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Hierarchical Quantification of Utilization Rate and Related Indicators of Mixed-Use High-Rise Buildings

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Abstract: Mixed-use high-rise buildings are vertical superpositions of various business types in the category of mixed-use development. It has become a highly intensive organizational form in the urban high-density environment. Under China's "height limit" policy, the simple superposition of business types does not meet the government requirements for planning, construction, and management, and does not fully utilize the advantages of the mixed development mode. The single utilization rate index used in the past could not accurately describe such buildings' usage value and spatial variation characteristics. In this study, a quantitative analysis of data from eight construction projects was carried out, and a utilization rate index system was established at three levels, namely, the typical floor utilization rate k_1, business utilization rate k_2, and building utilization rate k_3. In terms of k_1, the emphasis was placed on the design elements of the mixed-use development and the variation of relative indicators. In k_2 and k_3, it was found that the business type, floor area, and utilization rate were negatively correlated. In conclusion, by establishing a hierarchical utilization rate calculation method, the efficiency values and design characteristics of mixed-use high-rise (MUHR) buildings were explored, which provide references for the future design of such buildings.

Keywords: mixed-use high-rise building; utilization rate; quantification

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1. Introduction

The mixed-use high-rise building (MUHR) is a design concept proposed under the compact city theory according to the development trends of high-rise buildings, the development mode of modern commercial real estate, and the mixed use of land [1,2] (The concept of "mixed use" was first proposed by the Urban Land Institute (ULI) in 1976 in the book *Mixed-Use Development: New Ways of Land Use*. "Mixed use" originally belonged to the category of urban design. With time, the concept itself has undergone changes, and the scope of application has become increasingly extensive). It was formally proposed at the 2020 "Sustainable Supertall Buildings" forum held by the World Council on Tall Buildings and Urban Habitat (CTBUH) in Guangzhou.

In 2020, the Ministry of Housing and Urban-Rural Development (MoHURD) and the National Development and Reform Commission (NDRC) of China jointly issued the "Notice on Further Strengthening the Management of Urban and Architectural Features". In October 2021, the MoHURD and the Ministry of Emergency Management (MEM) jointly issued the "Notice on Strengthening the Planning and Construction Management of High-rise Buildings". Both notices provided clear instructions on the planning and construction management of high-rise buildings and the control of urban features. They also established demonstration requirements for projects to be constructed. However, the relevant evidence and theories are currently scarce, and thus, it is very important to promote the concept of the rational construction of high-rise buildings, as well as research on the efficient use and development of such buildings.

Most of the super high-rise buildings in China were built in the pursuit of economic benefits and also to be recognized as iconic/famous buildings due to their height. However, there are limited studies on the utilization rate of those high-rise buildings. In MUHR buildings, the overall efficiency is usually used to reflect the utilization rate of the building, and the utilization rate has not been directly analyzed from the point of view of individual components to the whole, in combination with the business types, the combination modes, and the vertical space layout. This study proposes efficiency values at different levels and relates key indicators in MUHR buildings. The data will guide future building design and provide a great reference value for the understanding and decision making of MUHR buildings.

1.1. The Development of Mixed-Use High-Rise Buildings

Over the past two decades, there has been unprecedented growth of high-rise buildings worldwide. By the end of 2020, the total number of high-rise buildings in the world, of higher than 250 m in height, reached 510, representing an increase of 192% compared with the 23 high-rise buildings reported in 2010. In particular, the proportion of MUHR buildings has seen a steady increase, as shown in Figure 1. In fact, the Chinese government issued several notices regarding the height of newly constructed buildings in second- and third-tier cities. However, as one of the highly intensive organizational forms of urban cities, the mixed-use development model in China's first-tier cities not only promotes the rational use of urban land, but also provides a more convenient and richer work and life experience for the high-density population. MUHR buildings have become an important carrier of urban life due to the aggregation of different businesses in a vertical space [3–5].

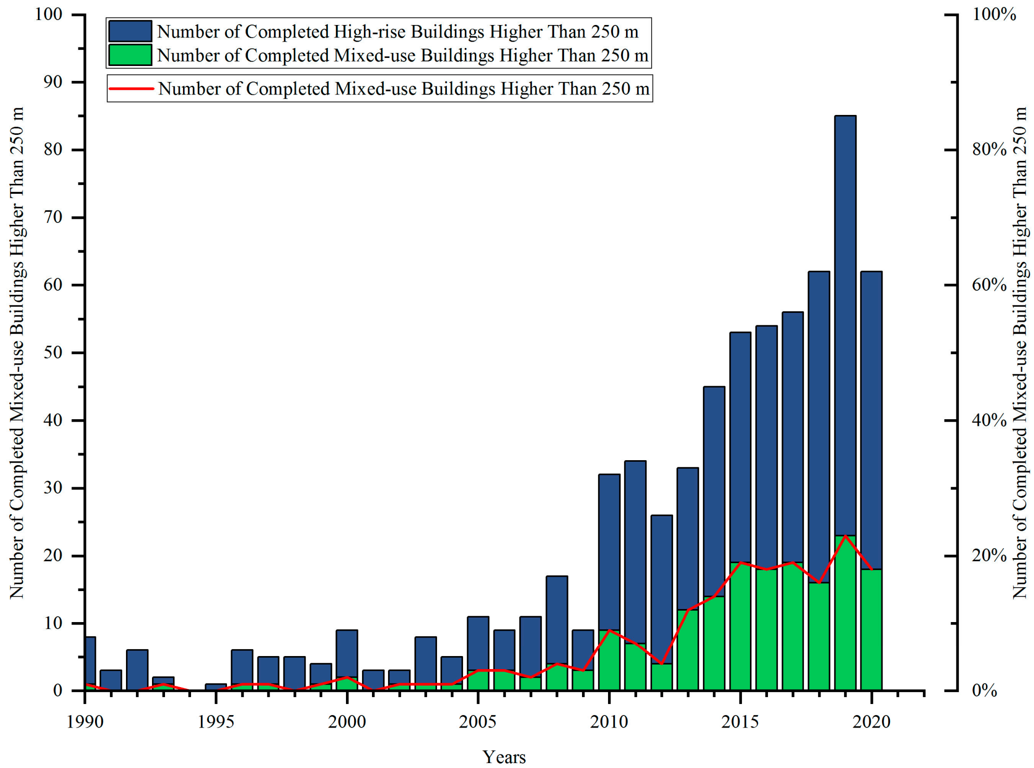


Figure 1. Number of completed high-rise buildings higher than 250 m and Variation of the proportion of mixed-use buildings in high-rise buildings.

1.2. Business Types of Mixed-Use High-Rise Buildings

The concept of "mixed-use" in mixed-use super high-rise buildings originated in the pursuit of their mixed use. Initially, it was proposed by the United States, then a large number of examples and extensive construction experience were achieved in Europe and America, and some books were published summarizing the experience. Generally speaking, the research in the USA is relatively comprehensive and complete. In 1977, the Urban Land Institute (ULI) published the first professional book on mixed use, titled *Mixed-Use Development: New Ways of Land Use* [1], in which the concept of mixed use was first formally introduced. In the same year, Dimitri Procos wrote an article titled *Mixed Land Use: From Revival to Innovation* [6]. The article explored the historical development of mixed use and investigated many aspects of socioeconomics, urban mega-configuration, and legal policy. In 2003, the Urban Land Institute published *Mixed-Use Development Handbook* [7], a theoretical summary of mixed use in urban design. This book introduced the whole process of mixed-use development and presented a dozen completed cases in recent years in the introduction. *Reclaiming The City-Mixed Use Development* [8], edited by a British scholar named Andy Coupland, presented the latest results of mixed-use development in the European region and the UK. Similarly, Building Research Association of New Zealand (BRANZ) published *Mixed-Use Urban Planning and Development* [9], intended for transport and urban planners as well as developers and architects involved in the design and planning of mixed-use development projects in New Zealand, in particular in Christchurch. The research on mixed use in China is still in its early stage, mainly focusing on the introduction of foreign theories and practices and the study of individual elements, with less systematic research discussions. In the results of the literature search, more journal articles and master thesis literature at the planning level and urban level were apparent [5,10–12], but at the building level, only *Research on Mixed-use Super High-rise Building Design on the Perspective of Synergy Effect* [4] proposed by Dr. Jianhe Luo was available. In response to the shortage of hybrid development models in the interdisciplinary research of super high-rise building development, design, and operation, Dr. Jianhe Luo conducted systematic research on the more complex vertical-oriented business combination model and presented the research results at the international conference of the Council of Tall Buildings and Urban Habitat (CTBUH). Other research results have been proposed to a lesser extent.

MUHR buildings refer to the type of high-rise buildings that integrates multiple business types in the vertical dimension, and it is often used to indicate an individual building or the main tower in a building complex [13]. When the building height reaches a certain limit, the building is not simply a superimposition of typical floors. The spatial characteristics and supporting service spaces of different business types change with the building shape and height, showing vertical distribution characteristics. Therefore, according to different development modes, a combination of various business types (e.g., office, hotel, apartment, business, etc.) is used, forming a complex development model [3,4,14,15]. In relation to sharing infrastructure, most developers claim that operating a mixed-use building can save up 20% of the overall operating cost compared to a separate building venture [14].

The main business types of MUHR buildings include commercial, office, hotel, and residential (apartment). Typical combinations of these business types include "office + hotel", "office + residential", "hotel + residential", and "office + hotel + residential". Because of the unique development model, the model has strong adaptability to the urban business environment, and there is a strong synergistic relationship between the main business types and the auxiliary business types, as detailed in Table 1 [16–20].

Table 1. The degree of the synergy of different business types.

Business Types	Office	Hotel	Residential	Commercial	Restaurant	Sightseeing	Conferences	Exhibition	Entertainment	Culture	Transportation Hub	Public Places	Healthcare	Club	Parking
Office	\														
Hotel	•	\													
Residential	•	—	\												
Commercial	•	○	•	\											
Restaurant	•	•	•	•	\										
Sightseeing	×	×	×	•	•	\									
Conferences	•	•	—	○	•	×	\								
Exhibition	○	○	×	•	•	○	×	\							
Entertainment	○	•	•	•	•	○	—	○	\						
Culture	—	—	—	○	○	•	—	—	○	\					
Transportation Hub	•	•	•	•	•	•	○	•	○	○	\				
Public Places	•	•	•	•	○	○	○	○	○	○	—	\			
Healthcare	○	○	•	○	—	—	—	×	—	○	○	—	\		
Club	—	•	•	○	○	—	—	—	•	○	—	○	—	\	
Parking	•	•	•	○	○	○	○	○	○	○	○	○	○	○	\

• Strong value synergy; ○ Weak value synergy; — No value Synergy; × Value contradiction.

2. Indicators of the Utilization Rate of Mixed-Use High-Rise Buildings at Three Levels

2.1. Research Background

The main literature surveyed in this study includes the Council of Tall Building and Urban Habitat (CTBUH) [21–24] database (www.ctbuh.org, accessed on 29 October 2019), peer-reviewed-research, M.Sc. theses and Ph.D. dissertations, proceedings, fact sheets, architectural and structural magazines, photographs, and videos. Super high-rise building heights have been competing for years, leading to higher construction and operating costs as the height of super high-rise buildings increases. Among them, a very interesting and important phenomenon is that current super high-rise buildings have less space available on their typical floors than traditional super high-rise buildings [4,13,25,26]. Thus, the study of spatial efficiency has invited more attention. In order to maximize the return for investors, more researchers have focused on the input-output ratio of super high-rise buildings with space efficiency and started to systematically study the building space efficiency and return on investment [24,26–30]. For example, Sev and Özgen [27] studied space efficiency mainly in the case of 10 office buildings in Turkey and many super high-rise buildings around the world. Mixed-function super high-rise buildings were first generated by Kim and Elnimeiri [24], who studied the design parameters of this building type, such as function, lease span, floor-to-floor height, and other design elements. Su Jian [26] systematically proposed strategies for designing the efficiency of typical floors in super high-rise buildings. The studies of these researchers clearly elaborated the factors related to space efficiency in super high-rise buildings. The following results were presented: (1) space efficiency is determined by the functional distribution of mixed-function super high-rise buildings; (2) the space efficiency of single-function buildings is generally higher than that of multi-purpose buildings; (3) the improvement of building structure technology greatly enhances the space efficiency of super high-rise buildings.

This research paper mentioned decision elements that affect the space efficiency of super high-rise buildings, which include (1) the core layout at the typical floor [25,26,31,32], (2) structural forms and structural sizes [33–38], (3) the choice of building sustainable materials for the building structure [39–46], (4) the space rentable on the typical floor of the building [24,26–30], (5) factors such as depth, floor height, vertical traffic, etc., in building floors [4,26,29,47], and (6) factors such as HVAC, elevators, water distribution, fire safety, etc. [48–51].

Through the study of existing literature and combined with the research objective of this paper, the shortcomings of existing research results are as follows.

(1) In previous studies, one typical floor was usually used as a sample for a building interval, and this calculation is only applicable to cases with low building heights. However, when the building height reaches 250 m or more, each typical floor will produce changes. In this case, using the previous calculation method may produce a large error.

(2) Although previous studies considered factors such as building lease span, floor-to-floor height, elevators, etc., which can affect the space efficiency of buildings, these factors can also vary in mixed-use super high-rise buildings due to the different types of businesses and different needs. These factors will affect the vertical layout, space design, and space efficiency of the business.

(3) Previous studies usually used one dataset to represent the efficiency value of a building. However, for mixed-use super high-rise buildings, this approach ignores the relationship between changes in building height and business type, and spatial efficiency. At the same time, it also ignores the impact on spatial efficiency that occurs with increasing building height as the building's load and vertical traffic demand decrease. These are also the reasons for the study presented in this paper.

