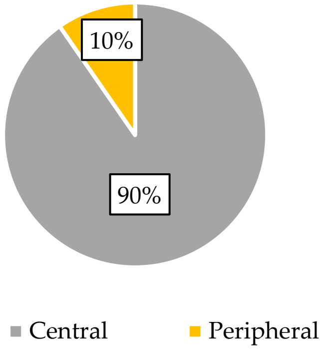

Figure 4. North American skyscrapers by core planning.

Setback, prismatic and tapered configuration stood out as the prevalent design choice, representing over 80% of examined skyscrapers. On the other hand, free forms made up less than 20%, as shown in Figure 5.

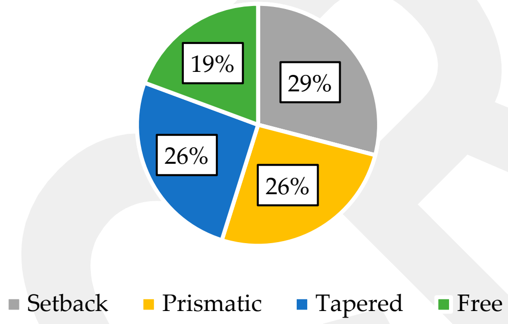

Figure 5. North American skyscrapers by building form.

Table 1 compares the outcomes on core planning and form with those of Asian skyscrapers [26] and Middle Eastern skyscrapers [27].

Table 1. Comparison of core planning and form.

	Findings	Asian Towers	Middle Eastern Towers
Core type	**Central (90%)** Peripheral (10%)	**Central (99%)** External (1%)	**Central (96%)** External (4%)
Form	Prismatic (26%) **Setback (29%)** Tapered (26%) Free (19%)	Prismatic (23%) Setback (13%) **Tapered (36%)** Twisted (1%) Free (27%)	**Prismatic (45%)** Setback (7%) Tapered (7%) Twisted (4%) Free (37%)

4.2. Main Structural Design Parameters: Structural Material and System

Concrete was predominant material in North American skyscraper construction, representing over half of its use, as depicted in Figure 6. Several factors likely contribute to this prevalence [49,50]: first, its cost-effectiveness in various countries makes it an economical choice for large-scale developments; second, its ease of usage in both building and production procedures allows for effective application on site; third, its inherent fire-resistant assets ensure higher safety measures in tall buildings; and its superior ability to minimize wind-induced sway compared to steel alternatives enhances structural stability and occupant comfort. The extensive acceptance of concrete highlights its adaptability and appropriateness for meeting the rigorous demands of high-rise projects in North America.

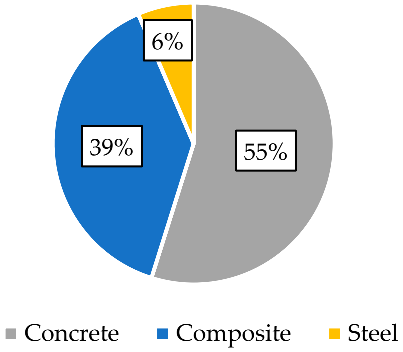

Figure 6. North American skyscrapers by structural material.

The preference for outriggered frame systems with 42% in North American skyscrapers, as seen in Figure 7, was largely due to offered flexibility in the arrangement of perimeter structural frame. This flexibility grants architect's greater creative freedom in designing the facade, specifically in terms of maintaining unobstructed views. As a result, this design versatility encourages the exploration of taller structures, making the outriggered frame system a practical alternative for constructing prismatic towers. The use of this load-bearing system represents a strategic decision to improve both visual and functional elements, highlighting its significance in modern high-rise towers.

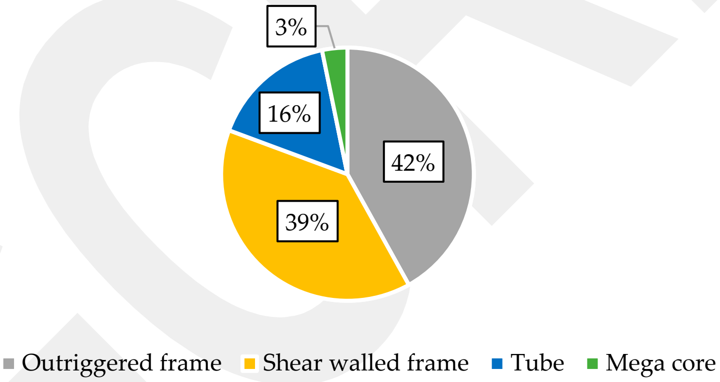

Figure 7. North American skyscrapers by structural system.

Table 2 compares the outcomes on structural material and system with those of Asian skyscrapers [26] and Middle Eastern skyscrapers [27].

Table 2. Comparison of structural material and system.

	Findings	Asian Towers	Middle Eastern Towers
Structural material	**Concrete (55%)** Composite (39%) Steel (6%)	Concrete (18%) **Composite (79%)** Steel (3%)	**Concrete (70%)** Composite (30%)
Structural system	**Outriggered frame (42%)** Tube (16%) Mega core (3%) Shear walled frame (39%)	**Outriggered frame (76%)** Tube (17%) Buttressed core (3%) Mega column & core (3%) Shear-frame (1%)	**Outriggered frame (44%)** Tube (26%) Buttressed core (4%) Mega column & core (15%) Shear-frame (11%)

4.3. *Space Efficiency in North American Skyscrapers*

In this research, it was found that average space efficiency was 76%, while the percentage of core area to GFA was 21%. The observed values ranged from the lowest of 62% and 13% to the highest of 84% and 31%, respectively, as shown in Appendix C. Table 3 compares the findings on average space efficiency and ratio of core to GFA with those of Asian skyscrapers [26] and Middle Eastern towers [27].

