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A study on space efficiency in contemporary supertall mixed-use buildings

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ABSTRACT

To date, no study provides an understanding of space efficiency in supertall (≥300 m) mixed-use buildings, taking into account key architectural and structural planning considerations. In this article, this critical issue was examined. Case study data were collected from 64 contemporary supertall towers to create more viable supertall mixed-use building projects. The results highlighted the following: (i) only the central core typology was used in the core arrangement; (ii) tapered and free forms were the most commonly employed; (iii) outriggered frame system was utilized predominantly; (iv) composite was the most preferred building material; (v) space efficiency varied inversely with the height of the building; and (vi) there was no significant difference between the effects of different structural systems on space efficiency, and similar findings were obtained for building forms. It is thought that this paper will guide key professionals such as architects, structural designers, and contractors in the planning of mixed-use towers.

1. Introduction

History of tall mixed-use building typology began at the beginning of the 20th century with a very modest step, namely Chicago Temple Building (Chicago, 1924, 173 m) (Fig. 1a) with office and religious functions [1]. Three iconic buildings followed: Civic Opera Building (Chicago, 1929, 169 m) (Fig. 1b) with office and other functions, The Downtown Club (New York, 1930, 165 m) (Fig. 1c) with office and other functions, and Waldorf Astoria New York (New York, 1931, 190 m) (Fig. 1d) with residential and hotel functions. This was followed by a period of 30 years (until the 60s) when mixed-use towers were not erected. Today, more than 500 tall mixed-use buildings (<300 m) and more than 70 supertall mixed-use structures have been constructed worldwide in the last decade alone.

The modern concept of qualified urban settings is based on mixed-use developments, including residential, office, and leisure facilities, rather than strict urban zoning. In today's urban densification process, it is critical to ensure the flexibility and solidity of urban growth in high-rise building forms, referred to as a 'vertical city' for the concepts of 'New Urbanism' and 'Smart Growth' [2–8]. In this sense, "sustainable vertical urbanism" is developing rapidly with the discovery of a new mixed-use tower typology. Mixed-use or multifunctionality means that a giant system has various functions [9]. It is worth noting that most of these multi-use buildings are inclusive of "adaptive" facade systems of various solutions [10]. They have a new generation of building adaptive enclosure systems with high-tech components [11].

Therefore, the demands for buildings in and around urban areas are increasing owing to economic competition, urban migration, and lack of resources. The mixed-use is on the rise, particularly in urban centers around the world, contributing to density and sustainability issues [12]. The high popularity of mixed-use buildings can be described by the concept of 'vertical communities' based on the principle that hybrid uses help growing populations and urbanization [13]. Because, especially in market fluctuations,

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multifunctionality has become popular to increase rental income and maintain a wide customer portfolio [14]. In this context, the necessity of mixed-use becomes a critical issue to preserve the value of the investment. This is directly related to service core, floor plan, and size of the structural elements to achieve profit and meet space efficiency.

There are very limited studies on space efficiency in tall and supertall towers. Among them [15], examined 10 mixed-use tall structures to demonstrate the relationship between design considerations including lease span, floor-to-floor height, function, and their relationship to space efficiency. Space efficiency in ten office towers was analyzed by Ref. [16] considering several design issues such as leasing depth, core integrity, and structural material [17]. scrutinized space efficiency in more than 40 supertall office towers with key architectural and structural planning considerations (e.g., form, service core design, structural material, and structural system), whereas [17] examined space efficiency in 27 supertall residential towers with the same criteria. To date, no research has been found in the literature that provides an understanding of space efficiency in supertall mixed-use buildings.

Overall, based on information from 64 detailed cases, this study aims to analyze space efficiency using key architectural and structural design parameters in modern supertall mixed-use buildings. In doing so, this paper attempts to understand how space efficiency changes with main planning considerations. This article covers four key points to examine the main parameters of planning and their interrelations with space efficiency: (i) building facts, (ii) key planning criteria having an effect on space efficiency, (iii) space efficiency, and (iv) its relationship to these criteria. By doing this, this paper, which shows the culmination of supertall mixed-use applications, will form the basis for more realistic decisions for newly designed mixed-use towers. Sustainable design considerations such as energy consumption are excluded from this study, as the focus is on space efficiency, and not all case studies have sufficient information to analyze these parameters.

In this article, a single-use tower is considered a building in which 85% or more of its height is occupied by a specific function. On the other hand, a mixed-use building consisting of 2 or more functions occupies a large part of the entire area of the building. In addition, while hotels, residences, and offices are considered the main functions in supertall building design, secondary areas such as parking lots are not included in mixed-use. It is also assumed that a supertall tower is equal to and taller than 300 m.

2. Research method

In this paper, case study method was utilized to examine the critical considerations for planning and their relationship to space

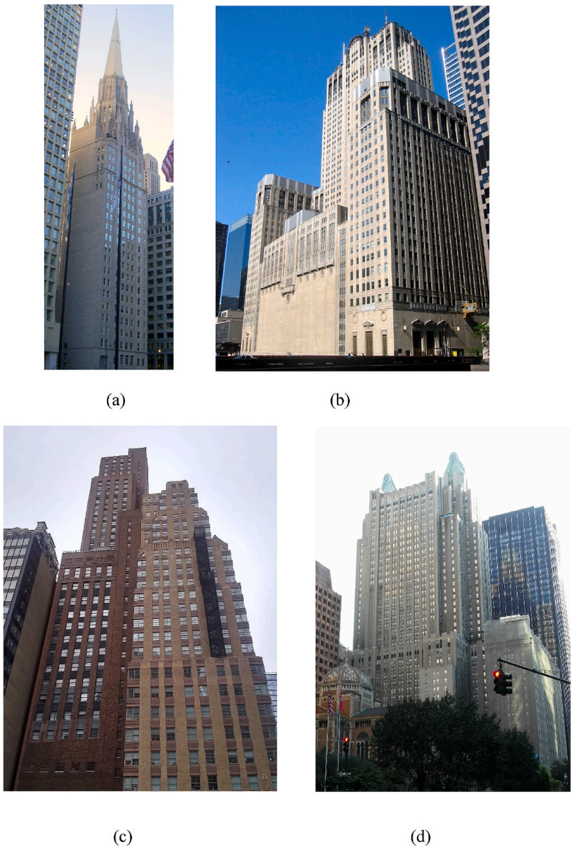

Fig. 1. Early examples of mixed-use typology in tall buildings: (a) Chicago Temple Building; (b) Civic Opera Building; (c) The Downtown Club; (d) Waldorf Astoria New York.
(Source: Wikipedia)

efficiency. As is known, this approach is frequently employed in research where projects are documented for qualitative and quantitative data with a comprehensive literature survey [18,19].

Cases were 64 supertall mixed-use towers in different countries [44 in Asia (34 in China), 9 in the Middle East (6 in Dubai, the United Arab Emirates), 5 in North America (USA), 1 in South America (Chile), 4 in Russia, and 1 in Europe (UK)] as seen in Fig. 2. Table 1 and Table 2 show detailed information on 64 contemporary supertall mixed-use towers. Taking into account the building form, extensive efforts were made to create floor plans (e.g. typical or ground or low-rise floors), and to produce more accurate and consistent information when comparing space efficiency in all the case study buildings.