2.2. Research Purpose

In China, a building with a building height of 100 m is called a super high-rise building, and a super high-rise building with a building height of 100 to 250 m usually contains only one type of business. Therefore, the design of the plan function, the choice of building technology, and the needs of the users are unified, and there is no major conflicts in terms of use. For the designers, they only need to focus on the design method of one type of business, and only need to meet the requirements of the business itself in the study of space efficiency. Therefore, it is comparably less difficult to design, and the efficiency index is individual and simple to calculate. However, super high-rise buildings over 250 m, as landmarks of the city they are in, are often formed by the superposition of multiple business forms and their supporting functions in order to meet the city's commercial needs and increase the economic value. The vertical mode of multiple businesses requires designers to pay attention to the relationship between the space requirements of different businesses and the reasonable organization of the businesses, so as to avoid the wastage of space due to unreasonable design and even a failure to meet the needs of users.

For a single business type building, a set of data is sufficient to describe the overall utilization rate of the building. However, for super high-rise buildings with mixed business modes and a scale of 200,000 m^2 or more, this calculation method is not suitable and the error is larger. The utilization rate of mixed-use super high-rise buildings is not only influenced by the design elements of the industry itself but also by the interaction between the industries. Therefore, the utilization rate of mixed-use super high-rise buildings is influenced by many factors, and it will be variable and unpredictable with the change in the business mode and increase in the number of floors.

By summarizing the references and literature and combining them with the research object of this paper, it can be concluded that the single data value cannot intuitively reflect the dynamic change rule and real usage rate of mixed-use super high-rise buildings, and the reference value for designers is relatively low. Therefore, this paper proposes a multi-level utilization rate calculation method based on the international calculation method and China's calculation standard and uses the unified measurement standard to quantify the typical floor area index, the business area index, and the tower area index at different levels. This is useful to explore the regularity of the utilization rate of mixed-use supertall buildings more clearly and the range of values of important indicators, to provide valuable reference data for designers and decision makers, and to help foreign architects to better understand the standards of China regarding the calculation of core, floor area, and other indicators when they participate in China's supertall building projects, and to contribute to the exchange and development of the industry.

2.3. Three-Level Indicators

In order to demonstrate the difference between MUHR buildings and single-use buildings, the calculation method of the architectural utilization rate was introduced. That is [4,24,26,29]:

$$\text{Utilization Rate } (k) = \text{Utilization Area}/\text{Building Area} \times 100\%$$

Based on the utilization rate, as well as the characteristics of the vertical superposition of business types, research indicators at three levels were proposed in this study, namely, the typical floor, business, and building, as shown in

(1) The typical floor utilization rate (k_1) refers to the efficiency value of each floor from the building's ground floor to the top floor. It is calculated based on the basic information of the typical floor of each business type.

$$k_1 = (c + b)/f \tag{1}$$

where f is the typical floor area ($f = a + b + c$), a is the core area of the typical floor, b is the typical floor traffic area, and c is the typical floor rentable area.

(2) The business utilization rate (k_2) refers to the overall efficiency value of each business and its supporting function. The calculation of the business utilization rate is based on the data of the typical floor utilization rate for a certain business type.

$$k_2 = (C + B)/F \tag{2}$$

$$F = \sum f_i \, (i = 1, 2, 3, \cdots, n, B = \sum b_i \, (i = 1, 2, 3, \cdots, n), C = \sum c_i \, (i = 1, 2, 3, \cdots, n)$$

where F is the sum of the area of each typical floor of a certain business type, B is the sum of the traffic area of each typical floor of a certain business type, C is the sum of the rentable area of each typical floor of a certain business type, and n is the number of floors of the building.

(3) The building utilization rate (k_3) refers to the overall efficiency value of all floors of the building. It is a study of the utilization rate of the entire building (i.e., superimposition of the typical floor, equipment floor, refuge floor, etc.).

$$k_3 = [S_{(c)} + S_{(b)}]/S_{(f)} \tag{3}$$

$$S_{(f)} = \sum f_i \, (i = 1, 2, 3, \cdots, n), S_{(b)} = \sum b_i \, (i = 1, 2, 3, \cdots, n), S_{(c)} = \sum c_i \, (i = 1, 2, 3, \cdots, n)$$

where $S_{(f)}$ is the sum of the area of each floor of the building, $S_{(b)}$ is the sum of the traffic area of each floor of the building, and $S_{(c)}$ is the sum of the rentable area of each floor of the building.

Figure 2, which helps to explore the efficiency value of MUHR buildings and its change.

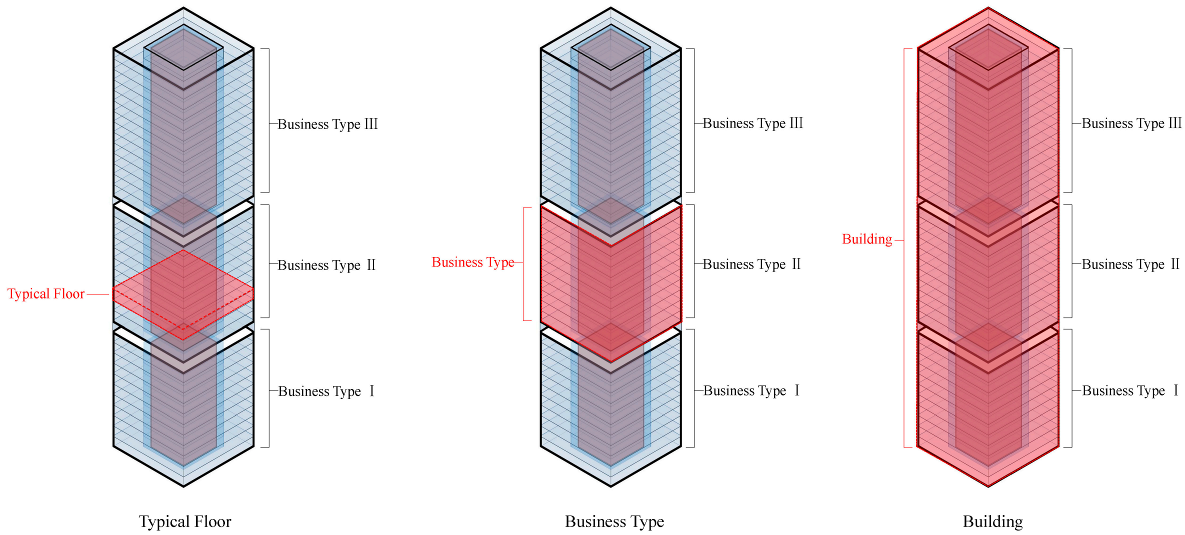


Figure 2. Schematic diagram of the three research indicator levels (i.e., typical floor, business, and building).

2.4. *Definition and Calculation of Key Indicators*

In the calculation of the utilization rate, we need to define the four basic concepts of typical floor area, core area, traffic space area and rentable area, so as to ensure the uniformity of definition and measurement standards. Meanwhile, the content of relevant technical elements in the core needs to be described, and the content of design elements within the core needs to be outlined. However, the technical elements are not the key point of this paper. This part has strong professionalism and technicality. The focus of this study is to explore the characteristics of the utilization rate of mixed-use high-rise buildings. There already exists extensive research on equipment rooms and tube wells of different business types. If the research detailed deviates from the framework of the article, it could skew the research focus. This paper only provides total data indicators. However, the relevant area data and information were measured and summarized, and will continue to be discussed in future research.

(1) The typical floor area refers to the horizontal projection area enclosed by the outer wall and the outer edge of the column or the axis of adjacent walls, as shown in Figure 3. When the building is connected to a podium, the podium typical floor area is the projected area of the ground floor of the building. This definition is also referred to as the Gross Area (GSF), which includes exterior wall thickness, and all vertical penetrations (mechanical/electrical, plumbing, elevator shafts, stairwells, etc.), as well as basements, garages, and penthouses. It excludes parking lots and loading docks outside the building line.

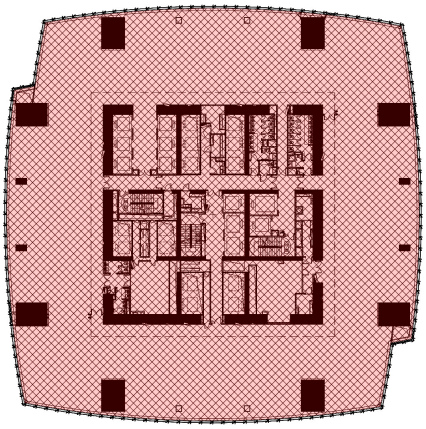


Figure 3. Legend of typical floor area.

(2) The traffic space area of typical floors refers to the space between the rentable space and the outer edge of the core, as shown in Figure 4. If the rentable space and traffic space are not divided in the CAD drawing of the office floor, the traffic space shall be calculated with a width of 1.8 m. China's standard (*Code for Fire Protection Design of Building*) clearly stipulates the setting of the traffic space area and does not allow the area outside the core to be used as a rentable area. (Note: Lobbies and hotel facilities are included in the traffic space). This definition is also known as the Circulation Area (Primary and secondary), and the Circulation Area can be broken into the following two types: primary and secondary. Primary circulation is the main route connecting the building core and common spaces, such as elevator lobbies, exit stairs, and core toilets. Secondary circulation refers to the aisles between individual and support spaces. According to the Chinese standard, the traffic space area and primary circulation contain the same content.

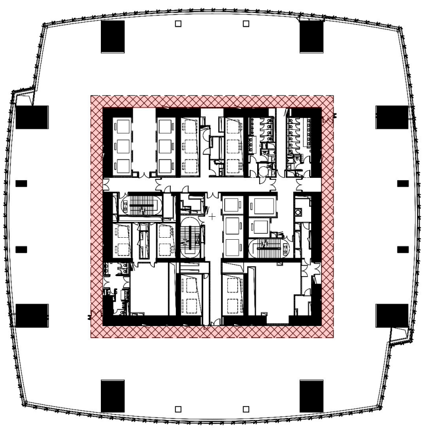


Figure 4. Legend of Traffic Space Area.

(3) The core area of the typical floors refers to the area enclosed by the outer boundary of the core structure, as shown in Figure 5. The core refers to the central part of a building, which consists of elevator shafts, stairs, ventilation shafts, cable shafts, public restrooms, and some equipment rooms. It forms a frame-tube structure with peripheral frames and is made of reinforced concrete. In all the studied buildings, the central tube design was adopted.

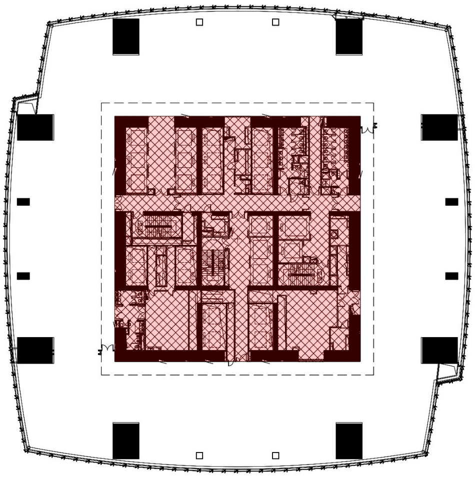


Figure 5. Legend of core area.

The size of the building core, which contains elevators, stairs, washrooms, and mechanical and service facilities, is a basic factor in determining the ratio of rentable space. Ideally, it should be the smallest possible size while still effectively accommodating the necessary functions. By rearranging the function components, core elements and structural system, the space efficiency can be increased. If the building acquires some areas of additional rentable space through the rearrangement of the core elements, the economic benefits over the potential building life can be considerable.

Here, some points are added.

① The space available for the rent and sale of the core is not included in the core area. When part of the space in the core can be used as a rentable area, this part of the space belongs to the rentable area.

② Core is a broad definition. It is a comprehensive concept based on the building structure and contains technical equipment, such as public restrooms, fire protection, electromechanical aspects, air conditioning, elevators, and auxiliary spaces. This explains two main cases. One is in the plan design. For example, when the auxiliary space such as the bathroom is located outside the core structure or even out of it, these auxiliary spaces are still calculated within the core. In China's area calculation, this part belongs to the public area (public use space) and is not included in the rentable area, as shown in Figure 6a. The other is arranged outside the core, even between the perimeter columns and the curtain wall, due to the technical needs of the equipment tube wells. This part is also considered to be part of the core area, as shown in Figure 6b. This definition allows the "core" to include all technical rooms, equipment tube wells, and ancillary services, and it can be applied to all cases to facilitate comparisons between cases.

③ In the calculation of the equipment room and equipment tube well area, it is necessary to identify which kind of business is served by these technical facilities. Especially in the area measurement of the equipment floor, it is necessary to know the purpose of the equipment room. When equipment such as fire-fighting pools and fire-fighting systems are shared by multiple businesses, the area of this part is calculated separately for each business by the ratio of the business area.

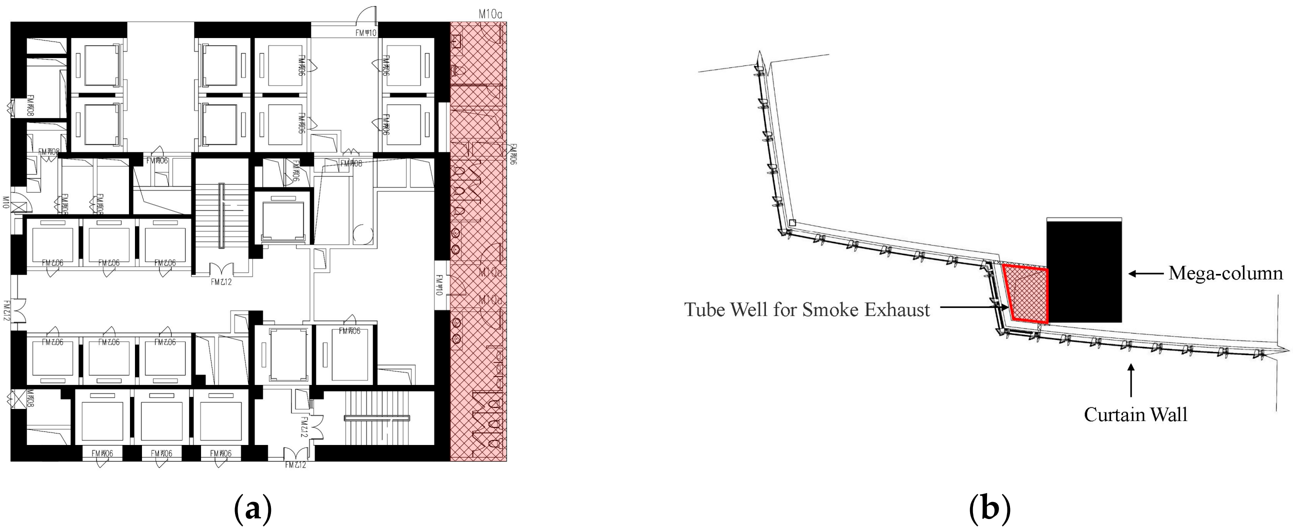


Figure 6. Calculation legend of core area. (**a**) Public space is located outside the core structure, (**b**) Equipment tube wells arranged outside the core.

