Low Carbon Design Research on the Space Layout Types of Office Buildings

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Abstract. It is beneficial to find out the relationship of the spatial layout and low-carbon design in order to reduce buildings’ carbon emissions in the conceptual design phase. This paper analyzes and compares shape coefficient values, annual energy consumption and lighting performance of office buildings of different space layout types in Shanghai. Based on morphological characteristics of different types, the study also analyzes and presents low-carbon design strategies for each single type. This study assumes that architects should conduct passive and active design according to the specific building space layout, so that to make best use of the advantages and bypassing the disadvantages, in order to maximally reduce buildings’ carbon emissions.

1. Introduction

1.1. Concept of space layout and research significance
The concept of “space layout” here mainly refers to the spatial topological relation of the volume of a building to itself, rather than the layout of the building in the base. The architect's idea of the spatial layout of the building volume mainly lies in grasping the general trend of the three-dimensional space form of the building. At this stage, the architect will draw up the general plan of the building in plane and section. Therefore, it is of great significance to improve the service performance of buildings and reduce the carbon emissions of buildings to find out the relevance between spatial layout and low-carbon design and to find out the low carbon design strategy suited to the type of spatial layout.

1.2. Classification of spatial layout
The spatial layout of various office buildings can be divided into integral type, enclosed type and semi-enclosed type, strip, and courtyard type in accordance with the spatial variation on the horizontal direction (i.e. the relationship between buildings and courtyard, solid and void). And it can be also divided into the uniform type, the set-back type and the cantilever type according to the spatial variation on the vertical direction (i.e. the relationship between the upper and lower layers on the section). Each type of spatial layout has its characteristics (Figure 1).
2. Simulation comparison of layout types of office buildings

2.1. Simulation methods

The main assumptions and technical parameters set in the simulation are as follows:

1) Area of architectural plane: Small-sized buildings (500m²), medium-sized buildings (1250m²) and large-sized buildings (2500m²)
2) Building storeys: High-rise buildings (10 floors), multi-storey buildings (5 floors) and low-rise buildings (2 floors)
3) Plane size: see Table 1 for details
4) Floor height of buildings: It is unified as 4.0 m
5) Material and thermal parameters of the main enclosure structure: Wall (U Value=1.0W/m²k), Glass (U Value=2.8W/m²k), Roof (U Value=0.70W/m²k)
6) Window-wall ratio: The ratio of the strip window is 0.50 (no sun shading), and the height of the windowsill is 1m and that of the window is 2m.
7) Calculation parameters of indoor air: 20°C ~ 26°C; refrigeration COP is 1.670; heating COP is 0.830; air permeability is 0.7ac/h
8) Opening and closing time of air conditioning: 7:00 to 19:00 on weekdays except for Saturday and Sunday
9) Equipment radiation: 5.0W/m²; lighting energy consumption: 10.0W/m²; personnel density: 0.11 person/ m²; body heat dissipation: 120W/ person

Table 1. Plane dimensions of office buildings of different layouts in simulation.

| Layout        | Small-sized (m) | Medium-sized (m) | Large-sized (m) | Remarks |
|---------------|-----------------|------------------|-----------------|---------|
| Integral      | a=22.36         | a=35.36          | a=50.00         | a-Length of a side |
| Enclosed      | a=7.50,b=9.16   | a=12.00,b=14.04  | a=15.00,b=26.60 | a-Building depth |
| Semi-enclosed | a=7.50,b=12.23  | a=12.00,b=18.72  | a=15.00,b=35.56 | b-Length of a short side of the courtyard |
| Strip         | a=27.80,b=9.00  | a=50.00,b=12.50  | a=62.50,b=20.0  | a-Length of a long side |
| Courtyard     |                | -                | a=7.50,b=8.89   | a-Building depth |
| Uniform       | a=22.36         | a=35.36          | a=50.00         | a-Length of a side |
| Set-back      | a=22.36,b=4     | a=35.36,b=4     | a=50.00,b=4    | a- Average length of a side |
| Cantilever    | a=22.36,b=4     | a=35.36,b=4     | a=50.00,b=4    | b-Distance of the set-back or the cantilever |
In this study, DesignBuilder is used as the simulation software of calculation of building energy consumption and carbon emission, and Ecotect is used as the simulation software of light environment. The meteorological data is selected from the data of Shanghai in EPW format.