As in office [17] and residential towers [20], architectural- and structural-based needs guide the planning of supertall mixed-use towers. These main aspects are.

(i) core design affecting vertical circulation and shaft distribution;
(ii) building form that affects the shape and size of floor slabs;
(iii) structural system, which has an impact on the sizes and location of load-bearing members; and (iv) structural material that affects the size of the load-bearing members.

The parameters mentioned above determine floor shape and floor size, structural layout, lease span, and core planning, which have a direct impact on space efficiency [15–17,20–22]. Thus, this paper relied on these four considerations for space efficiency, which were studied in detail below.

3. Findings

3.1. Core design

Core design, the combination of elements for vertical mobility and mechanical and electrical shafts, is critical to the space efficiency of a tower. In this paper, due to its most complete structure in the current literature (e.g. Refs. [23,24], the following core categorization of [25] was used: (1) central core; (2) atrium core; (3) external core; and (4) peripheral core.

Only the central core was used in 64 buildings (Table 2). Its compactness, important role in the structural system, its potential to free up facade design, and its contribution to fire safety scenarios may have made it the only option in core arrangements [21–23]. In addition, the compelling aspect of external and peripheral core typologies in terms of fire escape distances and circulation routes; and additional fire safety requirements in atrium core arrangement may explain their absence in study samples [17,22,26].

3.2. Building forms

The building form is an essential design parameter in space efficiency as it is related to floor slab size and shape. Compared with existing research on tall building forms in literature (e.g. Refs. [27,28], due to its more complete structure, the following were employed in this study [29,30]: (1) prismatic; (2) setback; (3) tapered; (4) twisted; (5) leaning; and (6) free forms.

As highlighted in Table 2, free and tapered building forms were most frequent in 64 supertall towers with a ratio of 27% and 38%, respectively. Its structural and aerodynamic efficiency and allowing different lease spans for mixed-use facilities can be the explanation for the highest ratio of the tapered form [31,32]. Architects' search for unique forms may be the justification for the high rate of free

Fig. 2. Supertall mixed-use buildings from different countries on the world map.

Table 1
Supertall mixed-use buildings considered in this research.

#	Building name	Country	City	Height (meters)	# of stories	Completion date	Function
1	Nakheel Tower	UAE	Dubai	1000	200	NC	H/R/O
2	Burj Khalifa	UAE	Dubai	828	163	2010	H/R/O
3	Suzhou Zhongnan Center	China	Suzhou	729	137	NC	H/R/O
4	Merdeka PNB118	Malaysia	Kuala Lumpur	644	118	UC	H/O
5	Shanghai Tower	China	Shanghai	632	128	2015	H/O
6	Goldin Finance 117	China	Tianjin	596	128	OH	H/O
7	Entisar Tower	UAE	Dubai	577	122	OH	H/R
8	Lotte World Tower	South Korea	Seoul	554	123	2017	H/R/O
9	Guangzhou CTF Finance Centre	China	Guangzhou	530	111	2016	H/R/O
10	Tianjin CTF Finance Centre	China	Tianjin	530	97	2019	H/O
11	Evergrande Hefei Center 1	China	Hefei	518	112	OH	H/R/O
12	Busan Lotte Town Tower	South Korea	Busan	510	107	NC	H/R/O
13	Greenland Jinmao International Financial Center	China	Nanjing	499	102	UC	H/O
14	Shanghai World Financial Center	China	Shanghai	492	101	2008	H/O
15	International Commerce Centre	China	Hong Kong	484	108	2010	H/O
16	Wuhan Greenland Center	China	Wuhan	475	97	UC	H/R/O
17	Chengdu Greenland Tower	China	Chengdu	468	101	UC	H/O
18	R&F Guangdong Building	China	Tianjin	468	91	OH	H/R/O
19	Vincom Landmark 81	Vietnam	Ho Chi Minh City	461	81	2018	H/R
20	Changsha IFS Tower T1	China	Changsha	452	94	2018	H/O
21	Zifeng Tower	China	Nanjing	450	66	2010	H/O
22	KK 100	China	Shenzhen	441	98	2011	H/O
23	Guangzhou International Finance Center	China	Guangzhou	438	103	2010	H/O
24	Multifunctional Highrise Complex - Akhmat Tower	Russia	Grozny	435	102	OH	R/O
25	Chongqing Tall Tower	China	Chongqing	431	101	OH	H/R/O
26	Haikou Tower 1	China	Haikou	428	94	OH	H/R/O
27	Marina 101	UAE	Dubai	425	101	2017	H/R
28	Trump International Hotel & Tower	USA	Chicago	423	98	2009	H/R
29	LCT The Sharp Landmark Tower	South Korea	Busan	411	101	2019	H/R
30	Guangxi China Resources Tower	China	Nanning	402	86	2020	H/O
31	Dynamic Tower	UAE	Dubai	388	80	NC	H/R
32	Shum Yip Upperhills Tower 1	China	Shenzhen	388	80	2020	H/O
33	Autograph Tower	Indonesia	Jakarta	382	75	UC	H/O
34	Guiyang World Trade Center Landmark Tower	China	Guiyang	380	92	UC	H/O
35	Federation Tower	Russia	Moscow	373	93	2016	R/O
36	Golden Eagle Tiandi Tower A	China	Nanjing	368	77	2019	H/O
37	St. Regis Chicago	USA	Chicago	362	101	2020	H/R
38	Greenland Group Suzhou Center	China	Suzhou	358	77	UC	H/O
39	OKO - Residential Tower	Russia	Moscow	354	90	2015	H/R
40	One Shenzhen Bay Tower 7	China	Shenzhen	341	78	2018	H/R/O
41	Comcast Technology Center	USA	Philadelphia	339	59	2018	H/O
42	Mercury City Tower	Russia	Moscow	338	75	2013	R/O
43	Hengqin International Finance Center	China	Zhuhai	337	69	2020	R/O
44	Wilshire Grand Center	USA	Los Angeles	335	62	2017	H/O
45	Shimao International Plaza	China	Shanghai	333	60	2006	H/O
46	China World Tower	China	Beijing	330	74	2010	H/O
47	Hon Kwok City Center	China	Shenzhen	329	80	2017	R/O
48	Keangnam Hanoi Landmark Tower	Vietnam	Hanoi	328	72	2012	H/R/O
49	Deji Plaza	China	Nanjing	324	62	2013	H/O
50	Nina Tower	China	Hong Kong	320	80	2006	H/O
51	Chongqing IFS T1	China	Chongqing	316	63	2016	H/O
52	MahaNakhon	China	Bangkok	314	79	2016	H/R
53	CITIC Financial Center Tower 1	China	Shenzhen	312	–	UC	R/O
54	Burj Rafal	Saudi Arabia	Riyadh	307	68	2014	H/R
55	The Shard	UK	London	306	73	2013	H/R/O
56	Northeast Asia Trade Tower	South Korea	Incheon	305	68	2011	H/R/O
57	35 Hudson Yards	USA	New York City	304	72	2019	H/R
58	Kingdom Centre	Saudi Arabia	Riyadh	302	41	2002	H/R/O
59	Supernova Spira	India	Noida	300	80	UC	H/R
60	Al Wasl Tower	UAE	Dubai	300	64	UC	H/R/O
61	Torre Costanera	Chile	Santiago	300	62	2014	H/O

(*continued on next page*)

Table 1 (*continued*)

#	Building name	Country	City	Height (meters)	# of stories	Completion date	Function
62	Abeno Harukas	Japan	Osaka	300	60	2014	H/O
63	Shimao Riverside Block D2b	China	Wuhan	300	53	UC	H/O
64	Aspire Tower	Qatar	Doha	300	36	2007	H/O

- Buildings are listed from highest to lowest.