(4) The rentable area refers to the building area on each floor where services are provided or rented to customers, as shown in Figure 7. (Note: Areas for rent and sale in the core and hotel facilities are all included in the rentable space). In the definition of this concept, there are some differences between China and other countries. Usually, in the international, e.g., US, calculation of the utilization rate (see Table 2 for the definition of area indicators in China and the USA), the utilization rate is the ratio of net floor area (NFA) to gross floor area (GFA) [4,24,26,29]. Net Area includes workspaces (office and workstations), dedicated support (conference rooms, supply rooms, etc.), shared support (shared copier rooms, break rooms, etc.), and special mission-critical support spaces (evidence rooms, laboratories, courtrooms, etc.). However, from the definition described, the rentable area in China is equivalent to the combination of both the Net Area and Secondary circulation area. This paper mainly focused on Chinese projects, and the target audience is domestic and foreign architects participating in Chinese architectural design. Therefore, in order to better suit the sales and operation mode of Chinese super high-rise buildings, the rentable area was measured and calculated according to Chinese standards in this paper.

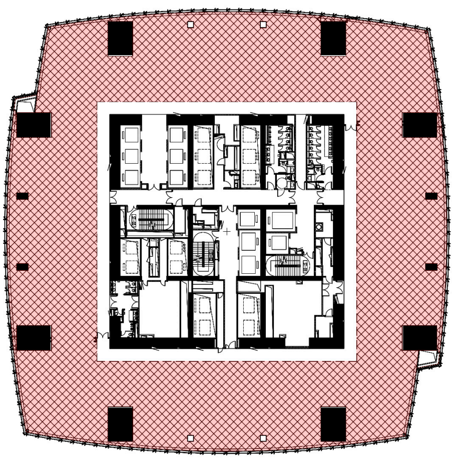


Figure 7. Legend of Rentable Area.

Table 2. Definition of area indicators in China and the USA.

Nation	Name of Indicators	How to Define
China	Typical Floor Area	The typical floor area refers to the horizontal projection area enclosed by the outer wall and the outer edge of the column or the axis of adjacent walls.
	Traffic Space Area	The traffic space area of the typical floors refers to the space between the rentable space and the outer edge of the core.
	Rentable Area	The rentable area refers to the building area on each floor where services are provided or rented to customers.
The USA	Gross Area	Total area of a building enclosed by the exterior face of the perimeter walls, calculated on a floor-by-floor basis.
	Rentable Area	Total Usable Area plus a prorated allocation of the floor and building common areas within a building.
	Usable Area	Area of a floor occupiable by a tenant where personnel or furniture are normally housed.
	Circulation Area	Primary circulation is the main circulation route connecting to the building core and common spaces, such as elevators and exit stairs.
		Secondary circulation includes the aisles between individual spaces, such as offices and cubicles, and support spaces.
	Net Area	The area of each identified program space. For example, the Net Area of an 8′ x 8′ workstation is 64 NSF. It includes individual workspaces, dedicated and shared support spaces, and special mission-critical spaces.

The reference material of China is *Calculation Code for Construction Area of Building* (GB/T 50353-2013), The reference material of the United States is *Circulation: Defining and Planning* (Definitions per ANSI/BOMA Z65.1-1996, "Standard Method for Measuring Floor Area in Office Buildings").

(5) Definition and measurement of other important indicators, as shown in Table 3.

Table 3. Name of technical indicators and Technical element definition.

Name of Technical Indicators	Technical Element Definition	
Depth	The maximum vertical distance from the outer edge of the outer envelope to the wall surface of the core outer wall (based on the depth of the main facade)	
Evacuation staircase area	In each floor plane of a super high-rise building, there is enough fireproof capacity to be used as a vertical passage of indoor stairs and outdoor stairs. It is not only an important passageway for personnel evacuation and safe evacuation in the vertical direction but also an auxiliary attack route for firefighters to extinguish the fire. (Calculation of net area).	
Structure area	Core part	The area of the core structural wall of the typical floor
	Outer part	The area of the structural columns of the outer columns of the typical floor.
Evacuation room area	The floor is used for fire evacuation in high-rise buildings. The evacuation floor of a high-rise building over 100 m in height is specially set up for people evacuation for fire safety. The measurement of the data is the area of the evacuation area on the evacuation floor.	
Elevator shaft area	Measure the area of all elevator shafts according to the technical drawings	
Area of equipment room and tube well	Measure the technical drawings and equipment tube well area of different disciplines according to the technical drawings.	

In this study, a long-term evaluation of eight MUHR buildings was carried out (higher than 250 m). For the definition of building height in this study, the efficiency of the building area was explored. Thus, the building height was defined as the height from the ground level of the first floor of the MUHR buildings, or the ground level of the public entrance, to the highest space that people (users, workers, and maintenance personnel) can reach. This definition is different from the fire height defined in the "Code for Fire Protection of Building

Design" (GB50016-2014) or the building's appearance heigh. Different business combination modes were analyzed, as detailed in Table 4. By standardizing the measurement of the utilization rate and other indicators, the relative parameters according to the blueprint were measured, and on-site surveys and data verification on completed construction projects were performed, as shown in Figure 8.

Figure 8. The eight MUHR buildings investigated in this study. (**a**) Dongguan International; (**b**) Guangzhou Fuli Yingkai; (**c**) Guangxi Jiuzhou; (**d**) Guiyang World Trade Center; (**e**) Guiyang International Financial Center; (**f**) Guangzhou International Financial Center; (**g**) Kingkey 100 Building; (**h**) Guangzhou Chow Tai Fook Financial Center.

Table 4. Building height and business combination mode of the eight high-rise buildings.

Project Name	Location	Designer	Height (m)	Status	Commercial	Office	Hotel	Residential	Sightseeing	Restaurant	Swimming Pool and Gym	Meeting, Banquet
(a) Dongguan International Financial Center	Dongguan, Guangdong	Tange Associates + SCAD	288	Completed		√	√	√		√	√	√
(b) Guangzhou Fuli Yingkai	Guangzhou, Guangdong	GP	296.2	Completed	√	√	√			√	√	√
(c) Guangxi Jiuzhou International Building	Nanning, Guangxi	SCAD	313.6	Completed	√	√	√			√	√	√
(d) Guiyang World Trade Center	Guiyang, Guizhou	SOM	379.8	In construction		√	√	√		√	√	
(e) Guiyang International Financial Center	Guiyang, Guizhou	SCAD	390.4	Completed		√	√	√		√		√
(f) Guangzhou International Financial Center	Guangzhou, Guangdong	WEA + ARUP + SCAD	433.1	Completed		√	√			√	√	
(g) Kingkey 100 Building	Shenzhen, Guangdong	TFP	441.3	Completed		√	√			√	√	√
(h) Guangzhou Chow Tai Fook Financial Center	Guangzhou, Guangdong	KPF	517.75	Completed		√	√	√		√	√	√

√ Including this business type.

3. Quantification of Indicators Related to the Utilization Rate of Mixed-Use High-Rise Buildings

3.1. Quantification of Typical Floor Utilization Rate and Related Indicators

3.1.1. Typical Floor Area

In terms of the typical floor area, the higher the building, the larger the floor area. Moreover, the greater the number of floors, the smaller the typical floor area. In the investigated buildings with a height range of 250–300 m, the typical floor area is about 2000–2300 m^2. In the buildings with a height range of 300–400 m, the typical floor area was about 2000–2600 m^2. In the buildings with a height range of 400–500 m, the typical floor area was about 2300–3000 m^2. In buildings higher than 500 m, the typical floor area ranged from 2600–3600 m^2. There is a sudden change in the curve of the typical floor area in the Guangzhou Chow Tai Fook Financial Center. Due to the increasing demand for building refuge floors and equipment floors, the mezzanine was set up on the 23rd, 40th, and 67th floors. The typical floor area curve shows that the building area reaches more than 5000 m^2, as shown in Figure 9.

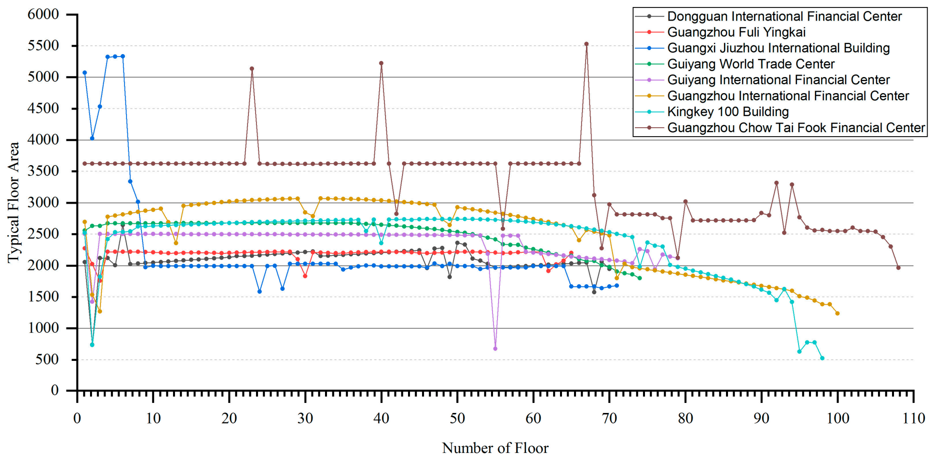


Figure 9. Variation of typical floor area in the studied high-rise buildings.

As shown in Figures 9 and 10, the eight buildings mainly showed three trends/categories. The first category is seen in the Guangzhou Chow Tai Fook Financial Center and the Guangxi Jiuzhou International Building. In order to adapt to the lease span requirements of different business types, the typical floor area is continuously reduced with the narrowing of the building shape. The second category is seen in the Guiyang World Trade Center, the Guangzhou International Finance Center, and the Kingkey 100 Building. This category shows a curved variation of the typical floor area from the ground floor to the top floor. The typical floor area gradually decreases as the building shape changes, in order to adapt to the changes in the lease span and core structure. The third category has a constant typical floor area, such as the Dongguan International Financial Center, the Guangzhou Fuli Yingkai, and the Guiyang International Financial Center. In these buildings, functional transformation was realized through the core design, which is common in high-rise buildings below 300 m. The variation of the typical floor area and the building shape are closely related to the lease span demand of each business type and the vertical distribution of the business types. Statistically speaking, the lease span of the typical floor of office spaces is in the range of 12–16 m. Except for the traffic space around the core, the lease span of the office space is generally 10–14 m. Considering the requirements for sunlight in the residential and hotel spaces, most rooms have a lease span of 9 m. The commercial space of the Guangxi Jiuzhou International Building had a lease span of about 25 m, which is less than that of the commercial complex buildings, as shown in Figure 11. Therefore, the vertical distribution of different business types and the demand for the lease span of each business type will lead to adjustments to the shape of MUHR buildings.

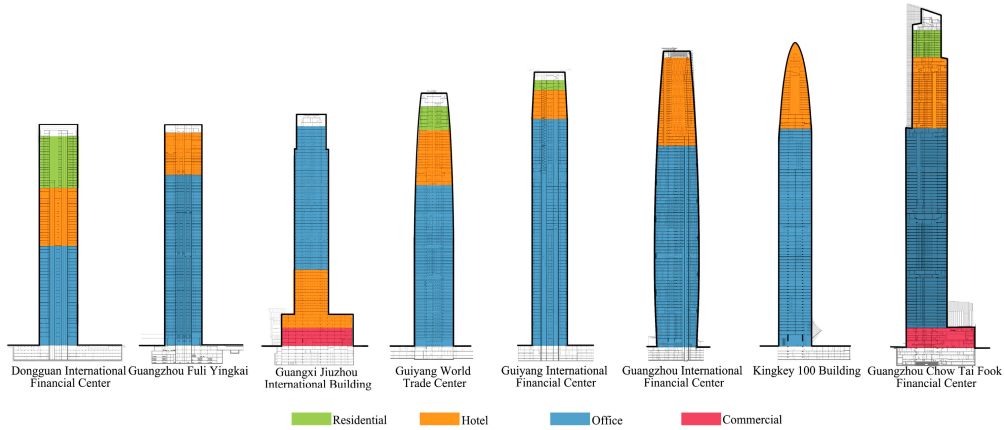


Figure 10. Building shapes and vertical distribution of business types.

