AE1212

Space Efficiency in Contemporary Supertall Office Buildings

Hüseyin Emre Ilgın[1]

[1]Dr., School of Architecture, Faculty of Built Environment, Tampere University, Rakennustalo, Korkeakoulunkatu 5, 33720 Box 600, FI-33014 Tampere, Finland. E-mail: hemreilgin@gmail.com

a

Abstract

Space efficiency in supertall building (300m+) is one of the most critical design parameters to make a project feasible. This issue becomes even more important in office buildings where the ability to increase rental income is a crucial indication of proper planning. This study analyzed space efficiency in contemporary supertall office buildings. Data was collected from the 44 buildings through literature surveys and the case study method to examine space efficiency and main architectural and structural parameters affecting it to contribute to designing more feasible office towers. The main findings of this study indicated that: (1) central core was the most preferred type, (2) frequent use of free and tapered forms were identified, (3) composite use was dominant over steel and concrete utilization, (4) the most used structural system was outriggered frame system, (5) space efficiency decreased as the height of building increased, where core area and planning were the most decisive factors, (6) when groups of building form were compared with each other, no significant differences were identified among their effects on space efficiency and similar results were valid for structural systems. This study will aid and direct architects in the sound planning and development of supertall office projects.

Keywords: supertall office building, space efficiency, building form, core planning, structural system and structural material.

1. Introduction

Tall buildings, which were generally designed for office use, had an important position in American architectural history at the beginning of the 20th century. They were primarily a reaction to the rapid population growth, expansive urban sprawl, economic cycles, and thus the need for business activities in the form of office units to be positioned as close to each other as possible. (Gunel and Ilgın, 2014). This tendency is still valid today. Moreover, through the years, the number of supertall buildings has been increasing, where one-third of them completed from 2000s onwards have an office function as single-use (CTBUH, 2020). Maximizing the leasable area is one of their most important design inputs.

Today, the race for height continues at an accelerating pace in the construction of office towers all over the world. However, supertall office buildings are more expensive to erect and operate per square meter, and they generate less usable space than conventional office buildings (Sev and Ozgen, 2009). Space efficiency stands out at this point as office function needs to fulfill the value and cost of the investment. Space efficiency, which is determined by the size of the floor plan, service core, and the dimension of the structural members, goes along with the financial return (Kim and Elnimeiri, 2004; Sev and Ozgen, 2009).

This paper aims to identify, gather, and consolidate the information about space efficiency in contemporary supertall office buildings from the main architectural and structural points of view to understand how space efficiency varies according to key design parameters. To achieve this goal, information was collected from the 44 case studies, most of which were the tallest office buildings of the last two decades.

The scope of the study was limited by using *four main points* to understand and analyze important parameters for design and their relationship with space efficiency in supertall office construction: *general information* (building name, location - country and city, height, number of stories, completion date), *main design considerations affecting space efficiency* (core planning, building forms, structural systems, and structural materials), *space efficiency*, and *interrelations of space efficiency and main design considerations.*

By revealing the up-to-date status of contemporary supertall office practices, this study provides insights into the making of more viable design decisions for future office towers. This research presents an introductory overview of considerations that are important to the design of supertall office buildings.

2. Literature survey

In the literature, a limited number of studies have focused on interconnected decisions on the space efficiency of tall buildings by examining a limited number (≤10) of case studies. Among these, Nam and Shim (2016) measured the effect of tall building's corner shapes on the spatial efficiency for its internal use of the space. They verified the assumption that ‘the actual influences by the corner shapes in a tall building can be significant owing to its numerous floors’. Some of the important key findings were: (1) square-cut corner shape is the most obstructive and the diagonal least, (2) the average number of the influential effect on spatial efficiency is about 4% comparing to the building without the corner cuts, (3) the relationship between the lease span and its spatial efficiency is directly proportional so that, at the early stage of a tall building planning, variations of the building corner shape and the lease span should be controlled together to obtain the desired level of objective spatial efficiency.

Sev and Ozgen (2009) examined high-rise office buildings in terms of space efficiency by comparing ten case studies from the world and Turkey. Gross and net floor areas, and space efficiency accordingly, leasing depth, floor-to-floor height, core integrity, structural material, and structural system were taken as main parameters in the research. The followings were among the main conclusions of the study: (1) structural system and core planning are the most important factors affecting the space efficiency of high-rise office buildings, (2) depending on the needs of the tenants, areas of the core elements could differ substantially, affecting the space efficiency, (3) central core type is commonly used in these buildings, (4) the two common structural systems for the tallest office buildings of the world are composite mega-columns and central core with outriggers, and reinforced concrete tube-in-tube without outriggers system, (5) the efficiency of the net-to-gross floor area is the key to balance construction costs and total rental values.

