International Journal of High-Rise Buildings
June 2018, Vol 7, No 2, 153-159
https://doi.org/10.21022/IJHRB.2018.7.2.153

International Journal of
High-Rise Buildings
www.ctbuh-korea.org/ijhrb/index.php

The Preliminary Research on the Relationship between Carbon Emissions and Typical Floor Design of High-Rise Office Buildings in Shanghai

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Abstract

The greenhouse effect caused by human activities is becoming increasingly serious. The building industry, which is directly related with carbon emissions, has the responsibility and potentiality to reduce carbon emissions. Recently, Chinese and foreign academics have achieved some research results with respect to building carbon emissions. This paper tries to examine these issues in the context of climate conditions in the Shanghai area. Based on the typical floor plans of high-rise office buildings, analysis was performed via software simulation and data analysis; the paper explores the relationship between different design methods of typical floor plans and carbon emissions. The objective is to deliver results beneficial to typical floor-design methods with respect to the reduction of carbon emissions, so as to provide a reference for architects.

Keywords: High-rise office building, Typical floor, Plane layout, Carbon emissions

In recent years, with the rapid progress of Chinese urbanization, the country has recorded the largest construction volume in the world. However, huge construction volume and a sometimes haphazard development model conspire to make China's building industry highly energy- and resource-consumptive. As based on the Intergovernmental Panel on Climate Change's (IPCC's) fifth estimated report, the building industry possess a great potential ability to meaningfully reduce global carbon emissions, starting with the fact that it is already a huge contributor to those emissions. By 2030, the building industry will have potential ability to reduce CO_2 volume that could highly 50-70 billion metric tons.[1] In order to capitalize on the potential for carbon reduction, first, the building industry must reduce carbon emissions of buildings in the process of their construction and operation through reasonable design. This paper focuses on high-rise office buildings and researches the relationships between their typical floor design and carbon emissions, so as to provide references for architects.

1. Research Target

The typical floors of high-rise office buildings have been chosen as the research targets for several reasons.

Firstly, the development of high-rise office buildings is an adaptation to land shortages in urban areas, which improves the efficiency of society and urban land usage. In recent years, high-rise (24 meters -100 meters) and super-high-rise (>100 meters) buildings have been rapidly developed in China; many Chinese cities have formed a central business district (CBD) characterized by high-rise buildings, and the number of high-rise buildings over 250 meters exceeds that of any other country.[2]

Secondly, high-rise buildings will consume more energy than those of other multi-story buildings in the process of construction and operation; the energy consumption of super-high-rise office buildings can reach 6-8 times that of common public buildings. Most of the energy in building operations is consumed by heating, ventilation and air conditioning (HVAC) systems, followed by lighting. Other factors (such as elevators, etc.) generally account for only a small part of energy consumption during operation. High-rise office buildings often use glass curtain walls for their facades, which have congenital deficiencies as building envelopes, in terms of thermal performance.[3] Therefore, researching how to reduce energy consumption on high-rise buildings will have practical significance.

Thirdly, high-rise office buildings generally have few functions, with every basic typical floor being extruded from the one below. Therefore, it is easier to carry out and extrapolate the research work by using the typical floor of high-rise office buildings as the subject.

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2. Research Method

2.1. Measuring of Building Carbon Emissions

Low-carbon buildings can be defined as having low energy consumption, low pollution and low emissions. In so doing, the building could minimize greenhouse gas emissions and provide people with reasonable comfort through its whole life cycle.[4] Most scholars believe that the measurement of building carbon emissions should adopt the theory of "whole life cycle," calculate the carbon emissions from building material production, construction, operation, and maintenance, through to final dismantling, and evaluate the impact of building on the environment from "cradle to grave."