2.2. Simulation results and analysis

2.2.1. Shape coefficient. From Figure 2, we can find that: firstly, in terms of the shape coefficient of the office buildings in horizontal spatial layouts, the integral layout has the smallest value, and the courtyard layout has the largest value, and the values of the strip, enclosed and semi-enclosed layouts are between the two without significant differences. Secondly, in terms of vertical spatial layout types, the cantilever layout has the largest shape coefficient, followed by the set-back layout and the smallest is the uniform layout. It can be seen that the set-back and cantilever designs have greater influence on the shape coefficient of the building. Thirdly, through the comparison of the same types in Figure 2, the influence of the change in the number of storeys and plane area on the shape coefficient of the building also has obvious regularity: the bigger the plane area and the higher the number of storeys is, the smaller the shape coefficient of the building will be.

2.2.2. Energy consumption and carbon emissions. As can be seen from Figure 3, in the horizontal layout types, the heating energy consumption of the courtyard-type office buildings is obviously higher than that of other layout types, followed by the enclosed type, and the integral layout has the relatively lowest heating energy consumption. In the vertical layout, the heating energy consumption of the cantilever layout is significantly higher than that of the uniform layout and the set-back layout. Different from heating energy consumption, in horizontal layout types, the refrigeration energy consumption of semi-enclosed office buildings is higher than that of other layouts, and that of the integral layout is still the lowest. In the vertical layout, uniform layout is higher than the set-back layout and cantilever layout. Through the comparison between Figure 3 and Figure 4, it can be seen that the heating energy consumption and refrigeration energy consumption of each type are opposite to the law of change of architectural form. That is to say, the architectural form with better performance in the heating energy index has slightly lower performance in the refrigeration energy consumption index, and vice versa. In the hot-summer and cold-winter Shanghai, there is no space layout type which can reduce heating and refrigeration energy consumption simultaneously when the form changes (floor height or plane area).

Through the comparison of the annual carbon emissions of the eight types of layout (Figure 5), it can be found that in horizontal layout types, the semi-enclosed and courtyard layouts have higher carbon emissions, the integral layout has the lowest emissions and the enclosed and strip layouts have similar emissions. In the vertical layout types, the cantilever layout has slightly higher carbon emissions than the uniform layout and the set-back layout. Compared with the shape coefficient in Figure 2, the shape coefficient of the strip office buildings is equal to that of the semi-enclosed layout, but its carbon emissions are smaller than those of the semi-enclosed layout, while the set-back and cantilever layouts have greater effect on the shape coefficient, but have little effect on the carbon emissions in the building operation, indicating that it is not entirely accurate to judge the thermal performance of the building purely on the shape coefficient, and it should be also be combined with specific morphological types to be taken into account.

Through the comparison of the unit carbon emissions of the buildings in different numbers of storeys and standard floor area in various layout types, it can be found that the change of the floor number has less effect on carbon emissions per unit area, while the construction area (building depth) plays a decisive role. As the thermal performance of the roof is much better than that of the wall in the enclosure structure (mainly because the heat-insulating property of the window is weaker than that of the wall), it is an effective means to save the energy and reduce emissions in design to improve the performance of the enclosure structure on the façade or reduce its area proportion on the whole outer surface of buildings.
2.2.3. **Light environment simulation.** From the comparison of daylighting performance in Figure 6, we can see that: firstly, the minimum daylight factor of all studied building models is greater than the minimum daylight factor 2% required in office building codes. The courtyard layout and the enclosed layout are the best, followed by the semi-enclosed and strip layouts, and the integral, uniform, set-back and cantilever layouts are worse. Secondly, for the whole air conditioned building, the lighting energy consumption of the building form is contrary to the energy consumption of the air-conditioning. The smaller the plane area is, the better the lighting effect will be. The larger the plane area is, the smaller the shape coefficient is, and the smaller the energy consumption of the air conditioning will be.