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

	Findings	**Asian Towers**	**Middle Eastern Towers**
Average space efficiency	76% (max. 84%, min. 62%)	67.5% (max. 82%, min. 56%)	75.5% (max. 84%, min. 63%)
Average ratio of core to GFA	21% (max. 31%, min. 13%)	29.5% (max. 38%, min. 14%)	21.3% (max. 36%, min. 11%)

Bank of America Tower and One57 exemplify significant advancements in architectural design and space utilization, achieving remarkable spatial efficiencies fluctuating from 82% to 84%, as detailed in Appendix C. These skyscrapers set a new benchmark with the smallest GFA ratio, largely attributable to innovative core planning and advanced structural systems. In these skyscrapers, the vertical transportation systems, such as lifts and staircases, are meticulously organized to minimize the core footprint. This strategic core planning significantly enhances the usable space within the buildings. Moreover, the adoption of highly efficient structural systems, including tube and outriggered frame systems, plays a crucial role. These systems not only use significantly less structural material compared to traditional skyscraper frameworks but also enhance the overall stability and resilience of the structures. Tube and outriggered frame systems contribute to the remarkable spatial efficiency by providing robust structural integrity while minimizing material usage. This combination of advanced design strategies maximizes usable space and ensures robust structural integrity, establishing an innovative benchmark for sustainable and efficient urban development. Such design innovations underscore the potential for integrating space efficiency with structural sophistication, paving the way for future high-rise constructions. These buildings exemplify how modern architectural practices can achieve a harmonious balance between maximizing space utilization and maintaining structural excellence. The advancements seen in the Bank of America Tower and One57 demonstrate the feasibility and benefits of these design principles, encouraging their adoption in future high-rise projects to achieve sustainable urban growth in North America.

4.3.1. Interrelation of Space Efficiency and Building Completion Period

Figure 8 presents data illustrating the relationship between space efficiency and period of skyscraper completion in North America. It employs gray shaded bars to depict the percentage of space efficiency segmented by various periods. Notably, the majority of skyscrapers in the case study sample, which are either under construction or completed between 2015 and 2019, exhibited space efficiency ratios of 77% and 75%, respectively. Figure 8 clearly indicates minimal variation in space efficiency ratios across different construction periods, including those skyscrapers planned for future construction. This suggests a consistent approach to maximizing space utilization in North American skyscraper design over recent years, regardless of the specific time of completion.

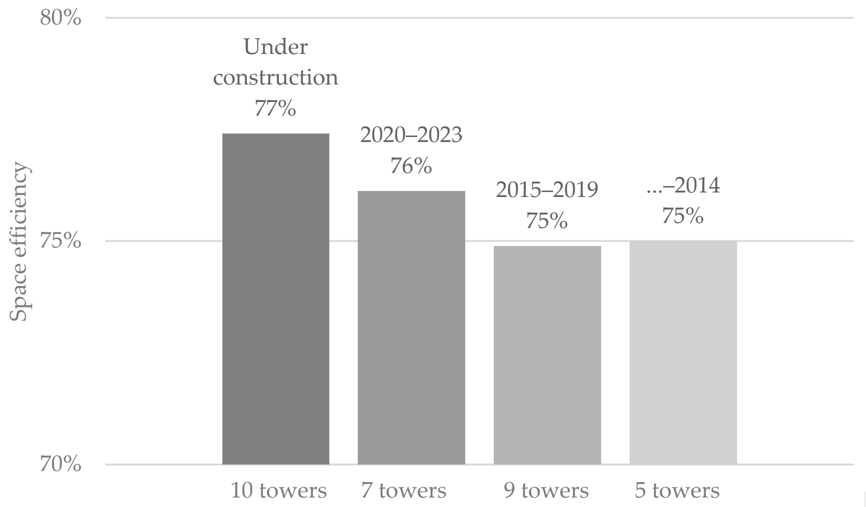

Figure 8. Interrelation of space efficiency and completion period.

4.3.2. Interrelation of Space Efficiency and Core Planning

Figure 9 reports data on the relationship of space efficiency with core planning. Bars on the right side display the total occurrence of towers clustered by core type. Orange dots signify the space efficiency of structures corresponding to each core type. Moreover, a gray bar is shown to indicate the occurrence of cases within the sample that share the same core type.

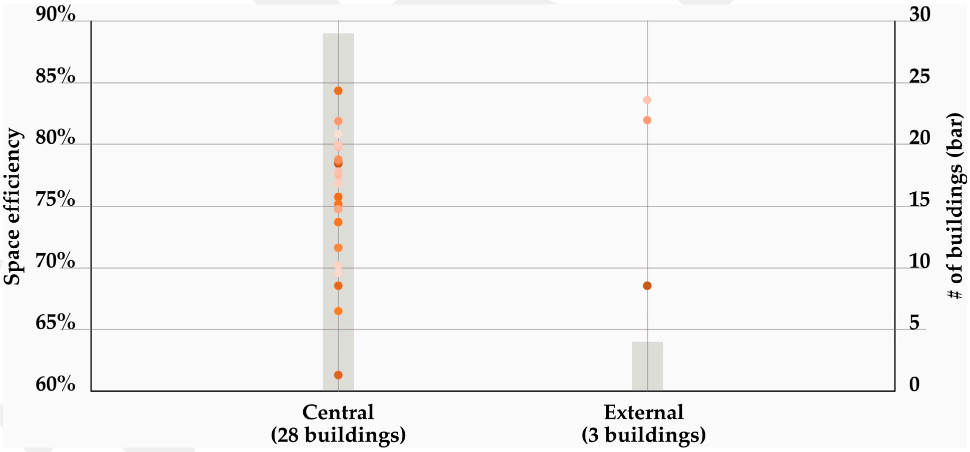

Figure 9. Interrelation of space efficiency and core type.