The industry-standard design life of a general building (including high-rise office building) is 50 years in China. The operation and maintenance stage of the building is the longest in whole life cycle, and carbon emissions during these two stages are the highest. For high-load operational office buildings, the building carbon emissions during the operation and maintenance stages represent 83% of emissions in its whole life circle; for a low-load office building, the figure is 75%.[5] Therefore, in order to simplify calculation, and meanwhile consider data shortages, many studies (including this paper) are dedicated to measurement and via simulation of carbon emissions in buildings' operation and maintenance stages.

2.2. Low-Carbon Computing Tools

This paper uses imitative methods of computer software, through Revit modeling and Autodesk Green Building Studio (GBS) energy consumption simulation software, to study the original data of carbon emissions caused by different design methods of typical floors in high-rise office buildings.

Green Building Studio is a flexible cloud-based service that allows the designer to run building performance simulations to optimize energy efficiency and to work toward carbon neutrality earlier in the design process. It also may be productively integrated with the Revit application, which has seen heavily used by design departments recently. With Revit, researchers can build a building from simulation, and integrate this with the GBS platform. Through computing, the energy consumption report could be part of the feedback in the user interface. Meanwhile, by running the programs side by side, the results could be checked and compared simultaneously.[6]

Through analyzing effective elements related to building form, materials, systems, functions and local climate features, etc., Green Building Studio uses DOE (US Department of Energy) 2.2 dynamic imitation to analyze energy consumption and operational costs in the whole building.

The advantage of Green Building Studio is that it is the first platform in the market that can integrate Revit with whole information model. It enables architects and engineers to design buildings and analyze building performance in the same software. The Revit 2014 version fully breaks the obstacle between modeling and simulation. Revit 2014 also has the ability to model the thermal performance of building elements (walls, floors, and roofs), beyond simply analyzing the room's thermal performance. The statistical function of the software could conveniently summarize building materials' quantity and building area, and extract the data of building materials' carbon emissions from the database. The software can also delicately analyze the specific sources of energy consumption, and distinguish between energy consumption by lighting, water and air conditioning, etc. It even includes energy consumption of different parts inside building, so as to allow architects to carry out specific follow-up improvements.

2.3. Data-Processing Method

In the simulation, two-way analysis of variance (double factors, with no repetition test) is used to discuss the significance of the two factors on the experimental results; that is, by using two-binary analysis of variance. In the testing process, using various influencing factors to combine one with another, which may reduce test time, researchers discuss the change of carbon emissions under two factors, and compare their degree of influence. Through the data analysis function of Excel, the complex two-way analysis of variance (two-factor, no-repetition test) process can be simplified. Quick data processing and comparison can be carried out.

3. Basic Data

3.1. Basic Data of the High-Rise Building

This paper only researches plans of a typical high-rise floor. In order to compare easily, united data for the building's general height, floor height and number of floors are used. The basic data of high-rise buildings in this paper were collected by http://top.gaoloumi.com, the largest skyscraper forum in China. The key discussion of the forum focuses on countrywide high-rise constructions, including housing, commercial real estate, hotels, rail transit facilities, office buildings, etc. This website also provides basic data on high-rise buildings' construction stage, quantities, functions, height, area, etc., in China and abroad.

According to the website, 80% of the existing sealed roofs of high-rise office buildings are between 100-200 meters high; the average height is 169 m and median is 159 m.[7] This paper picks the median of 159 m as a fixed reference figure in imitating calculation of buildings' general height. The median typical floor height is 4.3m, and the median number of floors is 37. The window-wall ratio in high-rise office buildings is 50%, and the opening-area ratio for ventilation is 5%.[8]

3.2. Specific Detail Design and Parameter Data

In order to avoid different detail designs of building envelopes that may cause differences for carbon emissions, the paper uses unified detail design for walls, roofs, floor slabs and ground. The data references are mainly originated from relevant local and national codes, including *Code for Design of Civil Buildings (GB50352-2005), Design Code for Heating Ventilation and Air-Conditioning of Civil Buildings (GB 50176-2016), Code for Fire Protection Design of Buildings (GB50016-2014), Design Code for Office Buildings (JGJ 67-2016), The Technical Evaluation Guidelines for Green Super-High-Rise Buildings (SRIBS (2012) No. 76).*

3.3. Weather Data Parameters

Weather parameters are the basic data for simulation and calculation. Outdoor temperature, humidity, wind speed and frequency, and solar radiation will affect indoor heating, ventilation and lighting environment, directly affect equipment use, and thus affect the building energy consumption. Via Green Building Studio software, researchers automatically obtained Shanghai's weather information, and used it as a simulation parameter.