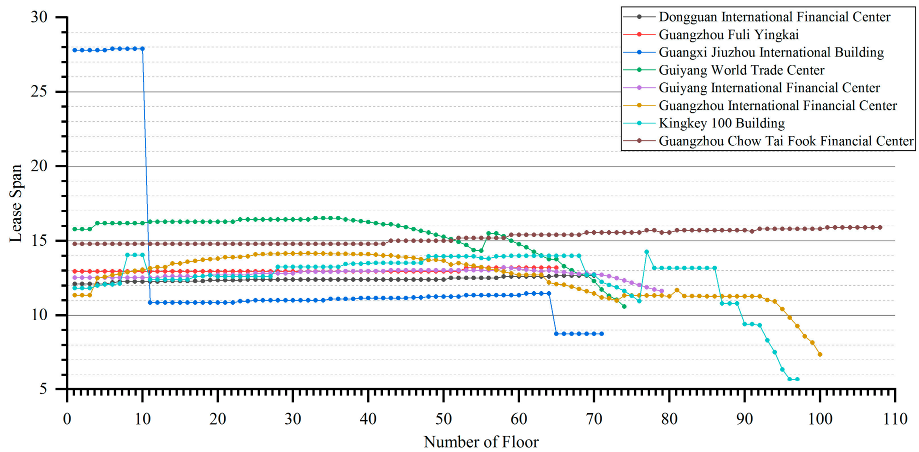


Figure 11. Variation of the lease span of the typical floor.

3.1.2. Core Area

From the change of the core area, it is clear that the higher the building, the larger the core area. The maximum core area of buildings with a height range of 250–300, 300–400, 400–500, and above 500 m are 650, 700, 870, and 1000 m^2, respectively. The trend of the core area change showed that it changed very little below the 42nd floor (about 180 m above sea level). With the increase in the number of building floors, the demand for the building structure and vertical traffic decreases, and thus, the core area shows a decreasing trend. For example, the core area of the 1st to the 52nd floors (office space) in the Guiyang International Financial Center gradually decreased from 712.8 to 660.4 m^2, as shown in Figure 12.

Compared with single-use high-rise buildings, the MUHR buildings have special core designs. On the one hand, the vertical traffic demands of different business types affect the core of the typical floor. It can be clearly seen that the cores of MUHR buildings change dynamically, as shown in Figure 12. Under the condition of meeting the structural and electromechanical requirements, core adjustment is necessary to achieve the flexible design of the vertical traffic of various business types. For example, the lower-level (the 4th to the 29th floors) office space in the Guangzhou International Finance Center has a core area of 840.01–771.26 m^2, while the core design of the hotel space (the 57th to the 72nd floors) has three sets of cores, with a core area of 178.52 m^2, as shown in Figure 13. In the Guangxi Jiuzhou International Building, the hotel space is located below the office space. The vertical superposition combination mode is the reason the core of the hotel space needs to meet the vertical traffic and tube-well equipment required by the large flow in the office space, as shown in Figure 14. As a result, the core area of the building is higher than that of the buildings with a similar height. The core area of the hotel space of the Guangxi Jiuzhou International Building is 600.02 m^2, while the core area of the hotel space of the Guangzhou

Fuli Yingkai, with a similar height of 286.7 m, is only 440 m^2. The hotel position in the Guangxi Jiuzhou International Building is unusual, which leads to an inefficient vertical transportation system, and the hotel space does not have a good landscape view, thereby reducing the spatial quality of the hotel.

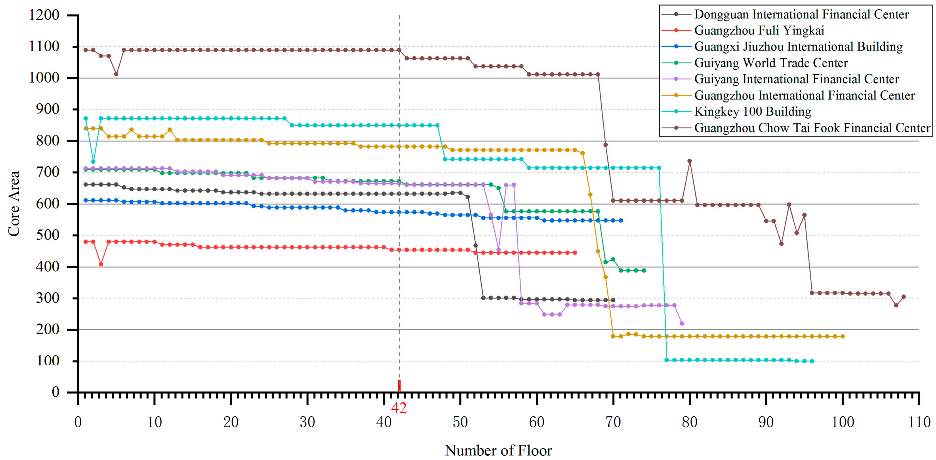


Figure 12. Variation of the core area of the typical floor.

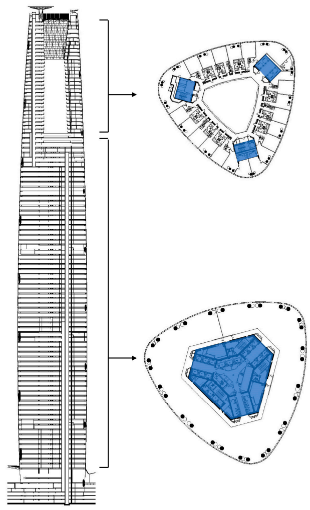


Figure 13. Schematic diagram of the core of Guangzhou International Finance Center.

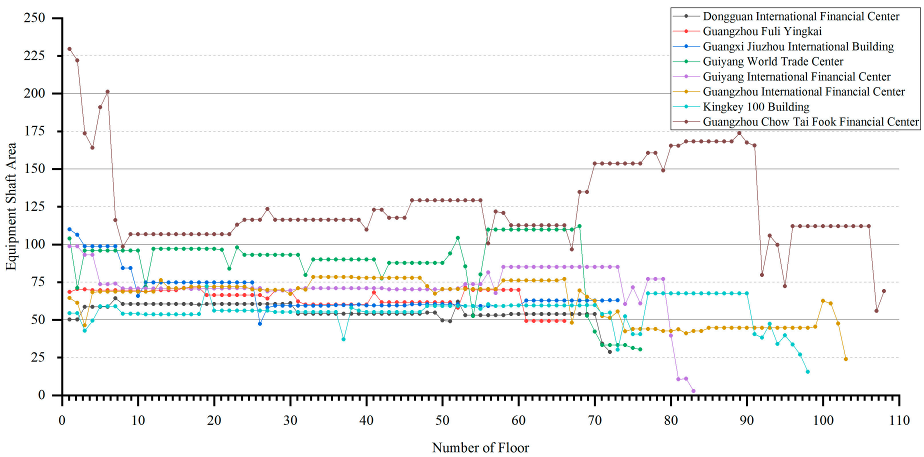


Figure 14. The total area of tube well equipment.

In addition, the vertical transportation design of MUHR buildings is different from that of a single-use building. Thus, existing design standards can only be used as a reference, and the design of the mixed-use building must consider the operating efficiency of different sections and business types and use double-deck elevators where appropriate. It was found that there is a certain discrepancy between the data in this study and the "Office Building Design Standards" in terms of the number of elevators and the main technical parameters, as shown in Table 5. Compared with multi-zone or high-rise office buildings, MUHR buildings have many business types, often on a large scale, and have complex transportation systems. The design of elevator systems is based on the overall operating efficiency, and thus, conventional reference data are not fully applicable. For example, considering the long operating time on high stories in the Guiyang International Finance Center, the elevators in the third and fourth groups (high stories) increased from four to six. Increasing elevator shafts for high stories reduced the ratio of the building area to the number of passenger elevators, thereby improving the elevator efficiency in the top stories, as shown in Figure 15. In addition, in the Guangzhou Chow Tai Fook Financial Center, a double-deck elevator system was adopted in order to improve the operational efficiency in the high-zone office space. As a result, the ratio of the building area to the number of passenger elevators in the double-deck elevator service section reached a ratio of 18,575:1, which fully reflects the efficiency of the double-deck elevator system, as detailed in Table 6. In general, a double-deck elevator system is used for buildings higher than 400 m, which can save 25% of the hoist-way space and improve the operating efficiency by 75% [29]. However, the double-deck elevator system requires constant floor height. Due to the different floor height requirements of various business types in MUHR buildings, it is not possible to set up double-deck elevator systems across different business types, as shown in Figure 16.

Table 5. The number of elevators and main technical parameters (Office Building Design Standards JGJ/T 67-2019).

Standard Building Category		Number				Rated Load Capacity (kg)	Rated Velocity (m/s)
		Economic	Standard	Comfortable	Luxury		
Office	By building area	Per 6000 m^2	Per 5000 m^2	Per 4000 m^2	<4000 m^2 per elevator	630 800 1000 1250 1600	0.63 1.00 1.60 2.50
	By effective office space	Per 3000 m^2	Per 2500 m^2	Per 2000 m^2	<2000 m^2 per elevator		
	By number of people	Per 350 persons	Per 300 persons	Per 250 persons	<250 persons per elevator		

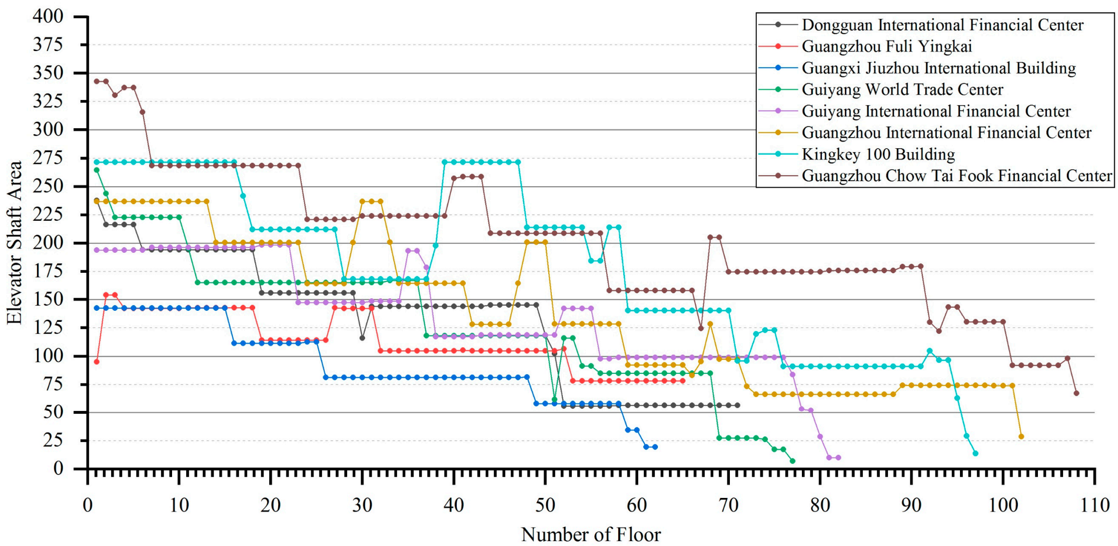


Figure 15. Elevator shaft area of the typical floor.

Table 6. Elevator data of office space in Guiyang World Trade Center and Guangzhou Chow Tai Fook Finance Center.

Elevator Data of Office Space in Guiyang World Trade Center				
Elevator group	#1	#2	#3	#4
Number of floors	10	11	14	14
Elevator between floors	4	4	6	6
Ratio of building area to the number of passenger elevators	6628:1	6697:1	5804:1	6404:1
Ratio of rentable area to the number of passenger elevators	4129:1	4192:1	3855:1	4113:1
Elevator Data of Office Space in Guangzhou Chow Tai Fook Finance Center				
Elevator group	#1	#2		#3
Number of floors	16	31 (double-deck)		10
Elevator between floors	6	6		4
Ratio of building area to the number of passenger elevators	9661:1	18,575:1		5710:1
Ratio of rentable area to the number of passenger elevators	5851:1	11,008:1		3855:1

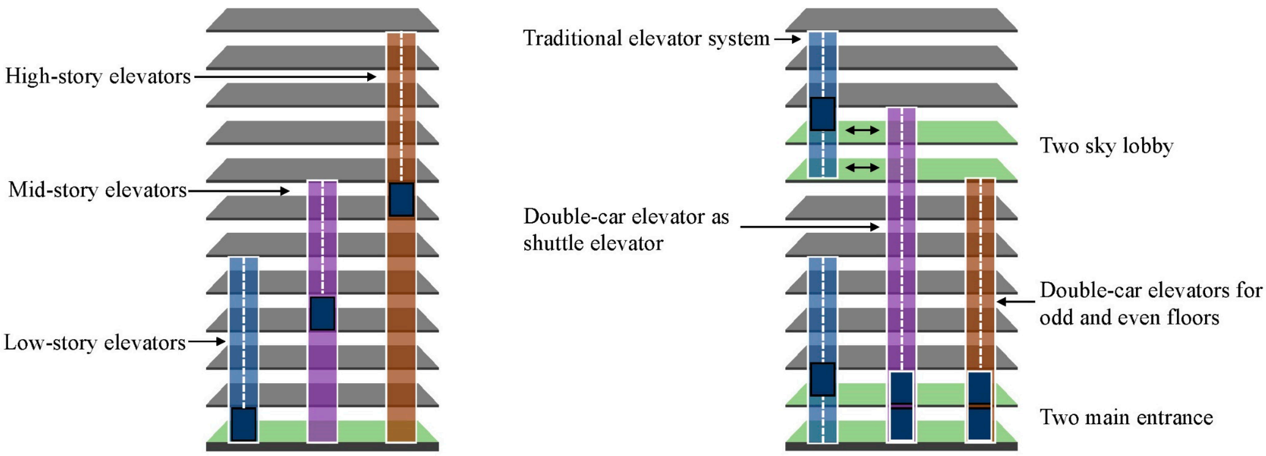


Figure 16. Schematic diagram of single and double-deck elevator system.

In MUHR buildings, service space and equipment requirements lead to changes in the core. From the statistical data, the service space such as restrooms in the core of the office space takes up 50–70 m^2, and the hotel and residential spaces have an increasing demand for supporting space and freight elevators. There are ten freight/fire elevators on the 69th to the 72nd floors of the Guangzhou International Finance Center. In the Guiyang International Financial Center, due to the layout of hotel and apartment spaces, two hotel elevators and two restaurant elevators were added on the 53rd to the 54th floors.