Central core was the most widespread, appearing in 28 structures. These buildings showed spatial efficiency between 62% and 84%, with an average efficiency of 76%. In contrast, external core type was found in only 3 cases, with spatial efficiency between 69% and 84% and an average of 78%. Therefore, there is no substantial difference in average spatial efficiency between different core arrangements.

4.3.3. Interrelation of Space Efficiency and Form

Figure 10 displays data on the relationship between spatial efficiency and structural forms. Bars on the right side demonstrate the total skyscrapers clustered by their respective forms. Blue dots denote space efficiency of these configurations within the case study for each specific form. The gray bar shows the frequency of buildings that share the same form.

Among the forms observed in the examined structures, setback, prismatic, and tapered forms occurred as the leading choices, totaling 25 occurrences. These arrangements have shown average spatial efficiency ratios of 80%, 80%, and 82%, respectively. In contrast, instances featuring free forms are less common, with only six cases identified.

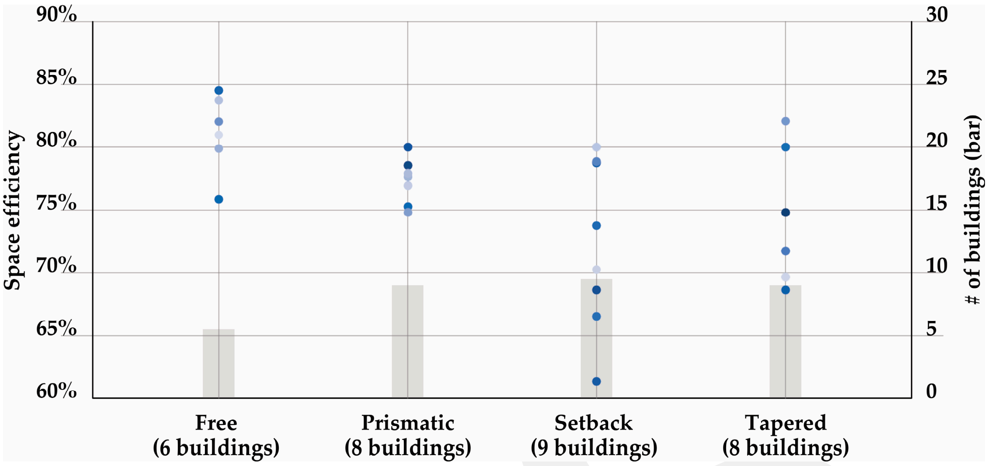

Figure 10. Interrelation between space efficiency and building form.

4.3.4. Interrelation of Space Efficiency and Structural System

Figure 11 portrays data focusing on the relationship between spatial efficiency and load-bearing systems. Visualization features bars on the right side, symbolizing the total count of towers clustered by their load-bearing systems. Orange dots imply the space efficiency of these cases corresponding to each specific load-bearing system. Additionally, a gray bar represents the number of towers sharing the same load-bearing systems.

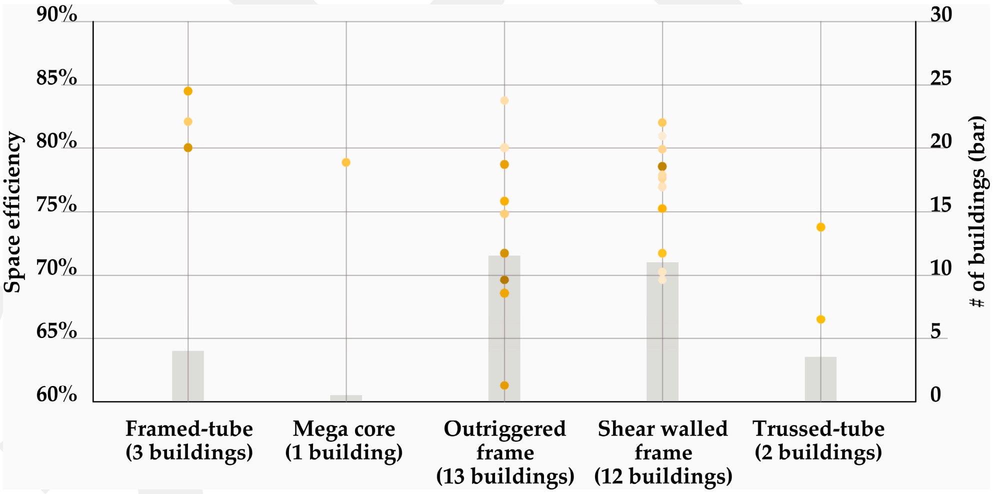

Figure 11. Interrelation between space efficiency and structural system.