Note on abbreviations: 'H' indicates hotel use; 'R' indicates residential use; 'O' indicates office use; 'UAE' indicates the United Arab Emirates; 'UC' indicates Under construction; 'NC' indicates Never completed; 'OH' indicates On hold.

form [33]. Prismatic and setback forms followed the most preferred forms with 17%, while the least favored form was twisted form utilized in a single tower.

3.3. Structural systems

Structural system selection is vital to space efficiency in supertall mixed-use developments, as it is directly related to the layout and size of structural elements. Since it is more comprehensive than the existing load-bearing system categorizations (e.g. Refs. [34–38], the following categorization by Ref. [39] for supertall buildings was used in this paper: (1) shear-frame with its subgroups of shear-trussed frame and shear-walled frame; (2) mega core; (3) mega column; (4) outriggered frame; (5) tube with its subgroups of framed-tube (with a subsection of diagrid-framed-tube), trussed-tube, and bundled-tube; and (6) buttressed core systems.

Outriggered frame system was mostly used (70%) in 64 supertall towers as shown in Table 2. This dominance might be largely attributable to its merits such as greater freedom in exterior column composition and thus comparatively greater flexibility in the building facade and the potential to achieve greater heights as in *Suzhou Zhongnan Center* and *Merdeka PNB118*. While tube systems constituted 17% of the study sample, shear-frame and buttressed core were the least preferred structural systems, with only 2 cases per category in supertall mixed-use cases.

3.4. Structural materials

Since the structural materials have an effect on the sizes of the structural components, it is also crucial consideration affecting space efficiency. They could be grouped into three categories: (i) steel, (ii) reinforced concrete, and (iii) composite. In this study, taking into account vertical load-bearing members e.g., shear walls and columns as the main load-bearing members, 'composite' was used as a term for buildings in which some load-bearing members are concrete, other load-bearing members are steel, or some load-bearing members are both steel and concrete together.

Composite was the most utilized (72%), while concrete occurred at 27% in the sample group (see Table 2). The combination of the high tensile and compressive strength of steel and concrete's fire safety performance and stiffness may be the reason for this widespread use of composite.

3.5. Space efficiency

Space efficiency, the ratio of net to gross floor area (GFA), is primarily dependent on building form, core design, structural material, and system. This could be improved by 'lease span', the distance between building facade and a fixed internal element [40]. As the building rises, it becomes a difficult task to achieve high space efficiency owing to increased core and load-bearing element sizes [41].

Based on studies by Refs. [42,43]; it can be accepted as a 75% limit value for space efficiency in high-rise tower design. In research by Ref. [17] on 44 supertall office towers, the average space efficiency and core over GFA were 71% and 26%, with 63% and 15% smallest and 82% and 36% highest, respectively. In the study on 27 supertall residential towers by Ref. [17]; the average space efficiency and core over GFA were 76% and 19%, respectively: ranging from 56% to 11% at the lowest to 84% and 36% at the highest, respectively. In this study, the average space efficiency and core over GFA ratio of the 64 cases were 71% and 26%, respectively: ranging from 55% to 16% at the lowest to 84% and 38% at the highest, respectively (Table 3 and Appendix).

Dynamic Tower had the largest space efficiency with 84% and the smallest core-to-GFA ratio in the study sample. Efficient core design, i.e. service area and shaft organization, trying to keep the core space as compact as possible can be the main reason behind this outstanding effectiveness. In addition, the tower has a mega core system. As the mega core could withstand all vertical and horizontal loads, there is no need to use additional vertical load-bearing elements around the building [44]. This may also have contributed to the tower's effectiveness.

3.6. Interrelations of space efficiency and key planning parameters

Interrelations of space efficiency and key planning parameters having an effect on it, building height, structural system, and building form were analyzed here. As only core typology was central core and the most used structural material (>70%) was composite in the study sample, no analysis was provided on these issues.

3.6.1. Interrelation of space efficiency and the height of the building

Fig. 3a and b shows the interrelationship between space efficiency and the height of the tower. In the figures, the dots correspond to supertall mixed-use towers in the sample group. A polynomial regression method was utilized to find correlations with dots. The polynomial approach was preferred because it provided a more accurate R-square coefficient of correlation compared to the other methods such as linear and exponential. Burj Khalifa at 828 m height with an 80% space efficiency ratio and 16% core to GFA ratio and Nakheel Tower with an extraordinary height of 1000 m, were taken as outliers. Fig. 3b illustrates how the regression line is affected by

Table 2
Supertall mixed-use buildings with architectural and structural design information.