Kim and Elnimeiri (2004) presented architectural design parameters such as function, lease span, floor-to-floor height for the design of multi-use tall buildings, and their interrelations to space efficiency. To do this, ten buildings were examined through specific case studies to show the relationship between the design factors. Some important research outputs as follows: (1) space efficiency should be considered together with other efficiencies such as structural, operational, and energy efficiency, (2) space efficiency is determined by the distribution of functions in multi-use tall buildings, (3) space efficiency in single-use buildings may be higher than that in multi-use ones, (4) space efficiency could be increased if optimum structural systems and resulted building forms are developed together, (5) space efficiency could be higher if the building sacrifices the building serviceability by reducing the number of elevators to provide a smaller core area.

3. Research methods

This research was conducted through a literature survey including the Council of Tall Building and Urban Habitat (CTBUH) database (www.ctbuh.org), peer-reviewed-research, MSc theses and Ph.D. dissertations, proceedings, fact sheets, architectural and structural magazines, photographs, and videos.

Furthermore, a case study method was used to identify, collect, and consolidate the information about contemporary supertall office buildings to understand and analyze important parameters for the design and their relationship with space efficiency. The cases were 44 supertall office towers in a variety of countries [28 from Asia (23 from China), 6 from the Middle East, 9 from North America (all from the United States), and 1 from Russia]. Among the 44 cases, Petronas Tower 1 & 2 (in Petronas Twin Towers) together with Jiangxi Nanchang Greenland Central Plaza Parcel A & B (in Jiangxi Nanchang Greenland Central Plaza Complex) were listed as different buildings based on the CTBUH database (CTBUH, 2020). Most of the 44 cases (>80%) were among the completed tallest office buildings from the last two decades (a few from 1990s) with exceptionally detailed information (see Table 1). It is worth mentioning here that the number of supertall office buildings completed in the last two decades was 55 in the world as of November 2020 (CTBUH, 2020). Buildings without adequate information about their load-bearing systems and floor plans were excluded from this list. Considering the building form, a vigorous effort was made by author in finding and selecting floor plans including ground floor or low-rise floor or typical floor plans to generate more consistent and accurate data for the comparison of space efficiency in the 44 cases. Moreover, this meticulous approach to the use of comparable floor plans as possible allows producing more reliable data for space efficiency, taking into account the fact that considering the building itself in many tall buildings, core area decreases as the building rises.

The case study method is a common strategy used in built environment evaluations wherein projects are identified and documented for quantitative and qualitative data through in-depth literature review (Teegavarapu and Summers, 2008; Kuzmanovska et al., 2018).

Although there is still no global consensus on the height or number of stories for tall buildings (Al-Kodmany and Ali, 2013; Gunel and Ilgın, 2014; Al-Kodmany, 2018), according to the CTBUH database, buildings of 14 stories or 50 meters height and above could be considered as ‘tall buildings’; buildings of 300 meters and 600 meters height and above are classified as ‘supertall buildings’ and ‘megatall buildings’ respectively. In the view of author of this paper, a supertall building is assumed to be a building of more than 300 meters height.

The requirements arising from architectural and structural needs are the basic decision-making criteria in the design of supertall office buildings as in many other buildings. These main parameters are as follows:

- core planning *affecting arrangement of vertical mobility and distribution of shafts (e.g. Trabucco, 2008),*
- building form *affecting floor slab size and shape (e.g. Sev and Ozgen, 2009),*

- structural system *affecting the dimensions and layout of the structural members (e.g. Ilgın et al., 2020),*
- structural material *affecting the dimensions of the structural elements (e.g. Ilgın, 2018).*

The criteria mentioned above govern the floor slab size and shape, lease span, structural layout, and core arrangement/dimension, which determines space efficiency (Ali and Armstrong, 1995; Kim and Elnimeiri, 2004; Trabucco, 2008; Sev and Ozgen, 2009; Ilgın, 2018; Ilgın et al., 2020). Therefore, this study focuses on these four parameters for the space efficiency in the design of 44 supertall office case study buildings. Their analyses are discussed in detail below.

4. Findings

4.1 Core planning

As an essential architectural parameter, core planning, i.e. the arrangement of vertical circulation elements, distribution of mechanical and electrical shafts, plays the most critical role to increase the overall space efficiency of a building. The author used the core classification of Ilgın et al. (2020) as shown in Figure 1, because of its more complete and detailed structure compared to prior literature (Yeang, 2000; Kohn and Katz, 2002; Trabucco, 2010; Oldfield and Doherty, 2019).