In the examination of North American skyscrapers, outriggered frame and shear walled frame occurred as the predominant structural systems, a total of 25 skyscrapers. These arrangements show space efficiency between 62% and 84%, and 70% and 82%, with averages of 75% and 77%, respectively. In contrast, structures utilizing framed-tube and trussed-tube systems, totaling five instances, have demonstrated average space efficiencies of 82% and 71%, respectively.

4.3.5. Interrelation of Space Efficiency and Structural Material

Figure 12 shows the relationship between spatial effectiveness and materials. Bars on the right side represent the total frequency of instances grouped by their respective building materials. Also, green dots denote the spatial efficiency of these constructions for each particular building material. A gray bar is incorporated into the visual representation to indicate the number of instances sharing the same building material.

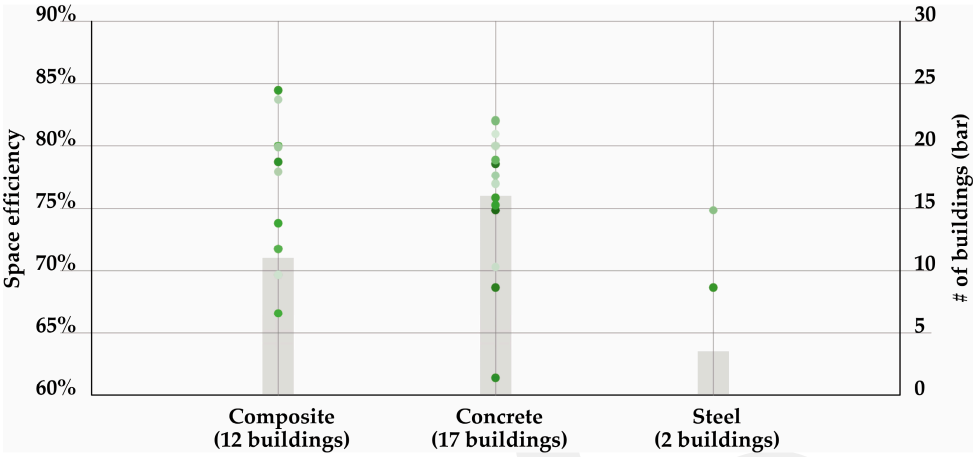

Figure 12. Interrelationship between space efficiency and structural material.

Concrete was as the primary structural material used. Spatial efficiency levels for these materials ranged from 62% to 82%, with an average efficiency of 77%.

5. Discussion

This study significantly contributes to the field of architecture and urban planning by offering the first comprehensive analysis of architectural and structural features influencing space efficiency in North American skyscrapers. Through the study of 31 skyscrapers, it identified prevailing design strategies that have a critical effect on space use—such as the use of central cores, common forms (setback, prismatic, tapered), and structural systems (outriggered and shear walled frames) and predominance of concrete as a building material. It also quantified space efficiency and core area ratios, providing benchmarks (average space efficiency of 76% and a core-to-floor area ratio of 21%) that can guide future designs. This innovative study is poised to assist designers and builders in enhancing skyscraper efficiency, supporting environmental sustainability, and responding to the challenges posed by high land costs and urban density.

Central core occurred as the dominant selection for core arrangement in numerous contemporary tall towers, as demonstrated by references [21–29]. North American skyscrapers often use central cores due to several advantages. First, central cores allow more residences along the building's perimeter, improving access to natural light and views, enhancing living quality and the building's aesthetic appeal. They also improve fire safety by simplifying evacuation routes, reducing risks during emergencies. Additionally, central cores offer architectural flexibility, blending seamlessly with the building's design without affecting its exterior. This flexibility lets architects study numerous design options while maintaining structural integrity and safety, making central cores a popular choice in modern skyscrapers. Just as Asian skyscrapers [26] often favored tapered forms and Middle Eastern towers [27] primarily utilized prismatic designs, these forms were also popular choices as well as setback configurations in the North American context.

Unlike the examination carried out on Asian towers [26], but consistent with investigations into Middle Eastern skyscrapers [27], the analysis of preferred structural materials indicates that reinforced concrete emerged as the primary selection for constructing North American towers. Reinforced concrete is popular for a few key reasons. It is cost-effective, making it a good choice for developers and builders. It is versatile and easy to work with, especially for tall buildings. Plus, it is fire-resistant, which is important for safety, especially in skyscrapers. Overall, these qualities make reinforced concrete the top pick for North American towers aiming for a balance of affordability, practicality, and safety. While outrigged frame systems were preferred in both Asian and Middle Eastern skyscrapers, shear walled frame configurations were also preferred along with this system in North America.

A proposed benchmark for space utilization in skyscrapers targets 75% utilization, which is well-supported by empirical data across different regions and building types [51]. Research on Asian skyscrapers [26] shows an average spatial efficiency of 67.5%, with a range between 56% and 82%, and a core area to GFA ratio averaging 30%, with variations from 14% to 38%. In contrast, Middle Eastern skyscrapers [27] exhibit higher space efficiency, averaging 76% and between 63% and 84%, with a core area to GFA ratio averaging 21% and varying between 11% and 36%. Finnish mid-rise timber housing units further illustrate potential efficiencies, with an average space efficiency of 83%, ranging from 78% to 88%. A comprehensive study of 31 cases corroborates these findings, revealing an average space efficiency of 76% and a core area to GFA ratio of 21%, with ranges from 62% to 84% for space efficiency and 13% to 31% for core area to GFA ratio. These diverse yet reliable data points indicate that a 75% benchmark is not only realistic but also reflective of competent practices in skyscraper projects. This benchmark is grounded in a variety of empirical studies and provides a scientifically supported objective for improving space utilization in skyscrapers. The variations in regional data highlight the influence of local building practices and materials on space efficiency, while the overall trends demonstrate the feasibility of achieving and even exceeding the 75% target. By adhering to these benchmarks, architects and engineers can enhance the functionality and sustainability of urban high-rise developments, ensuring efficient use of space and resources.