Table 1. The summary of the relationships between design elements for typical floor and carbon emissions per unit of floor area

Plane design elements for typical floor		Variation scope of data		Change situation of carbon emissions per unit of floor area			Explanation	Influence degree
Type	Design elements	Variation scope	Change	Trend of change	Amplitude of change	Inflection point		
Size of typical floor	L/W	0.8-1.8	L/W↑	↓↑	Slow, quick, slow	1.25	In the scope, carbon emissions per unit of floor area first fall slowly-- then fall quickly-- then rise slowly after the inflection point (1.25)	L/W > D
	D	11m-15m	D↑	↓	Quick, slow	13	In the scope, carbon emissions per unit of floor area first fall quickly -- then fall slowly	
Circulation core	Quantity	Single, double	Single core > Double cores				Lower effective degree	
	Eccentricity ratio for single circulation core	1-2.5; Side	E/e↑	↓↑	slow	1.7-2.1	In the scope, carbon emissions per unit of floor area first fall -- then rise slowly; When the circulation core is on the edge of the building, the carbon emissions are the highest.	Eccentricity ratio = D
	Eccentricity ratio for double circulation cores	1:1:1-1:2:1; Side	E:e:E↑	↑	Slow	-	In the scope, carbon emissions per unit of floor area rise slowly; When the circulation cores are on the edges of the building, the carbon emissions are the highest	Eccentricity ratio > L/W
Corner treatment	Type	Round angle, cut, re-entrant, double re-entrant angle	Round angle << cut angle < double re-entrant angle < re-entrant angle				Carbon emissions in round angle plane are much less than other ways	The corner treatment method > amending rate
	The corner amending rate γ_c	0.1-0.2	γ_c↑	↑↓	Slow	0.15	In the scope, carbon emissions per unit of floor area rise slowly-- then fall after the inflection point (0.15)	

Note1: ↑(rise): ↓(fall), ↓↑(fall first and rise after); ↑↓(rise first and fall after). Slow (relatively slow acceleration); quick (acceleration is relatively quick); — (no inflection point); < (effective degree lower than); > (effective degree higher than); << (effective degree much lower than).

Note2: L/W (length/ width); D (depth); E/e (eccentricity ratio for single circulation core); E:e:E (eccentricity ratio for double circulation cores); Side (The circulation core is located on the side of the building); γ_c (Corner modified ratio)

4. Research on the Relationships between Typical Floor Layout Elements and Carbon Emissions

Many factors are involved in the design of high-rise office buildings. This paper focuses on plan size, the location of the circulation core and plan corner treatment, trying to determine the relationship between typical floor design and carbon emissions through simulation and data analysis. Ultimately, this research hopes to provide references for architects in future practice.

4.1. Relationship between Plan Size and Carbon Emissions per Unit of Floor Area

The size of a typical floor can be shown by two parameters: length-width ratio (L/W) and depth (D). This paper defines the front side length of the plane as length (L) and the perpendicular direction to the core as depth (D) and to the opposite edge as width (W). Furthermore, it can be concluded that L/W is comparative ratio for building length and whole depth which can see Fig. 1.

4.1.1. L/W

According to the simulation, with L/W rising, carbon emissions per unit of floor area slowly fall when L/W is within the scope of (0.8, 1); quickly fall when L/W is within the scope (1, 1.2), and reaches its lowest point at 1.25. After that, carbon emissions per unit of floor area slowly go up, with L/W rising within the scope (1.25, 1.8).