3.1.3. Structural Area

In order to study the structural area of MUHR buildings, the structural area was divided into the peripheral column area and the core area, which facilitated the calculation of the ratio of different structural designs to the building area. The structural area of each typical floor of MUHR buildings is quite different. The structural area of the peripheral column and that of the core show the same trend, which is as follows: the higher the building, the larger the structural area. In the eight high-rise buildings, the structural area decreased with the number of floors, as shown in Figures 17 and 18.

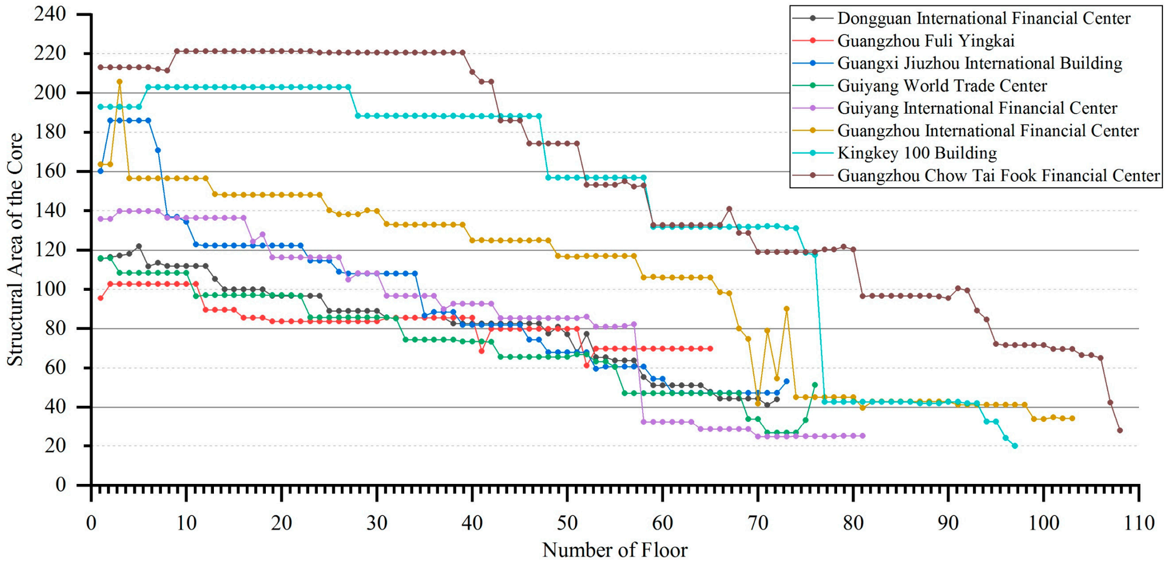


Figure 17. The structural area of the core.

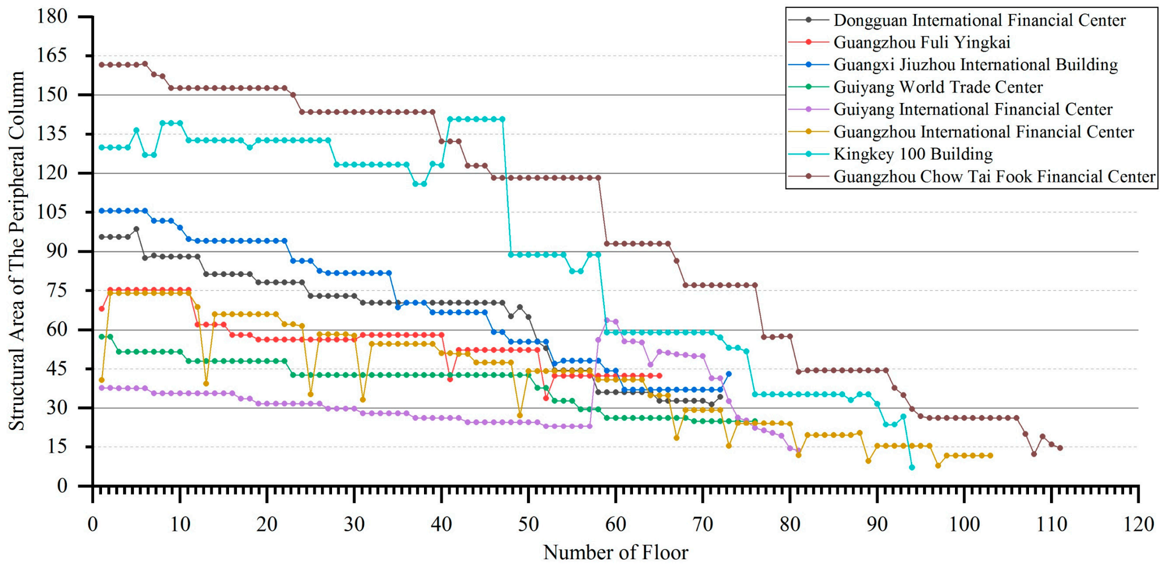


Figure 18. The structural area of the peripheral column.

The structure not only determines the economic, rationality, and safety aspects of the building, but also directly affects the comfort of each business area in the MUHR building. In the Guangxi Jiuzhou International Building, the hotel is located in a low-zone area. The size of the peripheral column of the hotel is 700 mm, while that of the office space on the 66th floor is only 450 mm. The peripheral column affects the indoor lighting conditions of the hotel space, and the core affects the comfort of the public space. The Guangzhou International Finance Center uses a tube-in-tube system, where the outer tube is giant concrete-filled steel tubular columns with diamond-shaped oblique grids, and the inner tube is reinforced concrete. The bottom peripheral column is about 1790 mm in diameter, and it gradually decreases with the increase in height. In the design, the influence of the oblique grid outer column on the indoor lighting condition of different business types needs to be fully considered. Moreover, when designing the night lighting effect of the outer column, it is necessary to consider its impacts on the hotel guests, as detailed in Table 7 and shown in Figure 19.

Table 7. Dimensions of structural components of Guangzhou International Financial Center.

Structure	Office-I (4F)	Office-II (24F)	Office-III (44F)	Office-IV (64F)	Hotel-I (70F)	Hotel-II (98F)
Total structural area of the typical floor	230.54 m^2	209.63 m^2	172.36 m^2	140.91 m^2	70.96 m^2	52.98 m^2
Total structural area of the core	156.44 m^2	148.14 m^2	124.85 m^2	106.09 m^2	41.75 m^2	41.23 m^2
Structural area of the peripheral column	74.10 m^2	61.49 m^2	47.51 m^2	34.82 m^2	29.21 m^2	11.75 m^2
Number and size of columns	30/1790 mm	30/1609 mm	30/1407 mm	30/1204 mm	30/1104 mm	30/702 mm
Thickness of the outer shear wall of the core	1100 mm	1000 mm	800 mm	700 mm	300 mm	300 mm
Thickness of the inner shear wall of the core	600 mm	600 mm	600 mm	600 mm	600 mm	600 mm
Ratio of structural area to typical floor area	8.31%	6.88%	5.74%	5.33%	2.86%	3.83%

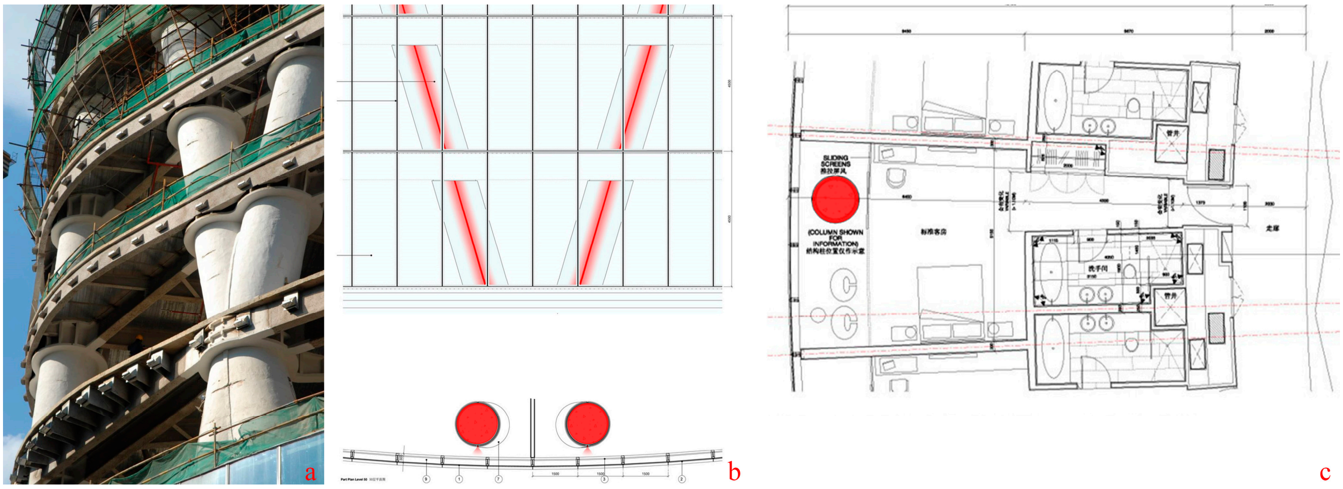


Figure 19. Diagram of the peripheral columns of Guangzhou International Financial Center. (**a**) Photos of construction site; (**b**) Schematic diagram of night light; (**c**) Location of structural columns.

3.1.4. Variation of Typical Floor Core Area and Utilization Rate (k_1)

(1) According to the division of the typical floors of MUHR buildings, the typical floors and cores are designed in a unified and coordinated manner in different buildings in line with the business combination mode. The typical floor and core of different cases show a uniform form of variation (Figure 20), with the following main types: Dongguan International Financial Center, Guiyang International Financial Center, and Kingkey 100 Building. As the building height increases, the demand for the core decreases. The partial space of the core forms an atrium, which provides a high-quality public space for the lobby or conversion level of the hotel and apartment. For example, in the Guiyang International Finance Center, the traffic flow of hotel guests and apartment residents is organized through the lobby on the 53rd floor. The 53rd to the 55th floors with a large lease span is equipped with the hotel's service lobby, dining space, swimming pool, and other supporting service spaces. The core of the typical floor above the 55th floor is split to form an atrium, the building shape is gradually reduced, and the typical floor area decreases to meet the needs of hotels and residential space. Figure 21 and project drawings show that the k_1 value is improved through different designs and reasonable structural changes. In the Guangzhou International Finance Center project, the area of the typical floor decreases as the number of floors increases. Through the conversion of the core structure, three small cores are formed.

A high-quality hotel lobby can also be formed at the conversion level. At the same time, the public corridor space of guest rooms is more suitable in scale. Moreover, the core structure conversion can make use of the natural light from the roof of the building to form a bright, comfortable, and energy-saving public space. The core area of the hotel space in the Guangzhou International Financial Center reduced to one-third of that of the office space, and the utilization rate of the hotel space increased to more than 80%, as shown in Figure 21. Therefore, a reasonable core design and vertical traffic organization gradually increase the utilization rate of the hotel space compared to that of the office space. In other projects, a gradual shrinkage or reduction in the core is more often used. For example, due to the relatively low heights of the Guangzhou Fuli Yingkai and the Guangxi Jiuzhou International Building, the relationship between the lease span and business type is mainly coordinated through the building shape and core. A statistical analysis of the eight buildings' typical floor and core designs was carried out to provide references for future design, as shown in Figures 20 and 21.

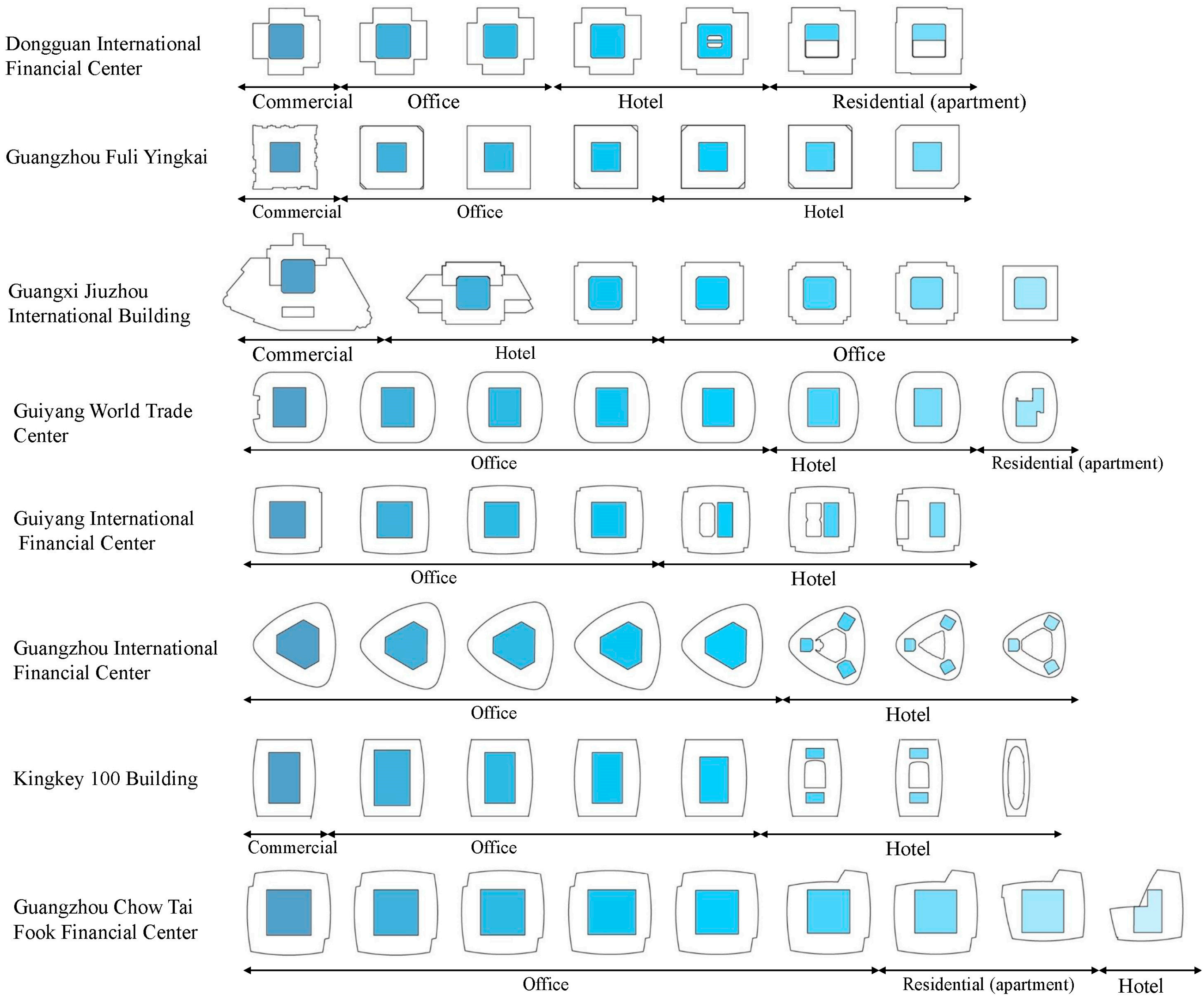


Figure 20. Typical floors division.