![Figure 2. Shape coefficient of different building layouts.](image1)

![Figure 3. Heating energy consumption of different building layouts.](image2)

![Figure 4. Refrigeration energy consumption of different layouts.](image3)

![Figure 5. Carbon emissions of different building layouts.](image4)

![Figure 6. Average and minimum lighting factor of different layouts.](image5)
3. **Analysis of low carbon design potential and strategy of spatial layout types**

After the designer selects a layout type for the scheme, he should also adopt the corresponding passive and active design strategies based on the particularity of such layout, guide the design in the light of its general trend and make best use of the advantages and bypass the disadvantages, so as to minimize the energy consumption and carbon emissions of buildings. This section attempts to propose different solutions for low carbon design according to the characteristics and design conflicts of different layout types of office buildings.

3.1. **Integral layout**

3.1.1. **Characteristics**

1) It is compact in the space and small in the shape coefficient, so that it is suitable for the scheme with narrow land and high land-use ratio.

2) The internal space is easy to be flexibly segmented, and adaptable to the change of functions.

3) There are always unified large roofs, which are very beneficial for the deployment of wind power and active solar energy systems.

4) The lighting in the plane is uneven, while the lighting in the middle area is obviously insufficient.

5) Excessive depth is also detrimental to good natural ventilation.

3.1.2. **Design strategy.** Increasing the depth of the integral layout of the office building can lower the shape coefficient and reduce the energy consumption of air conditioning, but the excessive depth brings inconvenience to lighting and ventilation. The solution is to add skylights to the interior area to introduce natural lighting, avoid dark lighting areas in the interior areas, and to combine the openings in the floors with skylights to form an inner atrium. Skylights are best designed to protrude from the roof, which not only gives light to the lower part, but also helps organize the natural ventilation during the transition season and improves microclimate. If the bottom part is retreated accordingly, a certain wind guiding effect will be formed. The integral layout has a large area of complete roof, which is conducive to building a good roof garden and may be considered to combine with a large area of solar photovoltaic system (Figure 7).

![Figure 7. Design strategy for Integral layout.](image)

3.2. **Enclosed layout**

3.2.1. **Characteristics**

1) The enclosed inner court is an independent area from the interference of external environment (e.g. noise), which is the focus in the design of the enclosed layout.

2) The introduction of the inner court improves the potential of the office space in natural lighting and natural ventilation.

3) The natural environment and green planting in the inner court can improve the quality of office space.

3.2.2. **Design strategy.** The focus of the enclosed layout is the pattern of the courtyard. It will be difficult to solve the lighting and ventilation of the office space in the lower courtyard when the depth-width ratio is too large in the courtyard. The solutions are to strengthen natural lighting of the courtyard through the fixed reflector panel, and to set up certain openings in the peripheral part of the building, and to strengthen the air flow of the courtyard, while the direction of openings should be
consistent with the predominant wind direction. The organization of ventilation can be through the building, or apply the height difference of the courtyard to form certain thermal pressure ventilation. Green planting is arranged in the courtyard and the outdoor balcony, which will not only improve the landscape quality, and the certain transpiration will also play a role in promoting thermal pressure ventilation (Figure 8).

![Diagram of Enclosed Layout](image1)

**Figure 8.** Design strategy for Enclosed layout.

### 3.3. Semi-enclosed layout

#### 3.3.1. Characteristics

1) The semi-open courtyard has certain directionality, and also has a stronger penetration of the external environment.

2) It is easily disturbed by adverse factors such as noise.