South is a very important orientation in Shanghai region. When Length is rising, it means more space faces south and it is therefore easier to arrange natural ventilation and day lighting. But according to the simulation, carbon emissions per unit of floor area rise slowly instead of continuing to fall, while the L/W ratio is greater than 1.25. The reasons may be as follows:

Firstly, accepting the premise that typical floor areas do not change within the building, while L/W increases, the surface area of the building becomes bigger simultaneously, leading to a larger building shape coefficient, that can generate more energy consumption.

Secondly, due to greater height of high-rise buildings, wind stress on building surfaces is much stronger than those of ordinary multi-story buildings. Generally speaking, for the internal environment, a too-large surface area strongly increases wind penetration (especially by cold wind in winter) and energy consumption.

4.1.2. Depth

Here, the depth refers to usable space, rather than whole building. With depth increasing, carbon emissions per unit of floor area decline, and the slope of the descent softens. Within the scope of (11 m, 13 m), with depth increasing, carbon emissions decrease faster, so increasing depth is an effective way to reduce carbon emissions. In the scope of (13 m, 15 m), while depth keeps on increasing, carbon emissions keep on falling, albeit slowly.

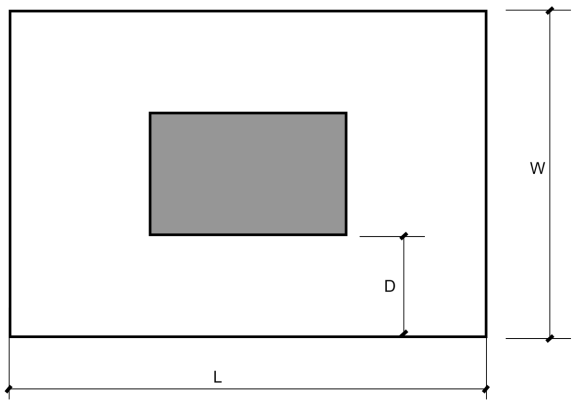

Figure 1. Typical floor plan of high-rise office building.

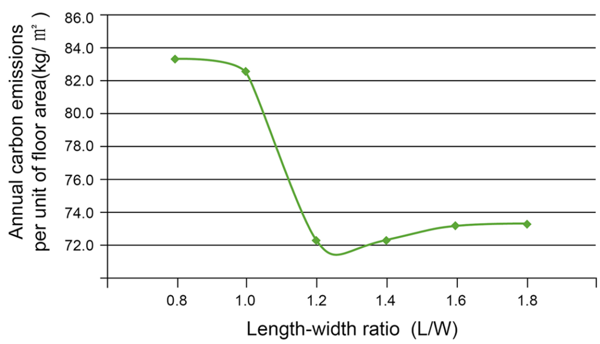

Figure 2. The effect of L/W on carbon emissions.

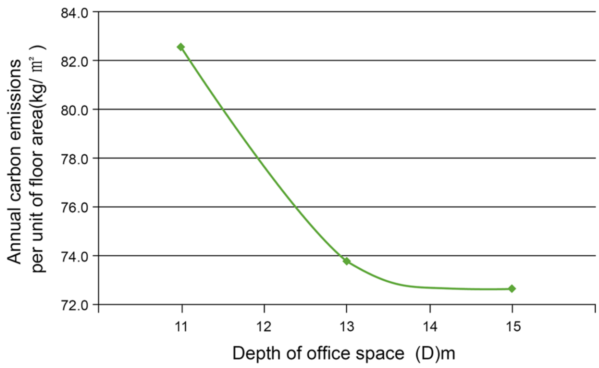

Figure 3. The effect of depth in office space on carbon emissions.

Increasing depth, of course, is detrimental to day lighting and natural ventilation, but it makes the shape of the building more compact and reduces the loss of heat. In general, increasing depth is still useful to reducing energy consumption.