The differing space utilization rates between the findings and those in Asian and Middle Eastern skyscrapers can be attributed to several key factors rooted in architectural design, building regulations, and construction practices. In Asia, this larger core area, which includes essential services like elevators, stairwells, and mechanical rooms, reduces the usable floor space, often due to stricter safety regulations and the need for higher redundancy in densely populated urban areas. Conversely, Middle Eastern skyscrapers exhibit a higher average space efficiency. This increased efficiency might be ascribed to advancements in construction technology and innovative design approaches that optimize core layouts, reducing the space taken up by non-leasable areas. Additionally, the climatic and cultural context in the Middle East often prioritizes larger, more open spaces within buildings, which can also enhance overall spatial efficiency. The findings reflect a balanced integration of advanced architectural design and efficient core space management. The variation in space utilization rates is also influenced by the specific functional requirements of the buildings studied, regional construction practices, and economic considerations driving the design process. Thus, the observed differences are a result of a complex interplay between regulatory environment, technological advancements, and contextual demands specific to each region.

Enhancing space efficiency in North America can involve various innovative and interdisciplinary research directions. Here are some potential future research areas:

1. Urban Planning and Smart Cities [52–54]: (a) Vertical Urbanism: Investigating high-density vertical cities with integrated residential, commercial, and recreational spaces to minimize land use. (b) Mixed-Use Developments: Researching designs that combine residential, commercial, and industrial spaces in a single area to reduce sprawl and improve efficiency. (c) Public Transportation Systems: Developing advanced public transportation networks to reduce the need for personal vehicle space and enhance urban mobility.
2. Sustainable Architecture [55–57]: (a) Green Building Materials: Exploring innovative, sustainable building materials that can improve insulation, reduce footprint, and integrate renewable energy systems. (b) Modular Construction: Advancing modular and prefabricated building techniques to enhance efficiency in both construction time and space usage.
3. Land Use Policy and Zoning [58–60]: (a) Adaptive Reuse of Buildings: Studying policies and methods for repurposing old buildings and spaces for new uses, reducing the need for new construction. (b) Zoning Reforms: Investigating zoning laws that promote higher density living and mixed-use developments.

4. Technology Integration [61–63]: (a) Internet of Things (IoT): Researching how IoT can optimize building operations and space usage, such as smart lighting, heating, and security systems. (b) Big Data and AI: Utilizing big data and AI to analyze and predict urban growth, traffic patterns, and optimize space utilization in real-time.
5. Environmental and Energy Efficiency [64–66]: (a) Green Roofs and Vertical Gardens: Exploring the use of green roofs and vertical gardens to enhance space efficiency while providing environmental benefits. (b) Energy-Efficient Building Designs: Studying passive and active energy-efficient designs that reduce the energy footprint of buildings.
6. Community and Social Aspects [67–69]: (a) Co-living and Co-working Spaces: Researching the viability and social impact of shared living and working spaces to maximize space usage. (b) Inclusive Design: Ensuring that space-efficient designs are accessible and beneficial to diverse populations, including low-income and marginalized communities.
7. Infrastructure Innovations [70–72]: (a) Underground Development: Investigating the potential of underground spaces for parking, storage, or even residential and commercial use to free up surface space. (b) Multi-purpose Infrastructure: Designing infrastructure that serves multiple functions, such as parks that double as flood control areas.
8. Renewable Energy and Microgrids [73–75]: (a) Distributed Energy Resources (DERs): Researching the integration of DERs in urban areas to enhance energy efficiency and reduce space required for large power plants. (b) Microgrids: Studying the implementation of localized microgrids that can operate independently, increasing energy resilience and efficiency. These research directions aim to address the challenges of urbanization, resource constraints, and environmental sustainability, promoting a more efficient use of space in North America.

The authors acknowledge the necessity of meticulously detailing the constraints encountered during this investigation and their ramifications for future research. This study identified several crucial limitations, each significant in guiding future research trajectories. Firstly, the sample size, consisting of 31 cases, was sufficient for detecting notable trends within this study's scope. However, this moderately small sample size may limit the generalizability of the findings to a larger array of tall structures. Future research could address this by employing larger and more varied datasets, including those covering low-rise North American towers. This approach would enhance the statistical robustness of the results and facilitate their wider applicability and validation across different architectural contexts. Secondly, this research was limited by the availability of data on North American tall towers. The authors mainly relied on publicly accessible sources, which may not fully capture all relevant parameters or the contemporary developments in skyscraper building technologies. Improving admission to more thorough and current datasets would significantly strengthen the methodological rigor and dependability of forthcoming studies in this area. Thirdly, the analysis primarily concentrated on spatial utilization and architectural characteristics, with restricted investigation into the financial and ecological effects of various design preferences. To provide a more comprehensive interpretation of North American skyscraper projects, future inquiries should include thorough scrutiny of these complex features.