As shown in Table 2, central core typology was the most preferred arrangement in the 44 case studies, with 95% occurrence, while external cores occurred in the 2 cases. This was similar to the findings by Oldfield and Doherty (2019) and Ilgın et al. (2020). Oldfield and Doherty (2019) found 85% of central core typologies among 500 complete (or under construction) tall buildings with heights between 247 and 1000m, while Ilgın et al. (2020) observed 95% of central core arrangements among 93 completed or under construction supertall buildings from 1980s onwards.

The merits of central core typology including its significant role in the structural system, compactness, enabling of more openness on the building façade for light and views, and better fire safety performance may have contributed to its dominance (Oldfield and Doherty, 2019; Ilgın et al., 2020). On the other hand, low space efficiency because of longer circulation routes, problematic fire escape distances, could be assessed as disadvantages of external core configuration. Peripheral core arrangement has similar weaknesses (Ilgın, 2018), and was not used in the case studies. The need for extra fire prevention and smoke control measures is one of the major drawbacks of atrium core, which may have helped this typology’s absence in the 44 cases (Hung and Chow, 2001).

4.2 Building forms

Among architectural design considerations affecting space efficiency in supertall office buildings, building form - also directly related to floor slab shape - is also a significant factor. In this paper, by taking into account existing literature (Vollers, 2008; Al-Kodmany and Ali, 2016; Szolomicki and Golasz-Szolomicka, 2019), the following classification by Ilgın et al. (2020) was employed for categorization of the 44 cases (Figure 2):

According to the building form classification above, free and tapered forms were most prevalent in the 44 cases with a ratio of 32% and 30%, respectively (Table 2). The architects’ enthusiasm to quest for creative and distinctive building forms could be an explanation for the highest utilization rate of free forms. On the other hand, the reason behind the high ratio of tapered form could be its aerodynamic and structural efficiency (Ilgın and Gunel, 2007). The prismatic form with a ratio of 20% occurance follows the most used forms, while the twisted form (in only one case) was the least occurring form. This was similar to the findings by Ilgın et al. (2020), who found 34% of tapered form, 29% of free form, and 22% of prismatic form typologies among 93 completed or under construction supertall buildings from 1980s onwards. Additionally, the findings from the 44 cases also reflected similar results with that of completed supertall office buildings as of November 2020 from 1990s onwards from the CTBUH database, where tapered and free forms are most prevalent in the 65 cases with a ratio of 32% and 28%, respectively, and the prismatic form with a ratio of 21% occurance follows these forms. In the general sample of supertall office buildings, the leaning/tilted form was not employed. The reason behind the absence of this form might be its structural disadvantage, where gravity-induced lateral displacement gets higher as the angle of tilt increases (Moon, 2014).

4.3 Supertall building structural systems

Structural system selection is a critical factor directly affecting space efficiency of supertall office towers due to the dimension and layout of the structural members. For lateral bracing of supertall buildings, many structural systems and classifications are discussed in the literature (Smith and Coull, 1991; Ali and Moon, 2007; Gunel and Ilgın, 2007; Baker and Pawlikowski, 2012; Parker and Wood, 2013; Gunel and Ilgın, 2014; Sarkisian, 2016; Taranath, 2016; Ilgın, 2018; Ali and Moon, 2018; Moon, 2018; Fu, 2018). The author utilized the structural system classification of Ilgın et al. (2020) due to its comprehensive nature (see Figure 3).

As highlighted in Table 2, outriggered frame system was predominantly employed (~60%) in the 44 cases. This was similar to the findings by Ilgın et al. (2020), who also observed this system as the most prevalent structural system (>65%) among 93 supertall buildings. The significant use of outriggered frame system can be mostly attributed to its advantages including flexibility in perimeter column compositions and hence relatively more freedom of the façade design, and great height potential as in the cases of *Ping An Finance Center* and *One World Trade Center*. Tube systems occurred 23% in the sample group.

4.4 Structural materials

The selection of structural material is another parameter having an effect on space efficiency since it affects the dimensions of structural elements. Structural materials can be divided into three main categories for supertall building construction: steel, reinforced concrete, and composite.

By taking into consideration the columns, beams, shear trusses, shear walls, and outriggers as the main structural elements (not floor slabs), this paper uses the term ‘composite’ construction for buildings in which some structural elements are made of reinforced concrete and other structural elements are made of steel, or those in which some structural elements are made of both structural steel and concrete together, or both.

In terms of structural material, for supertall office buildings, composite was the most commonly used (80%) structural material in the 44 case studies (Table 2). This ratio was higher than the finding in the study of Ilgın et al. (2020), where composite occurred 66%. This prevalence can be explained by the combination of the advantages of both materials, namely the rigidity and fire resistance of reinforced concrete, and the high tensile and compressive strength of steel sections.