#	Building name	Core type	Building form	Structural system	Structural material
1	Nakheel Tower	Central	Free	Mega column	Composite
2	Burj Khalifa	Central	Setback	Buttressed Core	RC
3	Suzhou Zhongnan Center	Central	Tapered	Outriggered Frame	Composite
4	Merdeka PNB118	Central	Free	Outriggered Frame	Composite
5	Shanghai Tower	Central	Twisted	Outriggered Frame	Composite
6	Goldin Finance 117	Central	Tapered	Trussed-tube	Composite
7	Entisar Tower	Central	Setback	Framed-tube	RC
8	Lotte World Tower	Central	Tapered	Outriggered Frame	Composite
9	Guangzhou CTF Finance Centre	Central	Setback	Outriggered Frame	Composite
10	Tianjin CTF Finance Centre	Central	Tapered	Framed-tube	Composite
11	Evergrande Hefei Center 1	Central	Free	Outriggered Frame	Composite
12	Busan Lotte Town Tower	Central	Free	Outriggered Frame	Composite
13	Greenland Jinmao International Financial Center	Central	Tapered	Outriggered Frame	Composite
14	Shanghai World Financial Center	Central	Tapered	Outriggered Frame	Composite
15	International Commerce Centre	Central	Tapered	Outriggered Frame	Composite
16	Wuhan Greenland Center	Central	Tapered	Buttressed Core	Composite
17	Chengdu Greenland Tower	Central	Tapered	Outriggered Frame	Composite
18	R&F Guangdong Building	Central	Setback	Outriggered Frame	Composite
19	Vincom Landmark 81	Central	Setback	Bundled-tube	Composite
20	Changsha IFS Tower T1	Central	Prismatic	Outriggered Frame	Composite
21	Zifeng Tower	Central	Free	Outriggered Frame	Composite
22	KK 100	Central	Free	Diagrid-framed-tube	Composite
23	Guangzhou International Finance Center	Central	Tapered	Outriggered Frame	Composite
24	Multifunctional Highrise Complex - Akhmat Tower	Central	Tapered	Framed-tube	Steel
25	Chongqing Tall Tower	Central	Tapered	Outriggered Frame	Composite
26	Haikou Tower 1	Central	Tapered	Outriggered Frame	Composite
27	Marina 101	Central	Prismatic	Framed-tube	RC
28	Trump International Hotel & Tower	Central	Setback	Outriggered Frame	RC
29	LCT The Sharp Landmark Tower	Central	Prismatic	Outriggered Frame	RC
30	Guangxi China Resources Tower	Central	Tapered	Outriggered Frame	Composite
31	Dynamic Tower	Central	Free	Mega core	RC
32	Shum Yip Upperhills Tower 1	Central	Prismatic	Outriggered Frame	Composite
33	Autograph Tower	Central	Prismatic	Outriggered Frame	Composite
34	Guiyang World Trade Center Landmark Tower	Central	Tapered	Framed-tube	Composite
35	Federation Tower	Central	Free	Outriggered Frame	Composite
36	Golden Eagle Tiandi Tower A	Central	Tapered	Outriggered Frame	Composite
37	St. Regis Chicago	Central	Free	Outriggered Frame	RC
38	Greenland Group Suzhou Center	Central	Free	Outriggered Frame	Composite
39	OKO - Residential Tower	Central	Free	Outriggered Frame	RC
40	One Shenzhen Bay Tower 7	Central	Tapered	Outriggered Frame	Composite
41	Comcast Technology Center	Central	Setback	Trussed-tube	Composite
42	Mercury City Tower	Central	Setback	Framed-tube	RC
43	Hengqin International Finance Center	Central	Free	Outriggered Frame	Composite
44	Wilshire Grand Center	Central	Tapered	Outriggered Frame	Composite
45	Shimao International Plaza	Central	Free	Mega Column	Composite
46	China World Tower	Central	Tapered	Outriggered Frame	Composite
47	Hon Kwok City Center	Central	Prismatic	Outriggered Frame	Composite
48	Keangnam Hanoi Landmark Tower	Central	Setback	Outriggered Frame	RC
49	Deji Plaza	Central	Prismatic	Outriggered Frame	Composite
50	Nina Tower	Central	Prismatic	Outriggered Frame	RC
51	Chongqing IFS T1	Central	Prismatic	Outriggered Frame	Composite
52	MahaNakhon	Central	Free	Outriggered Frame	RC
53	CITIC Financial Center Tower 1	Central	Tapered	Diagrid-framed-tube	Composite
54	Burj Rafal	Central	Prismatic	Outriggered Frame	Composite
55	The Shard	Central	Tapered	Shear Walled Frame	Composite

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Table 2 (*continued*)

#	Building name	Core type	Building form	Structural system	Structural material
56	Northeast Asia Trade Tower	Central	Tapered	Outriggered Frame	Composite
57	35 Hudson Yards	Central	Setback	Outriggered Frame	RC
58	Kingdom Centre	Central	Free	Shear Walled Frame	RC
59	Supernova Spira	Central	Prismatic	Outriggered Frame	RC
60	Al Wasl Tower	Central	Free	Outriggered Frame	Composite
61	Torre Costanera	Central	Tapered	Outriggered Frame	RC
62	Abeno Harukas	Central	Setback	Outriggered Frame	Composite
63	Shimao Riverside Block D2b	Central	Tapered	Outriggered Frame	Composite
64	Aspire Tower	Central	Free	Mega Core	RC

Note on abbreviation: 'RC' indicates reinforced concrete.

Table 3
Space efficiency and core over GFA ratio of supertall mixed-use towers.

#	Building name	Space eff. *	Core/ GFA**	#	Building name	Space eff.	Core/ GFA
1	Nakheel Tower	69%	26%	**33**	Autograph Tower	68%	31%
2	Burj Khalifa	80%	16%	**34**	Guiyang World Trade Center Landmark Tower	71%	27%
3	Suzhou Zhongnan Center	62%	33%	**35**	Federation Tower	82%	16%
4	Merdeka PNB118	65%	31%	**36**	Golden Eagle Tiandi Tower A	70%	27%
5	Shanghai Tower	71%	24%	**37**	St. Regis Chicago	76%	21%
6	Goldin Finance 117	68%	28%	**38**	Greenland Group Suzhou Center	70%	29%
7	Entisar Tower	74%	24%	**39**	OKO - Residential Tower	76%	20%
8	Lotte World Tower	69%	28%	**40**	One Shenzhen Bay Tower 7	81%	18%
9	Guangzhou CTF Finance Centre	65%	31%	**41**	Comcast Technology Center	74%	25%
10	Tianjin CTF Finance Centre	70%	27%	**42**	Mercury City Tower	80%	18%
11	Evergrande Hefei Center 1	59%	37%	**43**	Hengqin International Finance Center	67%	31%
12	Busan Lotte Town Tower	70%	27%	**44**	Wilshire Grand Center	80%	19%
13	Greenland Jinmao International Financial Center	55%	37%	**45**	Shimao International Plaza	67%	29%
14	Shanghai World Financial Center	69%	28%	**46**	China World Tower	79%	19%
15	International Commerce Centre	69%	29%	**47**	Hon Kwok City Center	70%	28%
16	Wuhan Greenland Center	67%	30%	**48**	Keangnam Hanoi Landmark Tower	72%	26%
17	Chengdu Greenland Tower	72%	24%	**49**	Deji Plaza	73%	24%
18	R&F Guangdong Building	68%	29%	**50**	Nina Tower	71%	27%
19	Vincom Landmark 81	69%	28%	**51**	Chongqing IFS T1	74%	25%
20	Changsha IFS Tower T1	63%	34%	**52**	MahaNakhon	65%	32%
21	Zifeng Tower	71%	28%	**53**	CITIC Financial Center Tower 1	70%	27%
22	KK 100	61%	34%	**54**	Burj Rafal	78%	21%
23	Guangzhou International Finance Center	71%	27%	**55**	The Shard	79%	20%
24	Multifunctional Highrise Complex - Akhmat Tower	75%	23%	**56**	Northeast Asia Trade Tower	72%	26%
25	Chongqing Tall Tower	81%	17%	**57**	35 Hudson Yards	80%	16%
26	Haikou Tower 1	75%	22%	**58**	Kingdom Centre	78%	20%
27	Marina 101	82%	16%	**59**	Supernova Spira	63%	33%
28	Trump International Hotel & Tower	62%	18%	**60**	Al Wasl Tower	74%	22%
29	LCT The Sharp Landmark Tower	56%	36%	**61**	Torre Costanera	69%	30%
30	Guangxi China Resources Tower	61%	38%	**62**	Abeno Harukas	79%	19%
31	Dynamic Tower	84%	16%	**63**	Shimao Riverside Block D2b	73%	26%
32	Shum Yip Upperhills Tower 1	64%	33%	**64**	Aspire Tower	72%	28%

Space efficiency*: calculated as the ratio of the net floor area (obtained by subtracting service core and structural elements from GFA) to GFA.
Core/GFA**: calculated as the ratio of the service core to GFA. *(see detailed Appendix with floor plans)*.

these outliers. As indicated by the trendline in Fig. 3a, space efficiency tends to decrease. As seen in the slope of the trendline, this decrease is more evident in the 300–400 m height range, where more than half of the case buildings are located. When the selected outliers are removed, it is seen that the downtrend spreads over the entire trendline, as shown in Fig. 3b. This decrease might be justified by that the taller the structure, the harder it is to get space efficiency as a result of the increased dimensions of core spaces and load-bearing components, as emphasized in the studies by Refs. [17,20].