6. Conclusions

This paper concentrates on space efficiency in North American supertall towers, filling a gap in the literature. This article systematically examines data from 31 buildings through case studies, identifying the key factors influencing space efficiency in these skyscrapers. These factors include core planning, the size of the service core, form, and structural materials and load-bearing system selections, considering structural member dimensions.

The findings have viable applications for skyscraper construction, highlighting several critical components. Central core is identified as the prevalent choice, offering architects guidance for layouts that enhance space utilization and availability while shortening building processes. Setback, prismatic, and tapered forms with outriggered frame and shear walled frame systems are endorsed for their structural stability and spatial efficiency. Prevalent use of concrete suggests a material policy that balances sustainability with structural strength.

With an average space efficiency rate of 76% and a core area-to-GFA ratio of 21%, the study offers standards for augmenting leasable space and achieving effective housing plans. By integrating these comprehensions, architectural specialists in North America can design tall buildings that are more competent, sustainable, and financially viable. This approach facilitates the creation of unique, high-rise spaces that reflect contemporary design approach and ecological awareness.

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

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

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

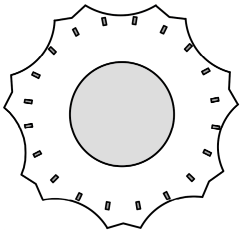
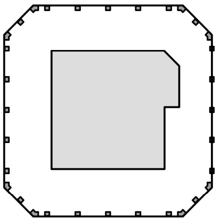
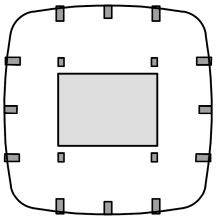
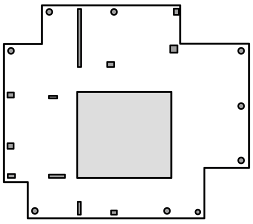
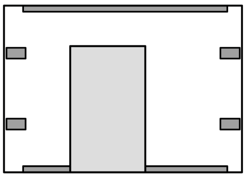
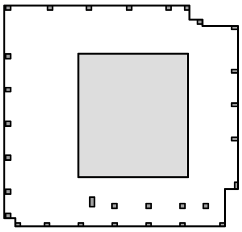
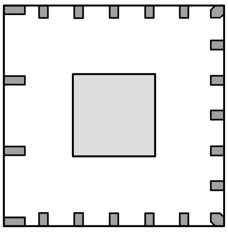
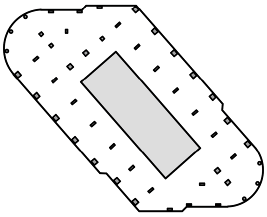
Appendix A. North American Skyscrapers

#	Name	Country	City	Height (Meters)	# of Stories	Completion Date
1	Chicago Spire	USA	Chicago	609	150	Never Completed
2	One World Trade Center	USA	New York	541	94	2014
3	Torre Rise	Mexico	Monterrey	475	88	Under Construction
4	Central Park Tower	USA	New York	472	98	2020
5	111 West 57th Street	USA	New York	435	84	2021
6	One Vanderbilt Avenue	USA	New York	427	62	2020
7	432 Park Avenue	USA	New York	426	85	2015
8	Trump International Hotel & Tower	USA	Chicago	423	98	2009
9	JPMorgan Chase World Headquarters	USA	New York	423	60	Under Construction
10	30 Hudson Yards	USA	New York	387	73	2019
11	Bank of America Tower	USA	New York	366	55	2009
12	The St. Regis Chicago	USA	Chicago	363	101	2020
13	SkyTower at Pinnacle One Yonge	Canada	Toronto	345	105	Under Construction
14	Comcast Technology Center	USA	Philadelphia	339	59	2018
15	Wilshire Grand Center	USA	Los Angeles	335	62	2017
16	3 World Trade Center	USA	New York	329	69	2018
17	Salesforce Tower	USA	San Francisco	326	61	2018
18	The Brooklyn Tower	USA	New York	325	74	2023
19	740 8th Avenue	USA	New York	325	52	Under Construction
20	53 West 53	USA	New York	320	77	2019
21	New York Times Tower	USA	New York	319	52	2007
22	Waldorf Astoria Hotel and Residences Miami	USA	Miami	317	98	Under Construction
23	The Spiral	USA	New York	314	65	2022
24	Waterline	USA	Austin	311	74	Under Construction
25	The One	Canada	Toronto	309	85	Under Construction
26	One57	USA	New York	306	75	2014
27	35 Hudson Yards	USA	New York	305	72	2019
28	T.Op Corporativo	Mexico	Monterrey	305	62	2020
29	520 Fifth Avenue	USA	New York	305	76	Under Construction
30	One Manhattan West	USA	New York	304	67	2019
31	Concord Sky	Canada	Toronto	300	85	Under Construction

Appendix B. North American Skyscrapers by Building Form, Core Type, Structural System, and Structural Material