4.5 Space efficiency

Space efficiency can be simply defined as the ratio of Net Floor Area (NFA) over Gross Floor Area (GFA). By considering the local codes and regulations, to get maximum returns for the investor, building floors should offer adequate functional space, namely high space efficiency (Kim and Elnimeiri, 2004). As highlighted in the previous section, this efficiency mainly depends on core planning, building form e.g. size and shape of the floor slab, structural system, and structural material. Additionally, space efficiency can be increased by 'lease span', which is defined as the distance between a fixed interior element (e.g. core wall) and exterior envelope (e.g. window) (Zils and Viise, 2003; Ko et al., 2008; Al-Kodmany, 2015).

In office towers with more than 40 stories, net to gross ratios of 68-73% in floor area were common by the end of the 1990s (Davis Langdon and Everest, 1997). According to Yeang (1995; 2000), 75% was considered as a minimum value for space efficiency in high-rise buildings. However, as the building goes higher, achieving high space efficiency becomes a harder task to complete due to the increasing dimensions of service core and structural elements to meet the requirements of vertical circulation and resistance against loading conditions (Watts et al., 2007; Sev and Ozgen, 2009; Lundberg, 2019). In the study of Sev and Ozgen (2009), space efficiency and core over gross floor area ratio of 10 supertall office buildings changed from 60% to 77% and from 22% to 30% with average values of 69% and 26%, respectively. In this research, the average space efficiency and core over gross floor area ratio of the 44 cases were 71% and 26%, with 63% and 15% smallest and 82% and 36% highest, respectively (see Figure 4).

Bank of China Tower has the highest space efficiency (>80%) as well as the lowest ratio of core over gross floor area among the 44 cases. The main reason behind these exceptional ratios might be explained by the fact that effective layout of core planning, i.e. the vertical lift and staircase organisation, may have helped to keep the core area as compact as possible. In addition to this, as one of the most structurally efficient and innovative systems, trussed-tube system, which uses less amount of structural material compared to many other supertall building structural systems may also have contributed to this efficiency (Moon, 2008; Moon, 2011). Furthermore, trussed-tube system in this tower took the advantage of mega columns at low-rise floor levels to provide more effective structural solidity. This efficient structural combination can also be classified as a mega column, a mega frame, or a space truss system (Ali and Armstrong, 1995; Ali and Moon, 2007; Gunel and Ilgın, 2014). Besides these reasons, the use of composite construction, which allows more effective structures, may have caused a positive impact on this highest space efficiency.

4.6 Interrelations of space efficiency and main design considerations

Interrelations of space efficiency and main design considerations affecting it, such as

- building height,
- building form, and
- structural system

were analyzed in this section. Since composite was the most commonly used (80%) structural material in the case studies, no analysis has been conducted on the interrelation of space efficiency and structural material. These interrelations have been examined as an insight into supertall office buildings to provide an introductory design guide for architects and developers.

4.6.1 Interrelation of space efficiency and building height

Figure 5a illustrates how space efficiency varies by building height, where dots represent supertall office buildings in this study. As the building height increases, space efficiency decreases as shown by the red trendline in Figure 5a. This can be explained by the fact that the higher the building, the more difficult it is to achieve high space efficiency due to the increased dimensions of both service areas and structural elements.

Additionally, Figure 5b shows the ratio of core over gross floor area as another manifestation of the fact above, the higher the building, the more service space required as demonstrated by the red trendline in the figure below.

4.6.2 Interrelation of space efficiency and building form

In Figure 6, the bars demonstrate the total number of supertall office buildings (right axis of the chart) by building form, whereas dots correspond to the space efficiency of those buildings (left axis of the chart) for that type of building form.

As seen in Figure 6, space efficiency of buildings with prismatic form occurs ranging between 63% and 76% with an average of 71%; while the average space efficiency of 7 supertall office towers with setback form occurs 73% including a marginal case of *Bank of China Tower* with 82%. As the most used building forms (in 14 cases), free forms have space efficiency ranging between 70% and 79% with an average of 72%; while as the least preferred form, twisted form is used for only one case with 67% of space efficiency. Tapered forms have space efficiency ranging between 65% and 75% with an average of 71%. As a result, by taking into the average values above, there are no significant differences among the building groups with different building forms examined in this study.

4.6.3 Interrelation of space efficiency and structural system

In Figure 7, the bars demonstrate the total number of supertall office buildings (right axis of the chart) by structural system, whereas dots correspond to the space efficiency of those buildings (left axis of the chart) for that type of structural system.

As highlighted in Figure 7, space efficiency of buildings with outriggered frame system occurs ranging between 65% and 79% with an average of 72%. Mega column and shear walled frame systems are less preferred for supertall office building construction, based on the study sample. Since the number of buildings with mega column and shear walled frame systems is low, deriving a correlation between space efficiency and structural system of those buildings is likely to be inaccurate. Space efficiency of buildings with tube system occurs at an average of 71% including a marginal case of *Bank of China Tower* (in trussed-tube system) with 82%. Consequently, no considerable differences are identified among the building groups with different structural systems in terms of average space efficiency.