When the depth is more than 13 m, and continues to increase, the downward trend for carbon emissions flatlines, so there is a strong disincentive to exceed this depth.

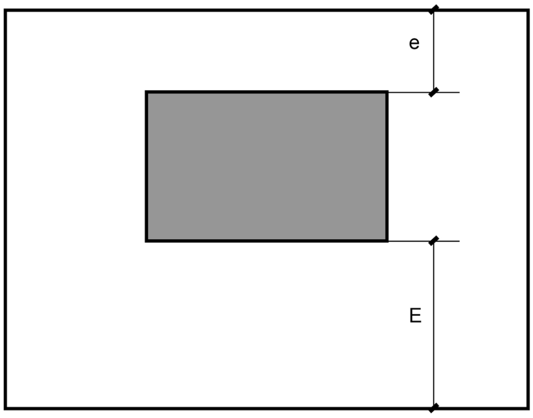

Figure 4. The diagram of eccentricity for a single core (Eccentricity ratio for single core in this paper is defined as E/e).

4.1.3. Comparison on Effective Degree

Through two-way analysis of variance, the conclusion could be reached that floor-plate depth (D) has an impact on carbon emissions. Particularly, the length-width ratio (L/W) has an obvious effect. The effective degree of two elements is L/W > D.

4.2. Relationship between the Circulation Core and Carbon Emissions per Unit of Floor Area

4.2.1. The Quantity of Circulation Cores

The study mainly compares a single circulation core with double circulation cores from the perspective of their impact on the release of carbon emissions. The simulation finds that using double circulation cores on a typical floor basically releases less than those using single cores. However, while further comparing specific emission figures, the gap between single and double cores for carbon emissions per unit of floor area does not reach 1 kg. Therefore, varying the number of cores has less impact on carbon emissions than varying floor plate depth.

4.2.2. Eccentricity for Single Cores

This case study shows that natural ventilation, daylighting, southern exposure, and usability of space would be main factors driving the location of a core nearer to the north side of a building, making the situation of E > e, in high-rise office buildings with single circulation core. This paper therefore concludes that the eccentricity ratio (E/e) has an effect on carbon emissions.

With the core situated off-center to the north, the proportion of south-facing office space has increased, so that daylighting and the thermal environment improve, and energy consumption can be reduced, which in turn reduces carbon emissions. After it reaches an inflection point, further displacement of the core to the north will cause the south-facing space to become too large and deep to take advantage of natural light or ventilation. The more lighting and ventilation rely on mechanical equipment, the higher the energy consumption. When e=0, that means, when the core is located on the building's northern side, generally, carbon emissions reach the high levels.

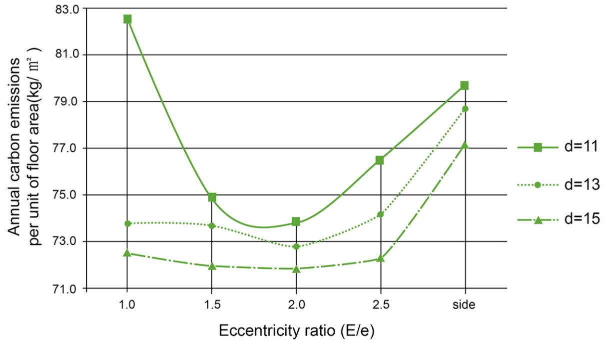

Figure 5. The effect of the eccentricity ratio of a circulation core on carbon emissions.

With the depth of office space expanding, the degree of change on the curve reduces. Comparing the slope of the curve at a floor-plate depth of 13 m, it is obviously shallower than at 11 m. However, the slopes when d = 13 m and d = 15 m are similar, implying that carbon emissions are more sensitive to the eccentricity of the core when floor plates are shallow, but as the depth increases, sensitivity is reduced. Accordingly, with increasing floor-plate depth, the external environment (daylighting, ventilation, thermal radiation, etc.) has less of an influence on indoor space, and gradually tends to stabilize, so that the rate of change is reduced. It can be seen via variance analysis, in this group of experiments, depth (D) affects carbon emissions, and has the same effect as the eccentricity ratio of the circulation core location (E:e).