#	Name	Building Form	Core Type	Structural System	Structural Material
1	Chicago Spire	Twisted	Central	Outriggered frame	Concrete
2	One World Trade Center	Tapered	Central	Outriggered frame	Composite
3	Torre Rise	Prismatic	Central	Shear walled frame	Concrete
4	Central Park Tower	Setback	Central	Outriggered frame	Concrete
5	111 West 57th Street	Setback	Peripheral	Outriggered frame	Concrete
6	One Vanderbilt Avenue	Tapered	Central	Outriggered frame	Composite
7	432 Park Avenue	Prismatic	Central	Framed-tube	Concrete
8	Trump International Hotel & Tower	Setback	Central	Outriggered frame	Concrete
9	JPMorgan Chase World Headquarters	Setback	Central	Outriggered frame	Composite
10	30 Hudson Yards	Tapered	Central	Outriggered frame	Steel
11	Bank of America Tower	Free	Central	Framed-tube	Composite
12	The St. Regis Chicago	Free	Central	Outriggered frame	Concrete
13	SkyTower at Pinnacle One Yonge	Prismatic	Central	Shear walled frame	Concrete
14	Comcast Technology Center	Setback	Central	Trussed-tube	Composite
15	Wilshire Grand Center	Tapered	Central	Outriggered frame	Composite
16	3 World Trade Center	Setback	Central	Trussed-tube	Composite
17	Salesforce Tower	Tapered	Central	Shear walled frame	Composite
18	The Brooklyn Tower	Setback	Central	Mega core system	Concrete
19	740 8th Avenue	Free	Central	Shear walled frame	Concrete
20	53 West 53	Tapered	Peripheral	Framed-tube	Concrete
21	New York Times Tower	Prismatic	Central	Outriggered frame	Steel
22	Waldorf Astoria Hotel and Residences Miami	Prismatic	Central	Shear walled frame	Concrete
23	The Spiral	Free	Central	Shear walled frame	Composite
24	Waterline	Prismatic	Central	Shear walled frame	Concrete
25	The One	Prismatic	Central	Shear walled frame	Composite
26	One57	Free	Peripheral	Outriggered frame	Composite
27	35 Hudson Yards	Setback	Central	Outriggered frame	Concrete
28	T.Op Corporativo	Prismatic	Central	Shear walled frame	Concrete
29	520 Fifth Avenue	Setback	Central	Shear walled frame	Concrete
30	One Manhattan West	Tapered	Central	Shear walled frame	Composite
31	Concord Sky	Free	Central	Shear walled frame	Concrete