5. Discussion and conclusions

Height and aesthetics are not the only objectives or challenges in the race for excellence in designing and constructing supertall office buildings. Architects should also make them economically sound and feasible. To do this, the study was based on the main architectural and structural design criteria affecting space efficiency, such as core planning, building form, structural system, structural material, and their corresponding interrelations with it in supertall office buildings (Ali and Armstrong, 1995; Kim and Elnimeiri, 2004; Trabucco, 2008; Sev and Ozgen, 2009; Ilgın, 2018; Ilgın et al., 2020).

The findings of this study regarding the main architectural and structural design parameters, which affect space efficiency, have some strong similarities to the results reported in other researches (e.g. Sev and Ozgen, 2009; Oldfield and Doherty, 2019; Ilgın et al., 2020). In this study, central core was the most common arrangement, as found in the studies by Sev and Ozgen (2009), Oldfield and Doherty (2019), and Ilgın et al. (2020). This dominance could be explained by that owing to its ease of integration into the main structural system, it can effectively contribute to structural solidity; and due to its potential of opening the building façade for daylight and view, an ideal work environment for office use could be generated. Frequent use of tapered and free forms, which resembled the findings in the study of Ilgın et al. (2020) and the results from the relevant building list in the CTBUH database (CTBUH, 2020), may indicate the architects' choice of unique and reasonable office buildings. Geometries derived from the square, which were the most employed floor plan shapes, could make the interior more functional and rentable compared to complex plan geometries. Additionally, these relatively simple and symmetrical floor plans offer similar stiffness in each direction against lateral loads as a structural advantage. In terms of structural system, similar to the results in the study by Ilgın et al. (2020), the extensive use of outriggered frame system was identified by a wide margin. In this research, the statistics on structural materials of these buildings pointed out that the most preferred material is composite, as found in the study of Ilgın et al. (2020). This prevalence may be due to the fact that composite construction utilizes the strongest features of both materials, steel and concrete.

Space efficiency decreased as the height of the building increased. This finding supported the fact that the higher the building, the harder it is to achieve high space efficiency, as underlined in the studies by Watts et al. (2007), Trabucco (2008), Sev and Ozgen (2009), and Lundberg (2019), due to the increased dimensions of the core and load-bearing members to meet circulation-based and structural requirements. In this research, core was the most significant consideration having a tremendous impact on space efficiency of supertall office buildings, as stated in the study of Sev and Ozgen (2009), since its planning and size directly affected net floor area. On the other hand, when structural system groups were compared with each other, no significant differences were identified among their effects on space efficiency. Similar results were valid for the group of building forms analyzed in this study. The proper selection of the load-bearing system for the corresponding building may have caused similar ratios among structural system groups. Additionally, even if the selection of building forms was free, utilization of functional squarish floor plans may have prevented considerable differences among the groups of building forms in terms of space efficiency.

In conclusion, 44 supertall office buildings (300m+) were analyzed through the main architectural and structural design features to provide a step towards examining space efficiency as one of the key design parameters to make an office project feasible. Besides general facts, information about core planning, building form, structural system, structural material, and interrelations of space efficiency and main design considerations of contemporary supertall office towers were scrutinized.

The contemporary trend towards overemphasizing aesthetics and height in supertall building design may sometimes result in less attention to service core planning together with structural design, and this approach can significantly threaten space efficiency as one of the most critical design parameters in supertall office projects. The main finding of this research indicated that the higher the building, the more difficult it is to achieve high space efficiency mostly because of the increased dimensions of service core. This fact inevitably forces the architects of supertall office towers to place great emphasis on service core planning (i.e. the arrangement of vertical circulation, distribution of mechanical and electrical shafts), especially in collaboration with MEP (mechanical, electrical, and plumbing) engineer. What is more, architects can collaborate early with elevator manufacturers to ensure space-saving vertical mobility. There is fierce competition among these manufacturers, too, to build ever taller and more efficient office towers. This multidisciplinary approach, led by the architect, enables allocating less space to the service core and thus providing more leasable space, which makes the prospect of constructing a supertall office building more attractive to developers. Overall, the presented results in this study on space efficiency in supertall office buildings are expected to provide architects with design standards and developers with potential rules-of-thumb.

Data Availability Statement

No data, models, or code were generated or used during the study.

References

Ali, M.M. and Armstrong, P.J. Architecture of Tall Buildings, Council on Tall Buildings and Urban Habitat Committee 30, McGraw-Hill Inc., New York, 1995.

Ali, M.M. and Moon, K.S. Structural Developments in Tall Buildings: Current Trends and Future Prospects. Architectural Science Review. 50 (3): pp.205-223, 2007.