Additionally, Fig. 4a and b highlight the ratio of core over GFA as an indication of the above expression, the need for more core area

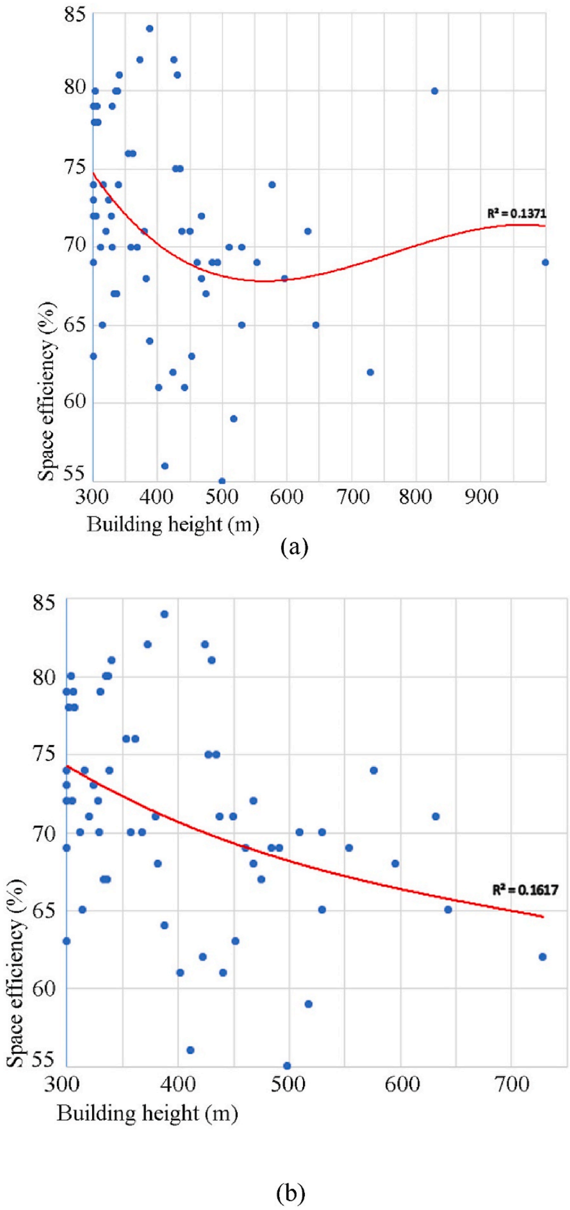


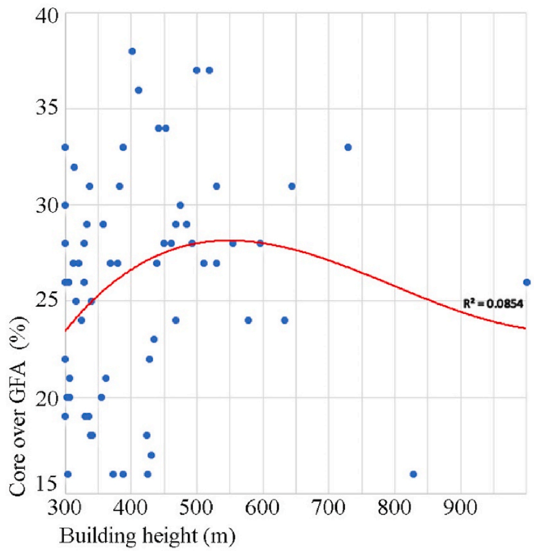
Fig. 3. The relationship between space efficiency and the height of the tower:
(a) including outliers, (b) excluding outliers.

tends to increase as the building height increases. Similar to above (Fig. 3b), when outliers are removed, this increase spans the entire trendline (Fig. 4b).

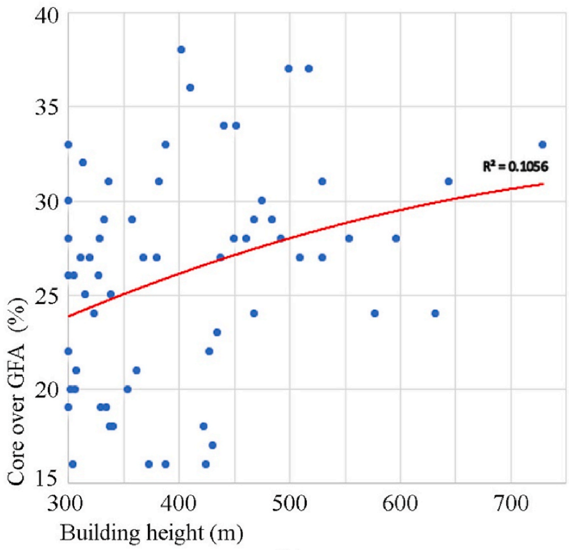
3.6.2. Interrelation of space efficiency and building form

As seen in Fig. 5, bars illustrate the total number of mixed-use towers by form (right axis), while dots represent space efficiency of these towers for this type of form (left axis).

The space efficiency of the towers with prismatic form was between 56% and 82% with an average of 69%. The average space efficiency of 11 supertall mixed-use cases with setback form occurred at 73% including 3 supertall towers with a space efficiency of 80%, as in Burj Khalifa (Fig. 5). As the most preferred building forms, tapered forms had space efficiency varying between 55% and 81% with an average of 71%. As the least used form, twisted form was used with a space efficiency of 71% for only one case. Free forms had space efficiency varying between 59% and 84% with an average of 71% including the marginal case of Dynamic Tower with 84%. Thus, considering the above-average values, there was no substantial difference between the effects of different building forms on space efficiency in supertall mixed-use cases.



(a)



(b)

Fig. 4. The relationship between core over GFA and the height of the tower:
(a) including outliers, (b) excluding outliers.

3.6.3. *Interrelation of space efficiency and structural system*

As seen in Fig. 6, bars indicate the total number of mixed-use towers (right axis) by structural system, whereas dots represent space efficiency of these towers for this type of structural system (left axis).

Space efficiency of towers with outriggered frame systems occurred varying between 55% and 82% with an average of 70%. The average space efficiency of 11 mixed-use towers with tube system occurred at 72% including 2 towers with a space efficiency of 80%, and above (Fig. 6). For supertall mixed-use building construction with only 2 cases per category, shear-frame and buttressed core systems were the least preferred structural systems, followed by mega column and mega core systems with 4 cases. Therefore, since the number of buildings with these structural systems was low, it was likely to be inaccurate to derive the scientific relationship between the structural systems of these towers to space efficiency. Thus, taking into account the above-average values, there was no substantial difference between the effects of different structural systems on space efficiency in the study sample.