Appendix C. Space Efficiency and Core/GFA of North American Skyscrapers

<table>
<tr><th colspan="6">#- Building Name
(Buildings are listed from highest to lowest.)</th><th colspan="2"># - 1 to 17</th></tr>
<tr><td colspan="4">Space Efficiency *</td><td colspan="4">Core/GFA **</td></tr>
<tr><td colspan="2">1-Chicago Spire</td><td colspan="2">2-One World Trade Center</td><td colspan="2">3-Torre Rise</td><td colspan="2">4-Central Park Tower</td></tr>
<tr><td>75%</td><td>24%</td><td>70%</td><td>30%</td><td>79%</td><td>18%</td><td>80%</td><td>18%</td></tr>
<tr><td colspan="2">
Typical floor</td><td colspan="2">
Low-rise floor</td><td colspan="2">
Low-rise floor</td><td colspan="2">
Typical floor</td></tr>
<tr><td colspan="2">5-111 West 57th Street</td><td colspan="2">6-One Vanderbilt Avenue</td><td colspan="2">7-432 Park Avenue</td><td colspan="2">8-Trump International Hotel&Tower</td></tr>
<tr><td>69%</td><td>24%</td><td>72%</td><td>27%</td><td>80%</td><td>14%</td><td>62%</td><td>18%</td></tr>
<tr><td colspan="2">
Typical floor</td><td colspan="2">
Ground floor</td><td colspan="2">
Typical floor</td><td colspan="2">
Low-rise floor</td></tr>
<tr><td colspan="4">9-JPMorgan Chase World Headquarters</td><td colspan="2">10-30 Hudson Yards</td><td colspan="2">11-Bank of America Tower</td></tr>
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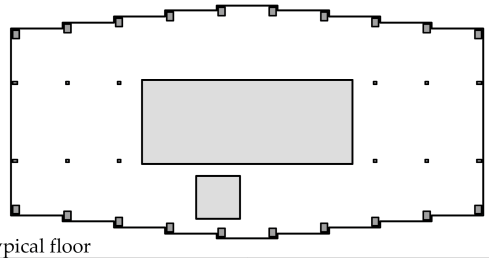
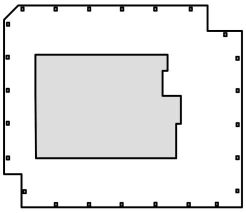
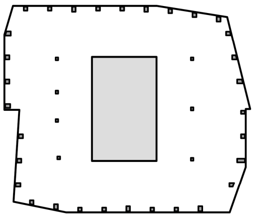
<tr><td colspan="4">
Typical floor</td><td colspan="2">
Low-rise floor</td><td colspan="2">
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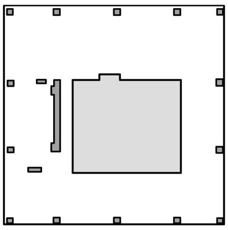
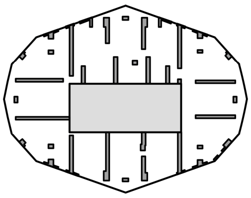
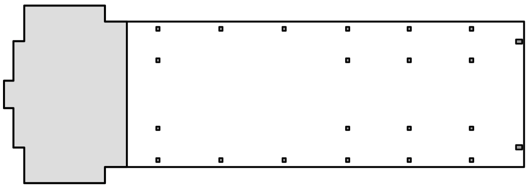
<tr><td colspan="2">
Typical floor</td><td colspan="2">
Typical floor</td><td colspan="4">
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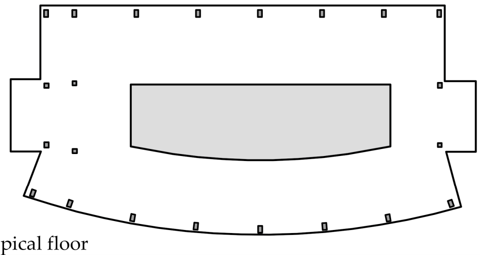
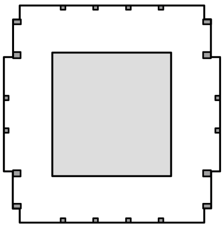
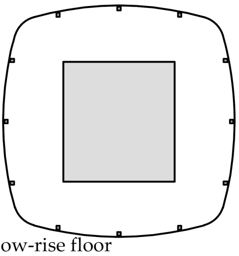
<tr><td colspan="4">
Typical floor</td><td colspan="2">
Low-rise floor</td><td colspan="2">
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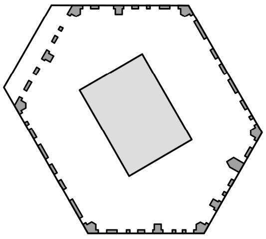
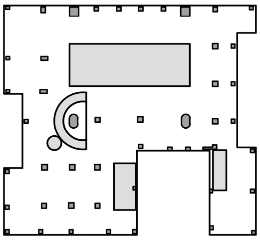
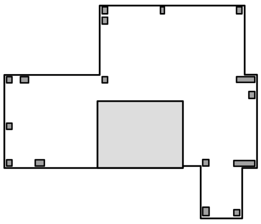
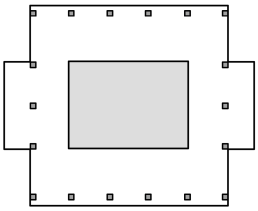
<tr><td colspan="2">
High Rise floor</td><td colspan="2">
Ground floor</td><td colspan="2">
Typical floor</td><td colspan="2">
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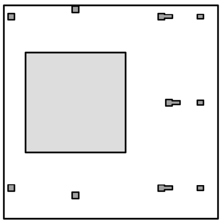
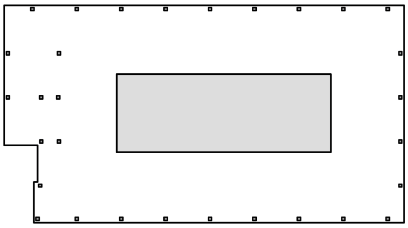
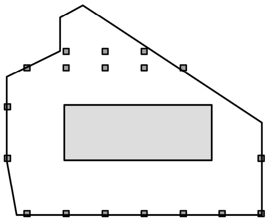
<tr><td colspan="2">
High Rise floor</td><td colspan="4">
Mid Rise floor</td><td colspan="2">
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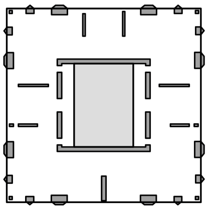
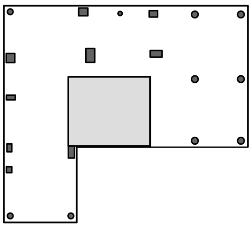
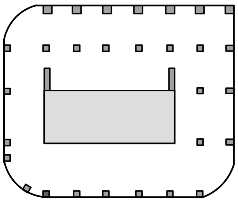
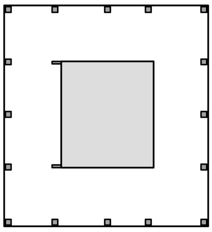
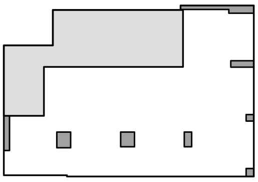
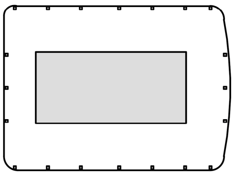
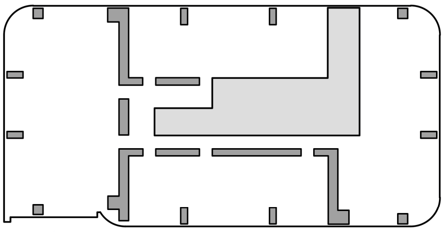
<tr><td colspan="2">
High Rise floor</td><td colspan="2">
High Rise floor</td><td colspan="2">
High Rise floor</td><td colspan="2">
Low-rise floor</td></tr>
<tr><td colspan="2">29-520 Fifth Avenue</td><td colspan="2">30-One Manhattan West</td><td colspan="4">31-Concord Sky</td></tr>
<tr><td>71%</td><td>26%</td><td>70%</td><td>29%</td><td colspan="2">81%</td><td colspan="2">13%</td></tr>
<tr><td colspan="2">
Low-rise floor</td><td colspan="2">
Low-rise floor</td><td colspan="4">
High Rise floor</td></tr>
<tr><td colspan="8">Space Efficiency* : calculated as the ratio of the net floor area obtained by subtracting the service core (the gray area on the floor plan) and structural elements from GFA to GFA.
Core / GFA** : calculated as the ratio of the service core (the gray area on the floor plan) to GFA.
In the floor plans,the gray area corresponds to service core, while black area signifies structural elements.</td></tr>
</table>

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