Ali, M.M. and Moon, K.S. Advances in Structural Systems for Tall Buildings: Emerging Developments for Contemporary Urban Giants. Buildings. 8 (104): pp.1-34, 2018.

Al-Kodmany, K. and Ali, M.M. The Future of the City: Tall Buildings and Urban Design, WIT Press, UK, 2013.

Al-Kodmany, K. and Ali, M.M. An Overview of Structural and Aesthetic Developments in Tall Buildings Using Exterior Bracing and Diagrid Systems, International Journal of High-Rise Buildings. 5 (4): pp.271-291, 2016.

Al-Kodmany, K. Eco-Towers: Sustainable Cities in the Sky, WIT Press, Southampton & Boston, p.57, 2015.

Al-Kodmany, K. The Sustainability of Tall Building Developments: A Conceptual Framework, Buildings. 8, 7, 2018.

Baker, W.F. and Pawlikowski, J. J. Higher and Higher: The Evolution of the Buttressed Core, Civil Engineering. 82 (10): pp.59-65. October 2012.

CTBUH. Council on Tall Buildings and Urban Habitat. Illinois Institute of Technology, S.R. Crown Hall, 3360 South State Street, Chicago, Illinois, USA. (accessed December 10, 2020) www.ctbuh.org.

Davis L. & Everest. High-Rise Office Towers - Cost Model, May 1997 (accessed December 10, 2020) https://www.building.co.uk/high-rise-office-towers-cost-model-may-1997/1025316.article

Fu, F. Design and Analysis of Tall and Complex Structures. Oxford and Cambridge: Butterworth-Heinemann, Elsevier, 2018.

Gunel, M.H. and Ilgın, H.E. A Proposal for the Classification of Structural Systems of Tall Buildings, Building and Environment. 42: pp.2667-2675, 2007.

Gunel, M.H. and Ilgın, H.E. Tall Buildings: Structural Systems and Aerodynamic Form. London and New York: Routledge, 2014.

Hung, W.Y. and Chow, W.K. A Review on Architectural Aspects of Atrium Buildings, Architectural Science Review. Vol. 44, pp.285-296, 2001.

Ilgın, H.E. Potentials and Limitations of Supertall Building Structural Systems: Guiding for Architects. PhD dissertation, Middle East Technical University, 2018.

Ilgın, H.E., Ay, B.O., Gunel, M.H. A Study on Main Architectural and Structural Design Considerations of Contemporary Supertall Buildings, Architectural Science Review. Vol. 63, Issue 2, pp.1-13, 2020.

Kim, H. and Elnimeiri, M. Space Efficiency in Multi-Use Tall Building, Tall Buildings in Historical Cities - Culture and Technology for Sustainable Cities, October 10-13, Seoul, pp.748-755, 2004.

Ko, D., Elnimeiri, M., Clark, R.J. Assessment and Prediction of Daylight Performance in High-Rise Office Buildings, The Structural Design of Tall and Special Buildings. 17, p.958, 2008.

Kohn, A.E. and Katz, J. Building Type Basics for Office Buildings, edited by S. A. Kliment, New York: Wiley, 2002.

Kuzmanovska, I., Gasparri, E., Monne, D.T. and Aitchison, M. Tall Timber Buildings: Emerging Trends and Typologies, Proceedings of 2018 World Conference on Timber Engineering (WCTE 2018), 20-23 August, Seoul, South Korea, 2018.

Lundberg, H. Space Efficiency of Technical Installations in Tall Office Buildings, MSc Thesis, Department of Architecture and Civil Engineering Division of Building Services Engineering Chalmers University of Technology Gothenburg, Sweden, 2019.

Moon, K.S. Sustainable structural engineering strategies for tall buildings, Structural Design of Tall Special Buildings. Vol 17, pp.895-914, 2008.

Moon, K.S. Sustainable Design of Braced Tube Structures: The Role of Geometric Configuration, International Journal of Sustainable Building Technology and Urban Development. Volume 2, Issue 3, 2011.

Moon, K.S. Comparative Evaluation of Structural Systems for Tilted Tall Buildings, International Journal of High-rise Buildings. Vol.2, No.2, pp.89-98, June 2014.

Moon, K.S. Developments of Structural Systems Toward Mile-High Towers." International Journal of High-Rise Buildings. 7 (3): pp.197-21, 2018.

Nam, H.J. and Shim, J.H. An Analysis of the Change in Space Efficiency based on Various Tall Building Corner Shapes and Lease Spans, Journal of the architectural institute of Korea planning & design, 32(8): pp.13-20, August 2016.

Oldfield, P. and Doherty, B. Offset Cores: Trends, Drivers and Frequency in Tall Buildings, CTBUH Journal 2019 (II): pp.40-45, 2019.