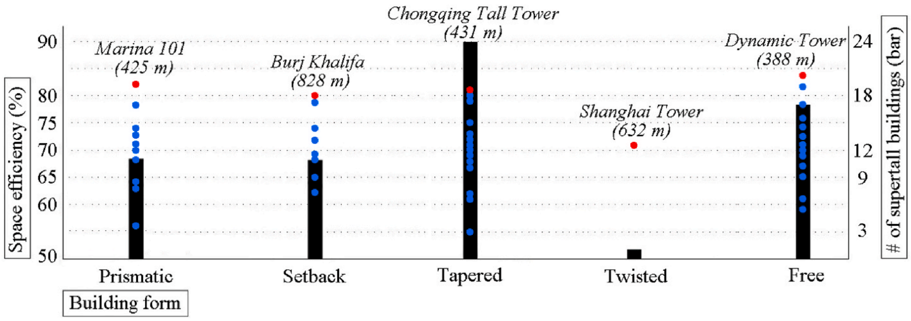


Fig. 5. The relationship between space efficiency and form.

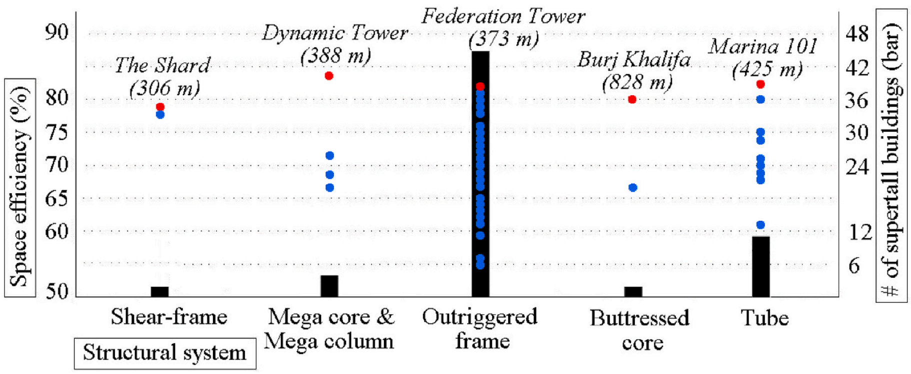


Fig. 6. The relationship between space efficiency and structural system.

4. Discussion

The findings in this paper showed similarities and differences with other research (e.g. Refs. [17,23]. In the sample, central core was the only type used, and this finding can be attributed to the works by Refs. [17,20,21,23]; and [16]. Central core dominance was reported in all these studies. This prevalence can be justified by the fact that central core can efficiently support structural integrity because of its easy incorporation into the primary load-bearing system. Especially considering the prevalence of outriggered frame system, the potential of the central core to open the façade to daylight and view may play a critical role in its dominance [17].

Among the 64 supertall mixed-use cases, tapered and free forms were the most common forms, which was similar to the findings by Refs. [17,21]. However, the findings of [20] showed that prismatic forms are the most commonly used in supertall residential towers. The enthusiasm of architectural designers seeking innovative and original building forms may be one reason for the greatest use of free forms. The reason for the highest rate identified in tapered forms may be its efficiency, both aerodynamically and structurally [32]. In addition, due to its nature, reducing the upper floor area in tapered forms may be suitable for planning a mixed-use building as it can offer different alternatives for lease spans.

Among structural systems, outriggered frame system was used predominantly. This finding verified the results of other papers such as [17,20]; and [21]. The widespread usage of this system can be justified by the flexible nature of the exterior column layout and the potential for greater heights in supertall mixed-use construction (e.g., Refs. [17,20]. In terms of structural material, as in the studies of [17,21]; the usage of composite was more dominant than steel and concrete in this research. However, the findings in Ref. [20] showed that reinforced concrete was mostly preferred in supertall residential buildings.

In this paper, among supertall mixed-use cases, as the height of the building increased, space efficiency decreased, which was supported by the studies such as [20]. This finding was also another indication that the taller the tower, the harder it is to get high space efficiency because of the increased dimensions of the core and load-bearing elements to meet structural and circulation-based needs [17].

The findings regarding the interrelations of space efficiency and form, and space efficiency and load-bearing system resembled the study conducted by Refs. [17,20]. In these studies, there was no substantial difference between the effects of structural systems on space efficiency, and similar findings were obtained for building forms as in this paper. Appropriate structural system selection might have ensured that there were no major ratio differences between these groups. Similarly, in terms of space efficiency, suitable interior layouts according to different mixed-use functions in the selected form may have prevented great differences between building form groups.

5. Conclusion

In this research, space efficiency in supertall mixed-use buildings was explored through case studies of 64 contemporary supertall towers with key architectural and structural design considerations. By doing this, building facts, key planning criteria that have an impact on space efficiency, and its relationship to these criteria were discussed.

The creation of diverse vertical communities and their social, operational, technical, and economic challenges are driving the adoption of new paradigms for the planning, implementation, and management of supertall mixed-use towers. Among these challenges, in the design of these buildings, specifiers need to combine various engineering systems into a single structure for a variety of business and residential activities. In this sense, from a design standpoint, for example, mechanical, electrical, and plumbing (MEP) infrastructure may need to be defined between uses to ensure proper separation of operating costs, incurring additional initial costs. These and similar issues (e.g. elevator layout) should be carefully coordinated by the architect and appropriate MEP zones and areas should be allocated that directly affect space efficiency.

Therefore, in supertall mixed-use building design, the architect's responsibility becomes more critical given that it becomes more difficult to get high rates of space efficiency as the building rises because of the increase in the core size. This requires, under the coordination and leadership of the architect, the incorporation of a wider range of competencies among the specializations in the relevant disciplines and a high level of information flow for every detail.

The results obtained in this study are expected to guide key construction stakeholders e.g., architects, structural designers, and builders in the planning of more viable mixed-use towers.

Author statement

I am the sole author of the Manuscript.