(2) When calculating the utilization rate of the typical floors, it was found that the utilization rate in the eight buildings fluctuated in the range of 65 to 80%, as shown in Figure 21. General service space accounted for 3–5% of the typical floor area.

Restrooms, storage, and equipment account for 3–5%, equipment space accounts for 8–12%, and public walkways account for 12–18% of the typical floor area. Due to the small sample size, only data statistics were included, and no graphs were included in the paper.

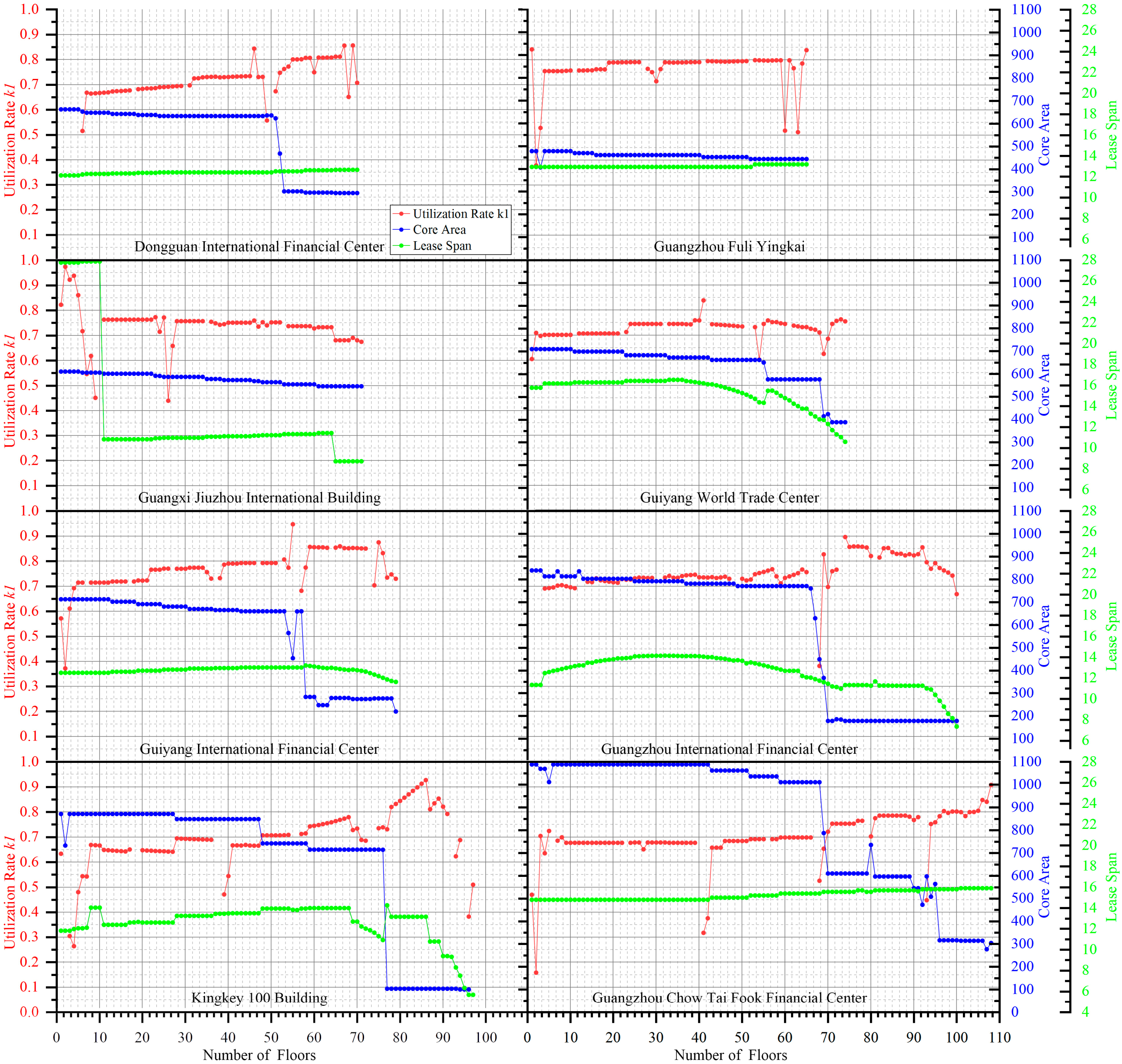


Figure 21. Relationship between the typical floor utilization rate k_1, core area, and the lease span.

(3) Except for the Guangxi Jiuzhou International Building, the typical floor utilization rate k_1 of all other buildings in this study showed an upward trend. Although the typical floor area of the low-zone area is large, the core carries the demands for the elevator system, structure, and equipment shafts from the high-zone area. In addition, the higher the building, the larger the demand, and the higher the ratio of the core area and traffic area. Therefore, the utilization rate of the low-zone area is low. For example, the low-zone office space (the 5th to the 21st floors) of the Guiyang International Financial Center has a k_1 value of about 71.93%, the mid-zone office

space's (the 22nd to the 36th floors) k_1 value is about 77.03%, the high-zone office space's (the 38th to the 51st floors) k_1 value is 79.33%, and the hotel and residential space's (the 53rd to the 9th floors) k_1 value reaches around 85.32%. For the Guangxi Jiuzhou International Building, as mentioned above, the hotel area was located below the office area. It can be clearly seen from the data that the typical floor and core area of the hotel area were larger than the buildings with a similar height. As a result, the typical floor utilization rate k_1 showed a decreasing trend, as shown in Figure 21.

(4) The data shows that the utilization rate of the lobby area and the business conversion floor is relatively low. To meet the demands of different business and vertical traffic and improve spatial quality, two lobbies (in the 7th, 8th, 41st, and 42nd floors) are set up in the office space of the Guangzhou Chow Tai Fook Financial Center, and the utilization rate is only 37%. In the hotel space (the 93rd to the 95th floors) there are supporting service spaces, the utilization rate on the 93rd floor is 44%, and the remaining space is mainly equipment space and public service supporting space. The fluctuation of the utilization rate demonstrates the difference between MUHR buildings and single-use models, as shown in Figure 21.

3.2. Quantification of the Business Utilization Rate and Related Indicators

3.2.1. Business-Related Area Indicators

MUHR buildings typically have two or more business types. In the Kingkey 100 Building, the office is the dominant business format, with a construction area of about 165,000 m^2, accounting for about 76% of the total area. In the Dongguan International Financial Center, three business types are similar in scale. The office space is about 39,000 m^2 (29%), the hotel space is about 50,000 m^2 (37%), and the residential space is about 40,000 m^2 (30%). Statistically speaking, the office is the main business type in the MUHR buildings. The higher the building, the larger the proportion of office space. The hotel and residential spaces are mainly determined by commercial positioning and market factors. The data show that the difference between the hotel and residential spaces is small. In addition, regarding the lobby area on the first floor, it was found that the larger the building area, the larger the lobby area. The largest lobby area on the first floor is nearly 1700 m^2. The lobby area of MUHR buildings accounts for 2–3% of the total area of the business type, which is much higher than that of high-rise office buildings, as shown in Figure 22.

3.2.2. Variation of the Business Utilization Rate (k_2)

The business utilization rate k_2 is derived from k_1. There are differences in the business utilization rate of the MUHR buildings in this study. The utilization rate of the hotel space is 70–85%, while the utilization rate of the office space is in the range of 60–80%, as shown in Figure 23. From the trend of the curve, it is clear that in the buildings that are lower than the Guiyang World Trade Center, the utilization rate of the office space is higher than that of the hotel space.

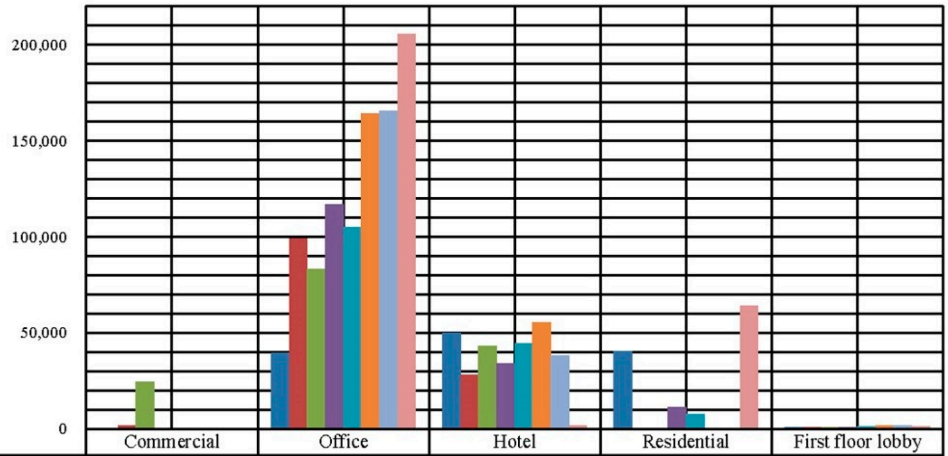
3.2.3. Correlation between the Business Area and the Business Utilization Rate k_2

As mentioned previously, office space is the main business type in MUHR buildings. In the eight buildings investigated in this study, the scale of office spaces was different. From the previous section, the larger the scale of the building, the larger the scale of office spaces. However, according to the relationship between the building area of the office and the business utilization rate k_2, although the larger the scale of office spaces, the larger the building area and rentable area of the office, the business utilization rate k_2 of the office is decreasing, as shown in Figure 24. By analyzing the correlation between the scale of the office space and the business utilization rate k_2, a significant negative correlation ($p < 0.05$) is evident, as detailed in Table 8. Therefore, although the typical floor area of a building with a large office space is relatively large, there are high demands of different business types for the lease span, vertical transportation systems, structural systems, shafts, and supporting service spaces, which lead to a decrease in the overall utilization rate.

Table 8. Correlation between business indicators and the business utilization rate k_2.

		Business Utilization Rate (k_2)	Building Area of Office Space
Business Utilization Rate (k_2)	Pearson correlation	1	−0.750 *
	Sig. (two-tail)		0.032
	Number of buildings	8	8
Building Area of Office Space	Pearson correlation	−0.750 *	1
	Sig. (two-tail)	0.032	
	Number of buildings	8	8

* Significant correlation ($p < 0.05$, two-tail test).



	Commercial	Office	Hotel	Residential	First floor lobby
Dongguan International Financial Center	0	39,380	50,167	40,201	931
Guangzhou Fuli Yingkai	1791	98,915	28,103	0	936
Guangxi Jiuzhou International Building	24,279	83,108	43,140	0	1020
Guiyang World Trade Center	294	116,879	33,820	11,421	940
Guiyang World Financial Center	0	104,778	44,530	7502	1187
Guangzhou International Financial Center	0	164,164	55,377	0	1727
Kingkey 100 Building	196	165,335	38,044	0	1629
Guangzhou Chow Tai Fook Financial Center	355	205,650	1964	63,892	1268

Figure 22. Statistics of the area of different business types (in m^2).

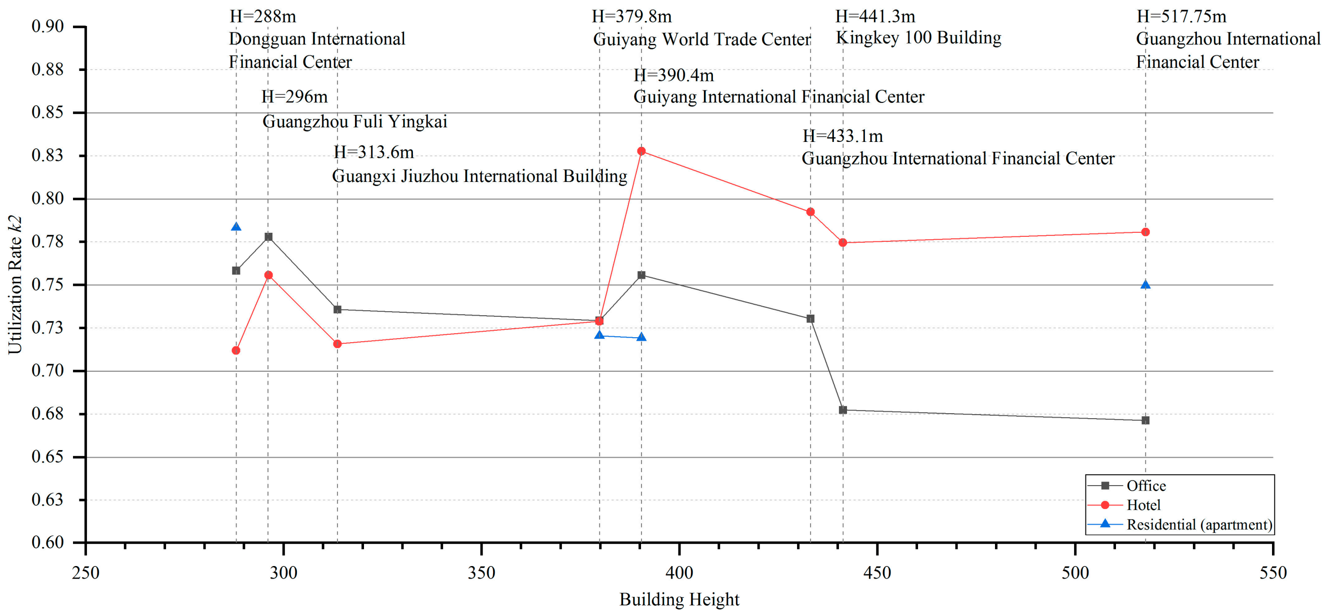


Figure 23. The business utilization rate k_2.