Parker, D. and Wood, A. The Tall Buildings Reference Book. London and New York: Routledge, 2013.

Sarkisian, M. Designing Tall Buildings: Structure as Architecture. London and New York: Routledge, 2016.

Sev, A. and Ozgen, A. Space Efficiency in High-Rise Office Buildings. METU Journal of the Faculty of Architecture. 26(2), pp.69-89, 2009.

Smith, B.S. and Coull, A. Tall Building Structures: Analysis and Design. New York: Wiley, 1991.

Szolomicki, J. and Golasz-Szolomicka, H. Technological Advances and Trends in Modern High-Rise Buildings, Buildings. 9(9), 193, 2019.

Taranath, B.S. Structural Analysis and Design of Tall Buildings: Steel and Composite Construction, CRC Press, Taylor & Francis Group, 2016.

Teegavarapu, S. and Summers, D.J. Case Study Method for Design Research, Proceedings of IDETC/DTM 2008 ASME 2008 International Design Engineering Technical Conferences & Computers and Information in Engineering Conference, August 3-6, 2008, New York, USA, 2008.

Trabucco, D. Historical Evolution of the Service Core. CTBUH Journal 2010 (1): pp.42-47, 2010.

Trabucco, D. An Analysis of the Relationship Between Service Cores and the Embodied/Running Energy of Tall Buildings. The Structural Design of Tall and Special Buildings. 17(5), 941-952, 2008.

Vollers, K. Morphological Scheme of Second-Generation Non-Orthogonal High-Rises. Proceedings of the 8th World Congress of the Council on Tall Buildings and Urban Habitat: Tall & Green: Typology for a Sustainable Urban Future, Post Congress Review. pp.504-512, 2008.

Watts, S., Kalita, N., Maclean, M. The Economics of Super-Tall Towers, The Structural Design of Tall and Special Buildings. (16), pp.457-470, 2007.

Yeang, K. The Skyscraper, Bioclimatically Considered, Academy Editions, London, 1995.

Yeang, K. Service Cores: Detail in Building. London: Wiley-Academy, 2000.

Zils, J. and Viise, J. An Introduction to High-Rise Design, STRUCTURE Magazine. November 2003, p.15, 2003.

Table 1. Contemporary supertall office buildings considered in this study

#	Building name	Country	City	Height (meters)	# of stories	Completion date
1	Ping An Finance Center	China	Shenzhen	599	115	2017
2	One World Trade Center	United States	New York	541	94	2014
3	CITIC Tower	China	Beijing	528	108	2018
4	TAIPEI 101	Taiwan	Taipei	508	101	2004
5	Lakhta Center	Russia	St. Petersburg	462	87	2019
6	Petronas Twin Tower 1	Malaysia	Kuala Lumpur	452	88	1998
7	Petronas Twin Tower 2	Malaysia	Kuala Lumpur	452	88	1998
8	The Exchange 106	Malaysia	Kuala Lumpur	446	95	2019
9	One Vanderbilt	United States	New York	427	58	2020
10	Al Hamra Tower	Kuwait	Kuwait City	413	80	2011
11	Two International Finance Center	China	Hong Kong	412	88	2003
12	China Resources Tower	China	Shenzhen	393	68	2018
13	CITIC Plaza	China	Guangzhou	390	80	1996
14	30 Hudson Yards	United States	New York	387	73	2019
15	PIF Tower	Saudi Arabia	Riyadh	385	72	ATO
16	Shun Hing Square	China	Shenzhen	384	69	1996
17	Central Plaza	China	Hong Kong	374	78	1992
18	Bank of China Tower	China	Hong Kong	367	72	1990
19	Almas Tower	UAE	Dubai	360	68	2008
20	Hanking Center Tower	China	Shenzhen	359	65	2018
21	Sino Steel International Plaza T2	China	Tianjin	358	83	on hold
22	Emirates Tower One	UAE	Dubai	355	54	2000
23	Spring City 66	China	Kunming	349	61	2019
24	The Center	China	Hong Kong	346	73	1998
25	ADNOC Headquarters	UAE	Abu Dhabi	342	65	2015
26	Tianjin World Financial Center	China	Tianjin	337	75	2011
27	3 World Trade Center	United States	New York	329	69	2018
28	Golden Eagle Tiandi Tower B	China	Nanjing	328	68	2019
29	Salesforce Tower	United States	San Francisco	326	61	2018
30	Sinar Mas Center 1	China	Shanghai	320	65	2017
31	New York Times Tower	United States	New York	319	52	2007
32	Bank of America Plaza	United States	Atlanta	312	55	1992
33	Shenzhen Bay Innovation and Technology Centre Tower 1	China	Shenzhen	311	69	2020
34	Menara TM	Malaysia	Kuala Lumpur	310	55	2001
35	Pearl River Tower	China	Guangzhou	309	71	2013
36	Fortune Center	China	Guangzhou	309	68	2015
37	Guangfa Securities Headquarters	China	Guangzhou	308	60	2018
38	One Manhattan West	United States	New York	303	67	2019
39	Two Prudential Plaza	United States	Chicago	303	64	1990
40	Jiangxi Nanchang Greenland Central Plaza, Parcel A	China	Nanchang	303	59	2015
41	Jiangxi Nanchang Greenland Central Plaza, Parcel B	China	Nanchang	303	59	2015
42	Leatop Plaza	China	Guangzhou	303	64	2012
43	NBK Tower	Kuwait	Kuwait City	300	61	2019
44	Golden Eagle Tiandi Tower C	China	Nanjing	300	60	2019
Note on abbreviations: **‘UAE’** indicates **the United Arab Emirates**; **‘ATO’** indicates **Architecturally topped out**						