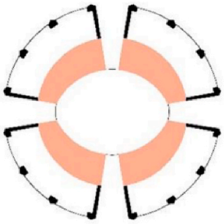
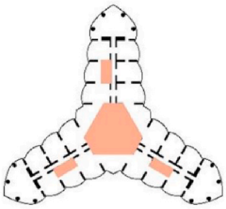
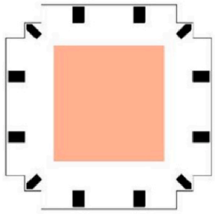
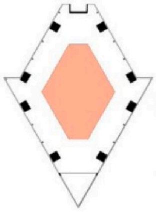
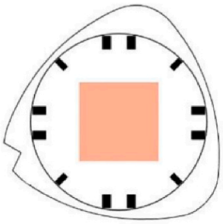
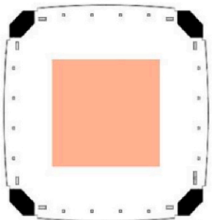
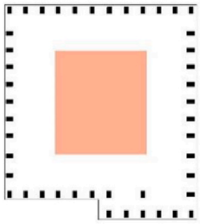
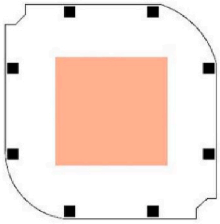
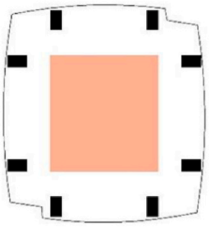
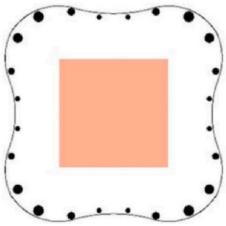
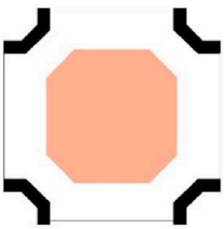
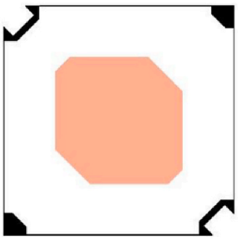
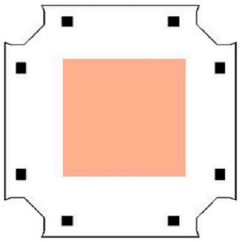
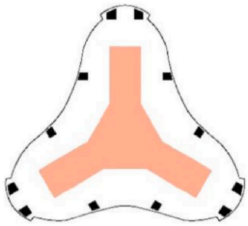
Declaration of competing interest

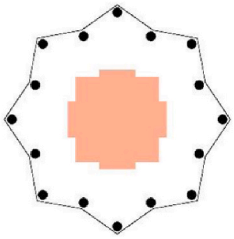
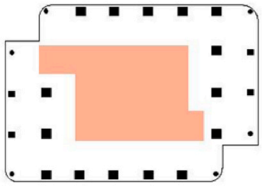
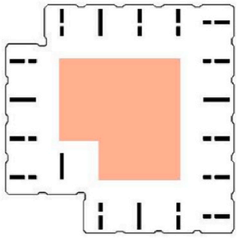
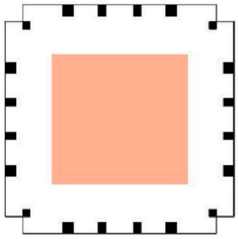
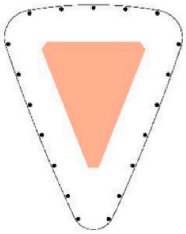
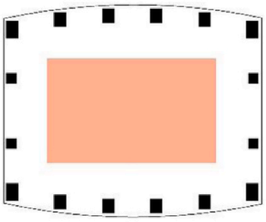
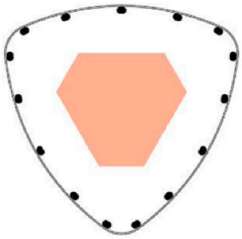
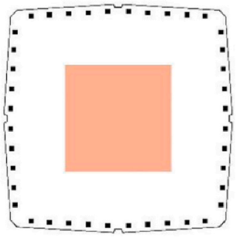
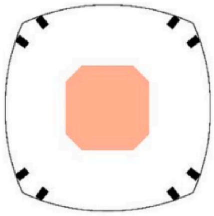
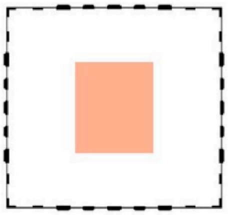
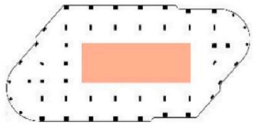
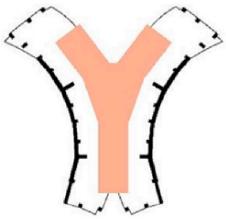
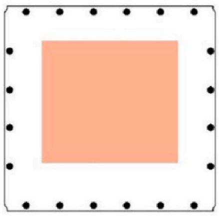
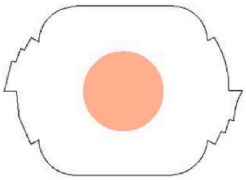
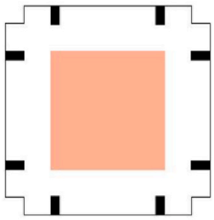
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

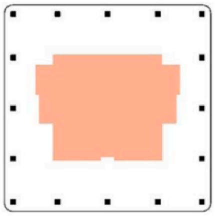
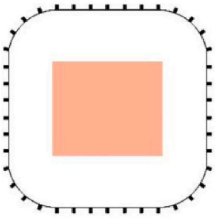
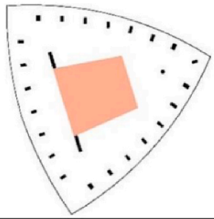
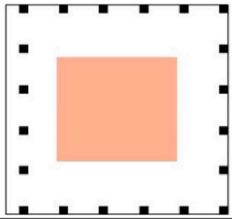
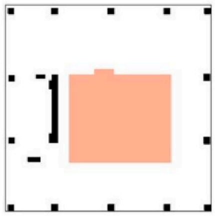
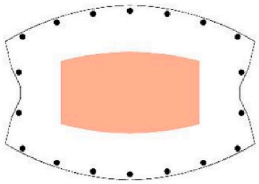
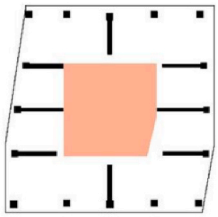
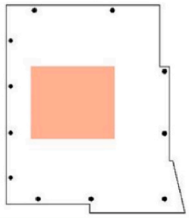
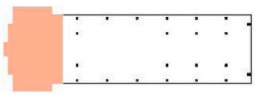
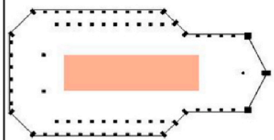
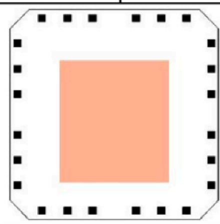
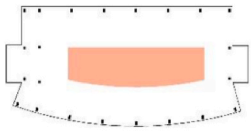
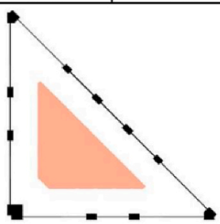
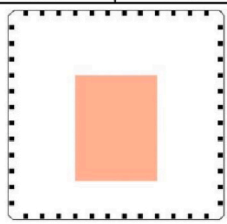
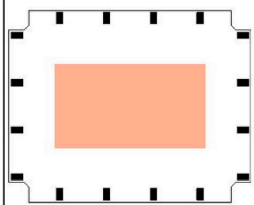
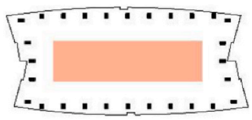
Data availability