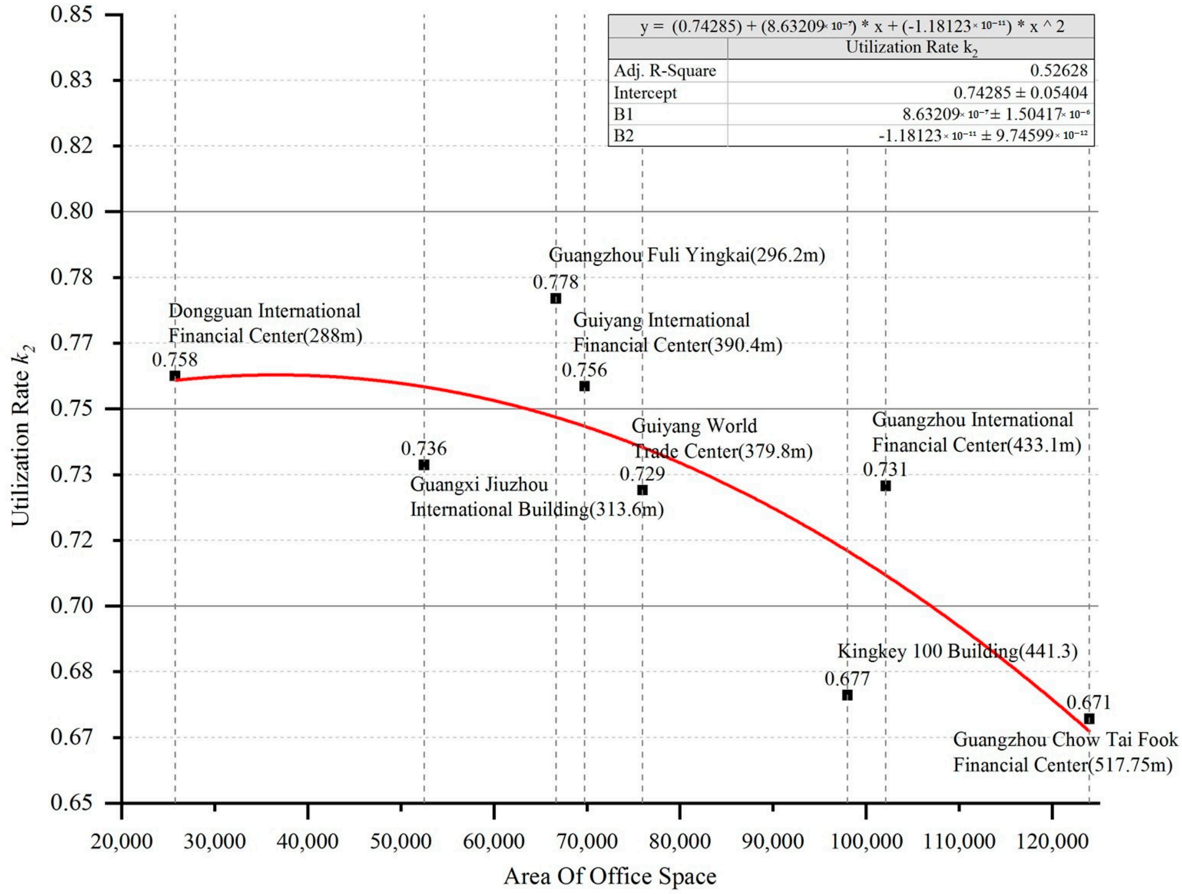


Figure 24. Relationship between the building area of office space and the business utilization rate k_2.

3.3. Quantification of the Building Utilization Rate and Related Indicators

3.3.1. Building-Related Area Indicators

The building floor area and the rentable area increased as the building height increased. The Guangzhou Chow Tai Fook Finance Center, which has the largest scale of the eight buildings, has a building area of 360,000 m^2, and a rentable area of over 200,000 m^2. The Guangzhou Fuli Yingkai, the smallest scale building, has a building area of 140,000 m^2, and a rentable area of over 86,000 m^2, as shown in Figure 25. In addition, the difference between the building area and the rentable area showed an upward trend with the increase in the building height, suggesting that the non-usable area increased with the scale and height of the building, which largely impacted the utilization efficiency, as shown in Figure 25.

3.3.2. Variation of Building Utilization Rate k_3

The building utilization rate k_3 of the buildings in this study was between 60% and 72%, which was significantly lower than the average values for k_1 and k_2, as shown in Figure 26. Refuge and equipment floors are included in the calculation of the building utilization rate. Since MUHR buildings are densely populated, emergency evacuation preparation is very important. Different business types have different population density and space characteristics. Taking the Dongguan International Finance Center as an example, the average height of each floor is within the range of 3.5–4.2 m. For buildings with more than 70 floors, assuming the average number of people on each floor is 100 to 150, then the total population in a building ranges from 7000 to more than 10,000. During evacuation procedures, people use the stairs with an average walking speed of 0.225 m/s, and thus, it is estimated that it takes about 10–15 s to go up or down one floor. Delayed evacuation in emergencies can present dire threats, such as toxic fumes in the event of a fire. Therefore, more refuge floors (rooms) are set up for larger-scale buildings, which will lead to a low overall efficiency value, as shown in Figure 27.

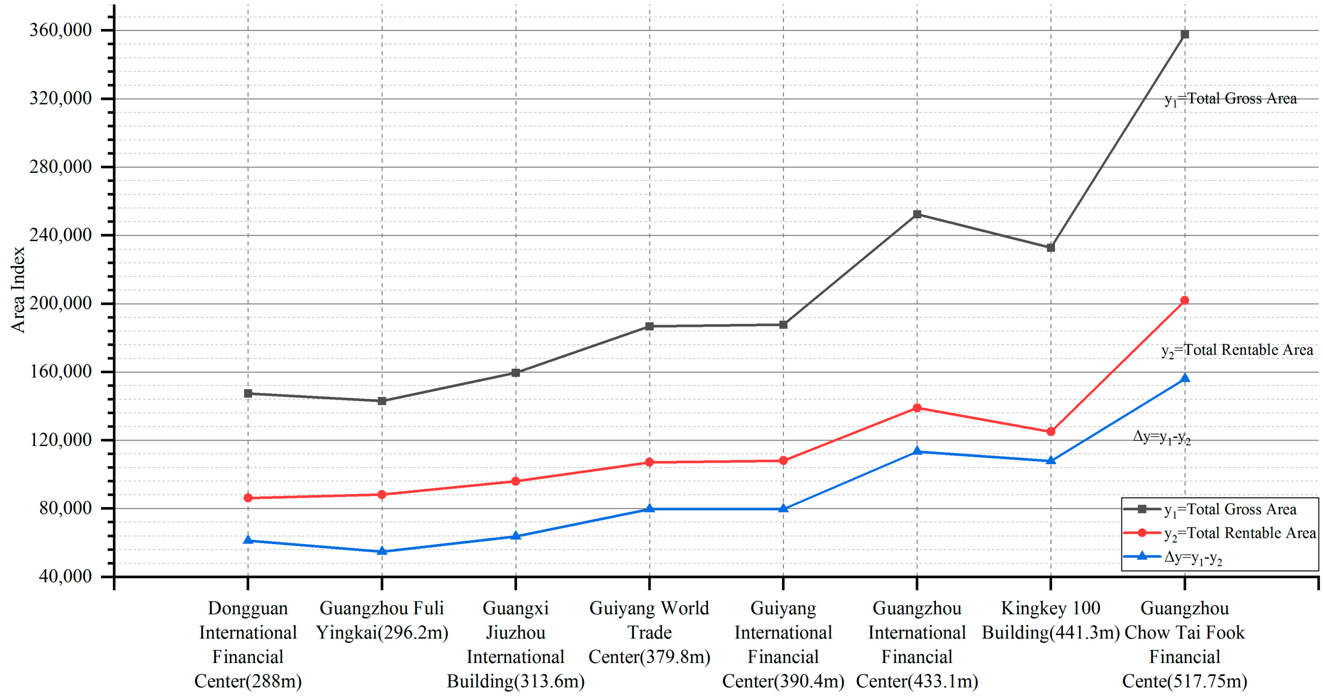


Figure 25. Comparison of building area and rentable area of the eight buildings.

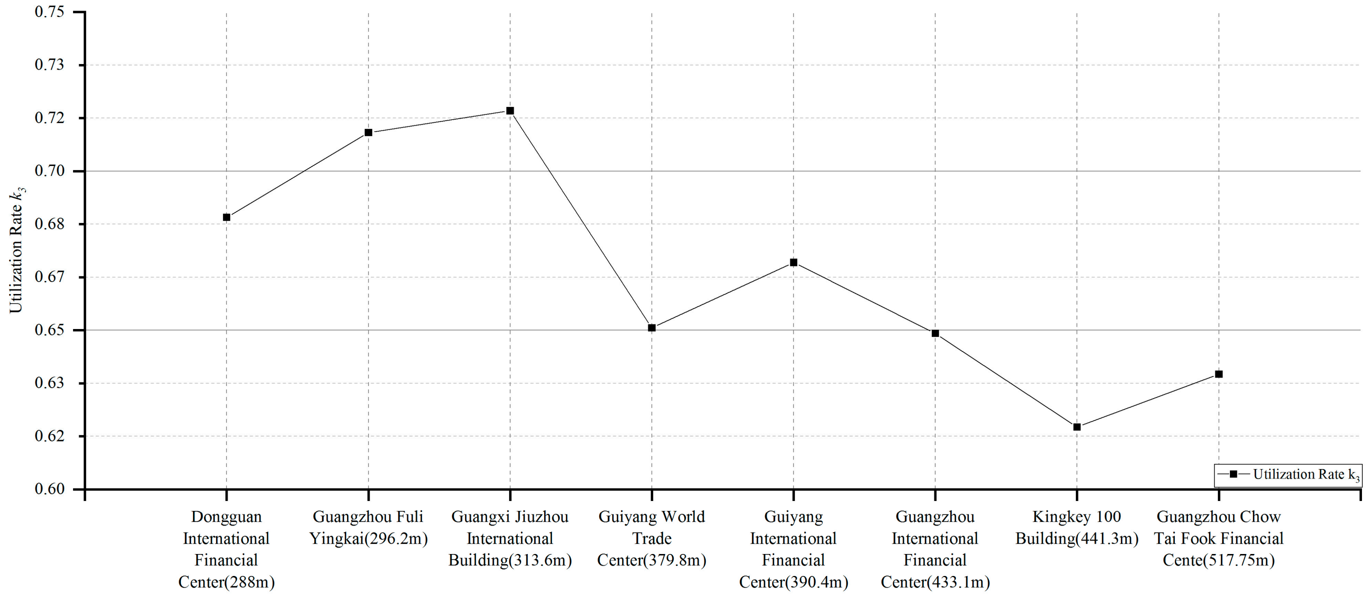


Figure 26. Building utilization rate k_3.

3.3.3. Building Height and Total Gross Area and their Correlations with the Building Utilization Rate k_3

From Figures 28 and 29, it can be seen that the higher the building, the smaller the building utilization rate k_3. The building height and the building utilization rate k_3 showed a significantly negative correlation ($p < 0.01$), and the total gross area and the building utilization rate k_3 had a significantly negative correlation ($p < 0.05$), as detailed in Tables 9 and 10.

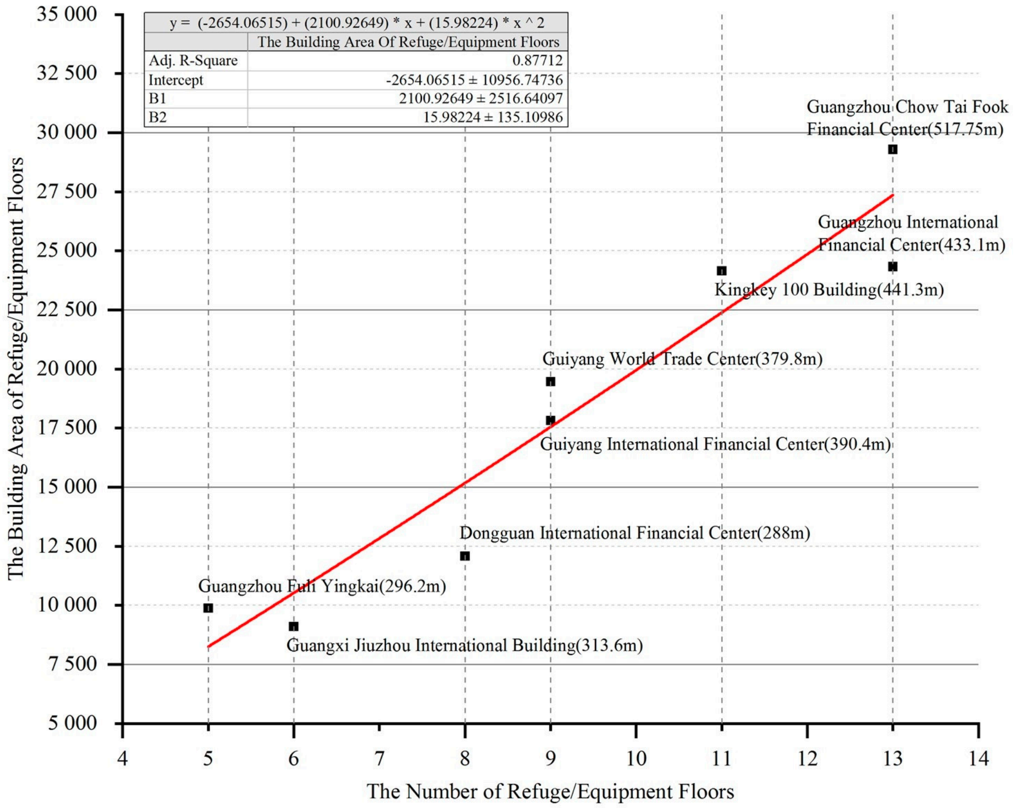


Figure 27. Relationship between the number of refuge/equipment floors and the building area of refuge/equipment floors.