4.2.3. Eccentricity of Double Cores

As the simulation study shows: generally, with a longer distance between two cores, carbon emissions show a slowly rising trend. Following the premise of E:e:E<1:2:1, the degree of change will be very low, and the annual carbon emissions per unit of floor area vary by 1 kg or less. Thus, the effect of eccentricity of double cores on carbon emissions is less.

When cores locate on the eastern and western sides respectively, and the office space locates in the middle, carbon emissions will suddenly rise. The reason is: if office space is located in the middle of typical floor, the energy required for lighting will increase. Moreover, inserting separations into office space is not conducive to natural ventilation and the use of a fan-driven fresh air system will consume more energy.

4.3. The Relationship between Corner Treatments and Carbon Emissions per Unit of Floor Area

With the use of light, high-strength materials, high-rise

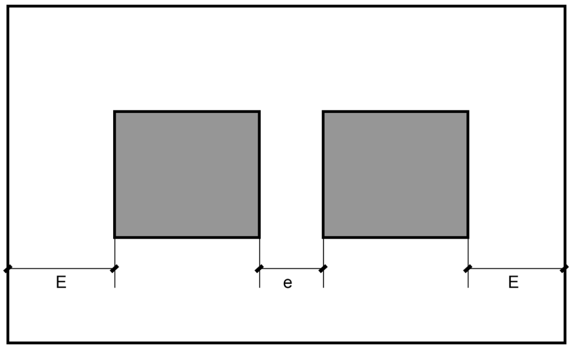

Figure 6. The diagram of eccentricity for double circulation cores (This paper defines the eccentricity ratio for double cores as E:e:E).

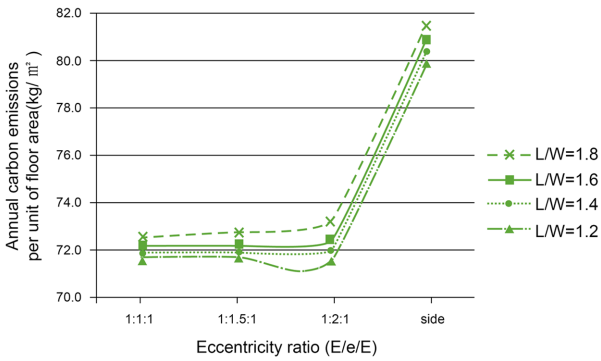

Figure 7. The effect on carbon emissions of changing the eccentricity ratios of double cores.

buildings are being developed to become increasingly flexible and require more damping, and will become more sensitive to wind influence. Thus, wind resistance is a key factor in structural design. There are three ways to divert wind and reduce vibrations: structural control, mechanical control and pneumatic control. The latter is achieved through a combination of architectural design and changing the building shape to reduce the wind load on the building's vertical surfaces and limiting the wind's effects. If using cut, re-entrant, rounded, etc. as the method of modified corner treatment, it is possible to change vortex shedding characteristics, so as to reduce the building's horizontal wind load and responses.[9] The common ways of corner treatment are shown in Fig. 8.

4.3.1. Corner Treatments

As simulation cases shows: the relative carbon emissions derived from the four methods of corner treatment mainly seen in Shanghai are: rounded corner < cut corner < double re-entrant corner < re-entrant corner. Furthermore, if using a rounded corner on a typical floor, the carbon emissions will be significantly lower than via the other three methods, between which there is not much difference.