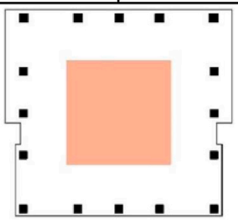
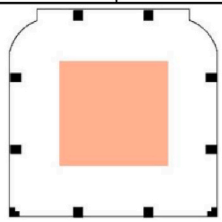
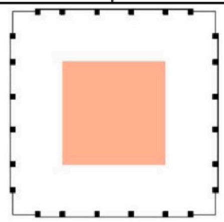
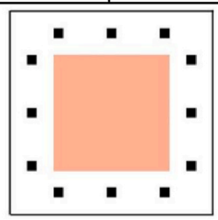
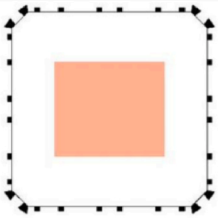
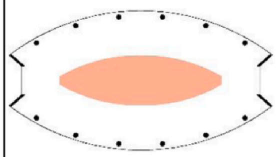
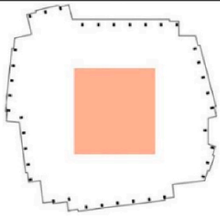
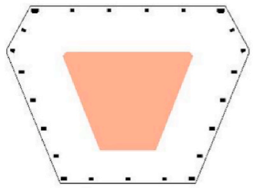
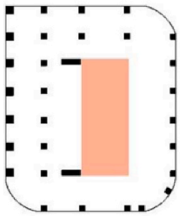
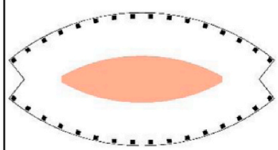
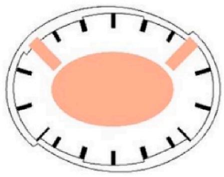
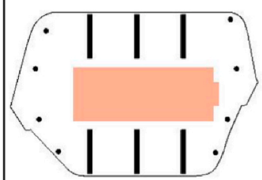
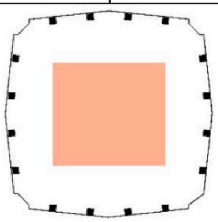
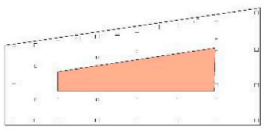
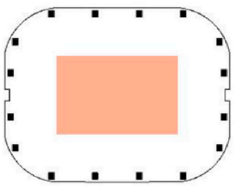
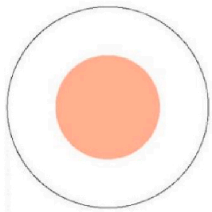
No data was used for the research described in the article.

Appendix. Supertall mixed-use towers' floor plan, space efficiency, and core/GFA ratio

Building name			
Space efficiency*		Core/GFA ratio**	
Nakheel Tower	**Burj Khalifa**	**Suzhou Zhongnan Center**	**Merdeka PNB118**
69% / 26%	80% / 16%	62% / 33%	65% / 31%
			
Low-rise floor	Typical floor	Low-rise floor	Low-rise floor
Shanghai Tower	**Goldin Finance 117**	**Entisar Tower**	**Lotte World Tower**
71% / 24%	68% / 28%	74% / 24%	69% / 28%
			
Low-rise floor	Ground floor	Low-rise floor	Low-rise floor
Guangzhou CTF Finance Centre	**Tianjin CTF Finance Centre**	**Evergrande Hefei Center 1**	**Busan Lotte Town Tower**
65% / 31%	70% / 27%	59% / 37%	70% / 27%
			
Low-rise floor	Low-rise floor	Typical floor	Low-rise floor
Greenland Jinmao International Financial Center	**Shanghai World Financial Center**	**International Commerce Centre**	**Wuhan Greenland Center**
55% / 37%	69% / 28%	69% / 29%	67% / 30%
			
Ground floor	Low-rise floor	Low-rise floor	Low-rise floor

Building name							
Space efficiency				Core/GFA ratio			
Chengdu Greenland Tower		**R&F Guangdong Building**		**Vincom Landmark 81**		**Changsha IFS Tower T1**	
72%	24%	68%	29%	69%	28%	63%	34%
							
Ground floor		Low-rise floor		Low-rise floor		Low-rise floor	
Zifeng Tower		**KK 100**		**Guangzhou International Finance Center**		**Multifunctional Highrise Complex - Akhmat Tower**	
71%	28%	61%	34%	71%	27%	75%	23%
							
Ground floor		Low-rise floor		Typical floor		Low-rise floor	
Chongqing Tall Tower		**Haikou Tower 1**		**Marina 101**		**Trump International Hotel & Tower**	
81%	17%	75%	22%	82%	16%	62%	18%
							
Low-rise floor		Low-rise floor		Typical floor		Low-rise floor	
LCT The Sharp Landmark Tower		**Guangxi China Resources Tower**		**Dynamic Tower**		**Shum Yip Upperhills Tower 1**	
56%	36%	61%	38%	84%	16%	64%	33%
							
Typical floor		Low-rise floor		Low-rise floor		Typical floor	

Building name	Space efficiency	Core/GFA ratio	Floor plan	Floor
Autograph Tower	68%	31%		Typical floor
Guiyang World Trade Center Landmark Tower	71%	27%		Low-rise floor
Federation Tower	82%	16%		Typical floor
Golden Eagle Tiandi Tower A	70%	27%		Typical floor
St. Regis Chicago	76%	21%		Typical floor
Greenland Group Suzhou Center	70%	29%		Low-rise floor
OKO – Residential Tower	76%	20%		Low-rise floor
One Shenzhen Bay Tower 7	81%	18%		Low-rise floor
Comcast Technology Center	74%	25%		Typical floor
Mercury City Tower	80%	18%		Low-rise floor
Hengqin International Finance Center	67%	31%		Ground floor
Wilshire Grand Center	80%	19%		Typical floor
Shimao International Plaza	67%	29%		Low-rise floor
China World Tower	79%	19%		Low-rise floor
Hon Kwok City Center	70%	28%		Typical floor
Keangnam Hanoi Landmark Tower	72%	26%		Low-rise floor

Building name							
Space efficiency				Core/GFA ratio			
Deji Plaza		**Nina Tower**		**Chongqing IFS T1**		**MahaNakhon**	
73%	24%	71%	27%	74%	25%	65%	32%
							
Typical floor		Typical floor		Typical floor		Low-rise floor	
CITIC Financial Center Tower 1		**Burj Rafal**		**The Shard**		**Northeast Asia Trade Tower**	
70%	27%	78%	21%	79%	20%	72%	26%
							
Typical floor		Typical floor		Low-rise floor		Low-rise floor	
35 Hudson Yards		**Kingdom Centre**		**Supernova Spira**		**Al Wasl Tower**	
80%	16%	78%	20%	63%	33%	74%	22%
							
Typical floor		Typical floor		Low-rise floor		Low-rise floor	
Torre Costanera		**Abeno Harukas**		**Shimao Riverside Block D2b**		**Aspire Tower**	
69%	30%	79%	19%	73%	26%	72%	28%
							
Typical floor		Low-rise floor		Ground floor		Low-rise floor	

Space efficiency*: calculated as the ratio of the net floor area [obtained by subtracting the service core (the pink area on the floor plan) and structural elements from GFA] to GFA.
Core/GFA**: calculated as the ratio of the service core (the pink area on the floor plan) to GFA.

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