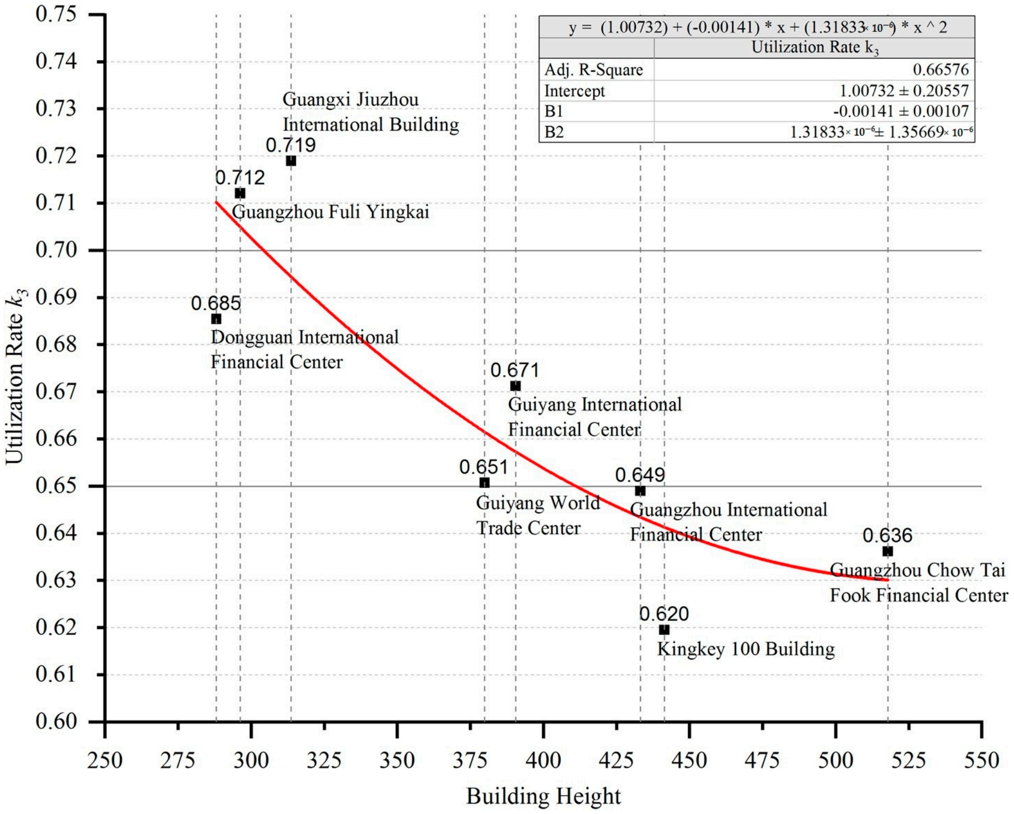


Figure 28. Relationship between building height and the building utilization rate k_3.

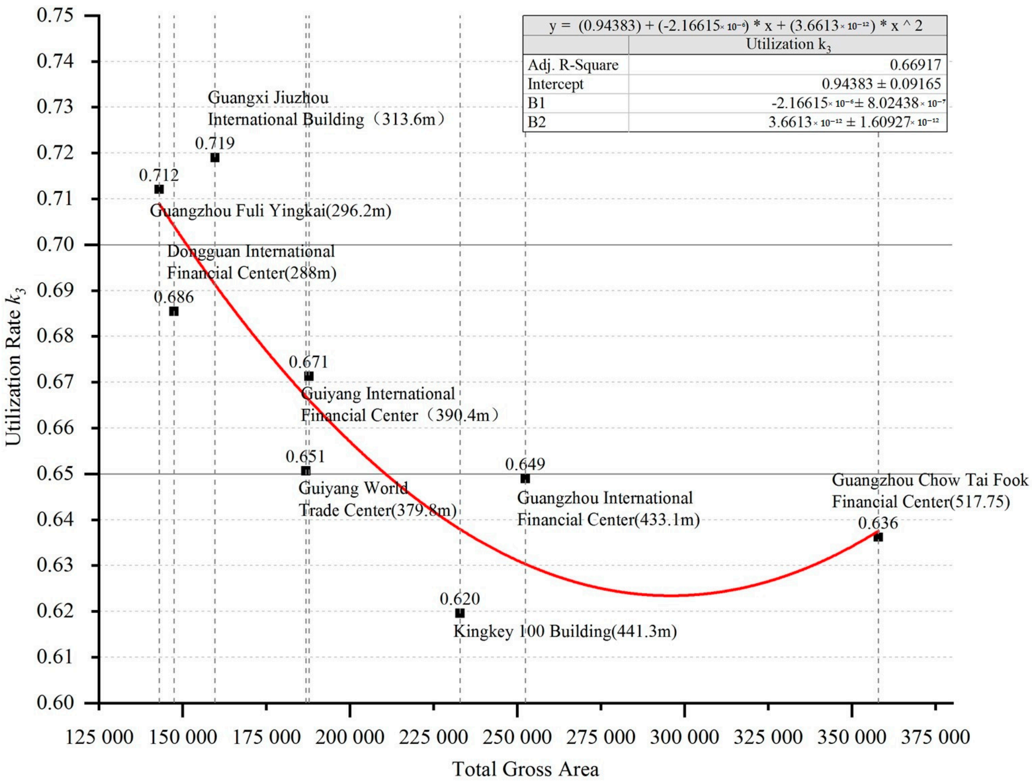


Figure 29. Relationship between total gross area and the building utilization rate k_3.

Table 9. Correlation between building height and the building utilization rate k_3.

		Utilization Rate k_3	**Building Height**
Utilization Rate k_3	Pearson correlation	1	−0.839 **
	Sig. (two-tail)		0.009
	Number of buildings	8	8
Total Gross Area	Pearson correlation	−0.839 **	1
	Sig. (two-tail)	0.009	
	Number of buildings	8	8

** Significant correlation ($p < 0.01$, two-tail).

Table 10. Correlation between total gross area and the building utilization rate k_3.

		Utilization Rate k_3	**Total Gross Area**
Utilization Rate k_3	Pearson correlation	1	−0.720 *
	Sig. (two-tail)		0.044
	Number of buildings	8	8
Total Gross Area	Pearson correlation	−0.720 *	1
	Sig. (two-tail)	0.044	
	Number of buildings	8	8

* Significant correlation ($p < 0.05$, two-tail).

4. Conclusions and Limitations

4.1. Conclusions

In the present study, a multi-dimensional, hierarchical quantification system on the utilization rate of MUHR buildings was established, and the variation of the utilization rate of MUHR buildings and related indicators were analyzed from three levels, as well as the characteristics of MUHR buildings. This method added to the tools available to study the utilization rate of MUHR buildings.

(1) First of all, the data of typical floor area, core area, and other indicators show that the typical floor-related indicators of mixed-use supertall buildings are in a dynamic process of change. This is not only influenced by the change of building form but also by a variety of internal factors, including structural load, vertical traffic demand, and change in business function. The findings of the study, such as the range of values and the variation pattern of the indexes, provide a valuable reference for designers of mixed-use supertall buildings for the first time and help them to better understand this type of building and improve the utilization rate of the building through rational design. Consider a 5000 sq ft of rentable space, representing a 1 percent increase in a 500,000 sq ft building. At a lease cost of $20 per sq ft, over the 20 years life, the additional income to the building owner would be $2,000,000 [29]. Secondly, after analyzing the quantitative data of vertical traffic, it was found that the actual situation of mixed-use supertall buildings can be somewhat different from the commonly used design guidelines. For example, through the calculation of actual cases, it was found from the case that the ratio of floor area to the number of passenger elevators in the office business was greater than the number of elevators, and the main technical parameters in the *Design code for office building*, which is often referred to by designers were analyzed. There are two main reasons for this. On the one hand, the standards and codes such as "Design code for office building" are only suited to the type of office business and do not consider the actual impacts of building height and building technology. On the other hand, the vertical traffic in super high-rise buildings is usually systematically calculated and designed by professionals, including the selection of double car elevators, the elevator speed, integration with the transition level, etc. This is the result of a comprehensive consideration and finally allows for the elevator system to meet the needs of the users. If the design is only designed according to the standard of *Design code for office building* in the scheme design stage, it will undoubtedly add more elevator tube shafts. This conclusion not only reflects the lack of relevant design standards in China but also points out the design key points and difficulties of mixed-use supertall buildings. It reminds designers to pay more attention to the complexity brought by the height and mixed mode of mixed-use supertall buildings, and all these data indicators bring accurate and efficient reference data to the building design process. Finally, through the horizontal comparison of the utilization rate k_1 of the standard floor and related indexes in eight cases, it can be clearly seen that the indexes of the area of the standard floor, the utilization rate k_1, and the depth of the building have the same change law in different cases (except Guangxi Jiuzhou International Building). At the same time, after analyzing the vertical combination pattern of the business mode of Guangxi Jiuzhou International Building, it became clear that the unreasonable vertical layout of business modes greatly influences the usage rate. After consulting with the person in charge of the project, we learned that the reason this is the rash decision of the developer in the design of this scheme. The authors also hope that the findings of this study can provide better guidance for decision makers.

(2) The business utilization rate k_2 and tower utilization rate k_3 were calculated from the basic data of the typical floor utilization rate k_1 study. Firstly, as mentioned above, the statistics of different cases, business types, tower utilization rates, and related data indicators can provide a high-value reference basis for designers who first encounter mixed-use super tall buildings. Secondly, after the k_2 calculation and data analysis of the utilization rate of office business, it was found that there is an obvious negative correlation between the utilization rate of a business and the floor area of a business. The larger the total area of the office business, the higher the demand for the vertical transportation system, structural system, pipe well, supporting service space, and so on. Under the demand of a high-quality space depth of office business, the utilization rate of the office business will always decrease. Using the tower utilization rate k_3, it was found that the number of equipment rooms and refuge floors in higher-tiered

projects is higher, and the usable area of the business space is constantly compressed. The balance between these supporting areas is the complexity of mixed-use super high-rise buildings, which is also a difficult design point. How to improve the utilization rate through good coordination in terms of building and structure, equipment, and the reasonable arrangement of vertical traffic is an urgent issue to be solved in future research. In addition, the lowest point value appears in Figure 29. Does it mean that there exists a minimum value of floor area and utilization rate k_3? This is a very valuable study. However, at present, due to the limited research sample, it is not possible to fully present this conclusion, and follow-up studies are required to confirm this conclusion.

(3) The research method and findings of this paper on stratified quantification effectively verify that the existing calculation method of the utilization rate is not applicable to the study of the utilization rate of mixed-use supertall buildings, and reflect the advantages and purposefulness of this method. Although the statistical data take longer to obtain and the workload is larger, the precise index of stratified data can better reflect the characteristics and rules of mixed-use super high-rise buildings and proposes a new research perspective for this building type. It is expected that as my team and I accumulate practical projects and incorporate more excellent cases, we will be able to increase the scientific validity of the research findings and present clearer data-based conclusions so as to promote the sustainability of mixed-use supertall buildings.

In recent years, some construction projects have deviated from the actual demand, and rather have pursued building height or peculiar shapes, resulting in high construction costs and energy consumption. This is the reason why the study began from the perspective of the building utilization rate. The conclusion of the study clearly suggests that it is misguided to pursue building height. In the development of mixed-occupation super high-rise buildings, the party, the government, and the architect should seek a reasonable scale of business and the vertical combination of business according to the market demand, so as to achieve a highly efficient development mode. In the design and construction of MUHR buildings, modern development concepts need to be implemented, and status or aesthetic value should not be pursued alone. Instead, the process should be scientific, intensive, efficient, and humanized, pursuing spatial quality in the design, and improving the utilization rate of typical floors of different business types through cooperation between the building, structures, and equipment, and through a reasonable arrangement of vertical traffic, thereby improving the overall quality of MUHR buildings.

4.2. Limitations

This study has potential limitations, as follows:

(1) In this study, the emphasis was on MUHR buildings with a height of over 250 m. Such buildings are usually important projects for the city and design institutes, and the relevant data are protected. The data of the eight buildings used in this study were those from projects the authors have been involved in recent years. Due to the long construction period of mixed-use super high-rise buildings and the limited number of studies, the sample size was small, and a reference range for the efficiency indicators could not be provided.

(2) China's high-rise building regulations have changed in recent years. The cases in this study implemented different fire codes during their design phase. The main regulations include "Code for Fire Protection Design of High-Rise Civil Buildings" and "Code for Fire Protection Design of Buildings". Currently, the standard fire protection code in China is the "Code for Fire Protection Design of Buildings" (GB50016-2014), which was implemented on 1 May 2015, and the "Code for Fire Protection Design of High-Rise Civil Buildings" (GB50045-95) was terminated at the same time. Changes in fire regulations can lead to certain fluctuations in some research indicators.

(3) MUHR buildings are key urban development projects, and each city has different land and real estate policies and regulations, which will influence the indicators such as development intensity, zone height, and building height.

These elements have a great influence on the design of super-tall buildings, thus also limiting case selection. To avoid these effects, the cases in this study were designed using the same code. Meanwhile, the geographical locations of these projects were not areas such as seismic zones. Therefore, the cases studied in this paper have certain generality, which greatly enhances the comparability of the study data across the studies.

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