Table 2. Supertall office buildings by core type, building form, structural system, and structural material

#	**Building name**	**Core type**	**Building form**	**Structural system**	**Structural material**
1	Ping An Finance Center	Central	Tapered	Outriggered frame	Composite
2	One World Trade Center	Central	Tapered	Outriggered frame	Composite
3	CITIC Tower	Central	Free	Trussed-tube	Composite
4	TAIPEI 101	Central	Free	Outriggered frame	Composite
5	Lakhta Center	Central	Twisted	Outriggered frame	Composite
6	Petronas Twin Tower 1	Central	Setback	Outriggered frame	RC
7	Petronas Twin Tower 2	Central	Setback	Outriggered frame	RC
8	The Exchange 106	Central	Tapered	Outriggered frame	Composite
9	One Vanderbilt	Central	Tapered	Outriggered frame	Composite
10	Al Hamra Tower	Central	Free	Shear walled frame	Composite
11	Two International Finance Center	Central	Setback	Outriggered frame	Composite
12	China Resources Tower	Central	Tapered	Diagrid-framed-tube	Composite
13	CITIC Plaza	Central	Prismatic	Shear walled frame	RC
14	30 Hudson Yards	Central	Tapered	Outriggered frame	Steel
15	PIF Tower	Central	Free	Trussed-tube	Composite
16	Shun Hing Square	Central	Free	Outriggered frame	Composite
17	Central Plaza	Central	Prismatic	Trussed-tube	Composite
18	Bank of China Tower	Central (split)	Setback	Trussed-tube	Composite
19	Almas Tower	Central	Free	Outriggered frame	Composite
20	Hanking Center Tower	External	Tapered	Trussed-tube	Steel
21	Sino Steel International Plaza T2	Central	Prismatic	Framed-tube	Composite
22	Emirates Tower One	Central	Prismatic	Mega column	Composite
23	Spring City 66	Central	Free	Outriggered frame	Composite
24	The Center	Central	Prismatic	Mega column	Composite
25	ADNOC Headquarters	External	Prismatic	Shear walled frame	RC
26	Tianjin World Financial Center	Central	Tapered	Outriggered frame	Composite
27	3 World Trade Center	Central	Setback	Trussed-tube	Composite
28	Golden Eagle Tiandi Tower B	Central	Tapered	Outriggered frame	Composite
29	Salesforce Tower	Central	Tapered	Shear walled frame	Composite
30	Sinar Mas Center 1	Central	Free	Outriggered frame	Composite
31	New York Times Tower	Central	Prismatic	Outriggered frame	Steel
32	Bank of America Plaza	Central	Setback	Mega column	Composite
33	Shenzhen Bay Innovation and Technology Centre Tower 1	Central	Prismatic	Framed-tube	Composite
34	Menara TM	Central	Free	Outriggered frame	RC
35	Pearl River Tower	Central	Free	Outriggered frame	Composite
36	Fortune Center	Central	Free	Outriggered frame	Composite
37	Guangfa Securities Headquarters	Central	Tapered	Outriggered frame	Composite
38	One Manhattan West	Central	Tapered	Shear walled frame	Composite
39	Two Prudential Plaza	Central	Setback	Outriggered frame	RC
40	Jiangxi Nanchang Greenland Central Plaza, Parcel A	Central	Free	Outriggered frame	Composite
41	Jiangxi Nanchang Greenland Central Plaza, Parcel B	Central	Free	Outriggered frame	Composite
42	Leatop Plaza	Central	Prismatic	Trussed-tube	Composite
43	NBK Tower	Central	Free	Outriggered frame	Composite
44	Golden Eagle Tiandi Tower C	Central	Tapered	Outriggered frame	Composite

Note on abbreviation: **'RC'** indicates **reinforced concrete**