4.3.2. The Effect of γc on Carbon Emissions

Here, the cut angle rate, re-entrant angle rate, and round angle rate are all defined as:

$$\gamma_c = b / B$$

B - the length of the side of a typical floor

b - the length of the angled cut /radius of the round angle/ re-entrant length for re-entrant and double re-entrant angles[10]

Each corner treatment shares a similar trend with respect to a changeable γ_c. With the growth of γ_c, carbon emissions per unit of floor area show that the trend will rise first and fall later, and that the inflection point is at about 0.15, but the change in degree is not significant.

4.3.3. Compare Effective Degrees of Change

After conducting variance analysis, it is concluded that corner treatment has an obvious effect on carbon emissions. Meanwhile, the changing the round angle rate, cut angle rate and re-entrant angle rate have little effect on carbon emissions. In terms of effective degrees of change,

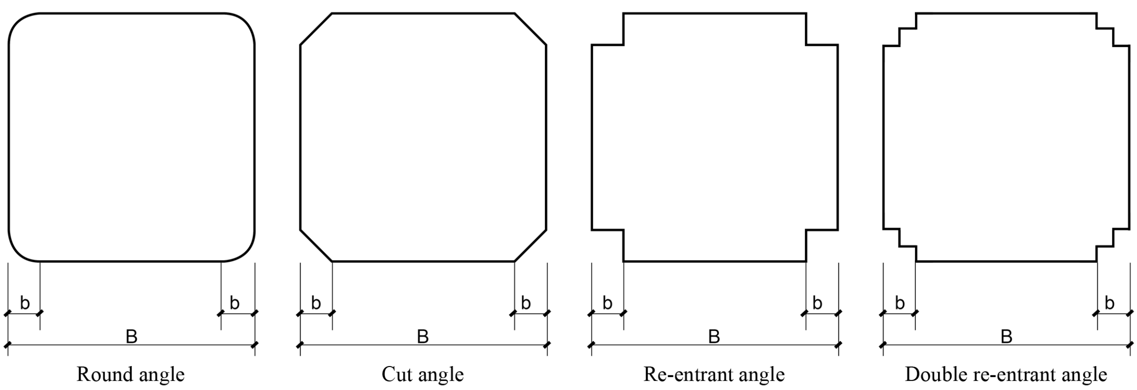

Figure 8. Common corner treatments to control wind effects on tall buildings.

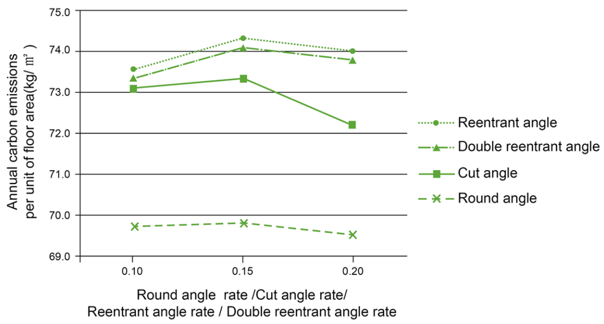

Figure 9. The effect of corner treatments on carbon emissions.

corner treatment methods > amending rate (γ_c).

5. Conclusion

The paper reports on the simulation experiment of carbon emissions for a typical floor of a high-rise office building using Green Building Studio software. It's concluded that design elements such as plan dimensions; size, number and location of the circulation core(s); and corner treatment methods in typical floor plans, within a certain variation of scope, do affect the carbon emissions per unit of floor area. Moreover, via variance analysis, the effective degree of each factor on carbon emissions is analyzed.

This paper is based on the study of typical floor designs and assumes that all conditions are ideal. However, it can nevertheless provide scientific references to architects at the stage of conceptual design, when coming up with methods to lower carbon emissions. Afterwards, through more simulations and analyses, design teams can generate more particular and deeper research results, and further reveal the relationship between the typical floor design factors and carbon emissions, so as to provide architects with an easy and scientific evaluating method for low-carbon design.

Acknowledgement

This study is supported by Science and Technology Committee of Shanghai Municipality for a research project titled "Theory System and Technical Promotion for Mega Resilience City" (Grant No. 17DZ1203200).

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