3) It is suitable to introduce an environment in a certain direction under the condition of good external natural environment.

| Table 2 Carbon emissions in a building of semi-enclosed layout with different opening orientations (in the case of medium-sized and multi-storey buildings; Unit: $10^3$kg) |
|----------------------------------|----------------|-------|-------|-------|-------|-------|-------|-------|
| Orientation                      | East  | South | West  | North | Southeast | Northwest | Southwest | Northeast |
| Carbon emissions                | 137.0 | 139.5 | 137.0 | 139.5 | 139.5     | 139.5     | 139.5     | 139.4     |

#### 3.3.2. Design strategy

The orientation of the courtyard and the depth-width ratio of the courtyard are major concerns in the design of the semi-enclosed layout. Although the carbon emissions of southward courtyard buildings are slightly higher than those of the eastward buildings (Table 2), the courtyard has the best quality when facing the south. In summer, the volume of the two sides can block the sunlight on the east and west, and it can gain more passive heat in winter. The practice of local set-back on both sides of the building not only increases the vision of the landscape, but is also beneficial to the internal lighting of the courtyard on the premise of a small depth-width ratio. In the natural ventilation, it should maintain the depth of less than 15m while building part of the bottom on stilts, so that the ventilation structure will be smoother in the courtyard. And the balcony and the courtyard should also be designed in combination with the greening (Figure 9).

![Diagram of Semi-enclosed Layout](image2)

**Figure 9.** Design strategy for Semi-enclosed layout.
3.4. Strip layout

3.4.1. Characteristics

1) It is suitable for long and narrow plots. At the same time, because of the small depth inside the building, the passive design is of great potential.

2) The space between the front and back buildings forms a relatively inward space due to the shelter of two rows of buildings.

3) The strip buildings can be connected by ancillary spaces, such as corridors, to form a larger architectural complex.

| Table 3. Carbon emissions in a building of strip layout in different orientations (in the case of medium-sized and multi-storey buildings; Unit: 10^3 kg/m²). |
|-----------------|--------|--------|--------|--------|--------|--------|--------|
| Orientation     | 0°     | 15°    | 30°    | 45°    | 60°    | 75°    | 90°    |
| Carbon emissions| 135.9  | 137.1  | 139.5  | 142.0  | 143.2  | 143.7  | 143.6  |

Note: This orientation refers to the angle between the long axis of the building and the east-west direction

3.4.2. Design strategy. The orientation of the strip building and the relationship of spatial locations of the front and back buildings are the focus of such architectural design. It is the most beneficial to reduce carbon emissions to maintain the east-west arrangement of the long axis of the strip buildings (Table 3). In case that the fore-and-aft clearance is smaller than the height, it is disadvantageous to the lighting and the back buildings in winter, as it may slightly increase the carbon emission (Table 4). For the organization of natural ventilation, the vertical direction between the building and the dominant direction of summer is the method of improving indoor natural ventilation. When the site is limited, the back row can be slightly higher than the front row, so that it can maximize the use of daylight and slightly reduce carbon emissions (Table 5). It is also possible to choose the most favourable orientation according to the specific conditions of the site, or to make a certain transition in the strip buildings (Figure 10).

| Table 4. Carbon emissions in a building of strip layout in different spacing (in the case of medium-sized and multi-storey buildings; Unit: 10^3 kg/m²). |
|-----------------|--------|--------|--------|--------|--------|--------|--------|
| Spacing         | 6m     | 10m    | 15m    | 20m    | 25m    | 30m    | 35m    | 40m    |
| Carbon emissions| 136.8  | 136.5  | 136.4  | 135.9  | 135.5  | 135.4  | 135.5  | 135.6  |

| Table 5. Carbon emissions in a building of strip layout in different floor height differences between the front and back rows (in the case of medium-sized and multi-storey buildings; Unit: 10^3 kg/m²). |
|-----------------|--------|--------|--------|--------|--------|--------|
| Floor height difference | -6     | -4     | -2     | 0      | +2     | +4     | +6     |
| Carbon emissions  | 136.2  | 136.0  | 135.8  | 135.9  | 136.5  | 137.2  | 137.3  |

Note: “+” — The front row is higher than the back row. “-” — The back row is higher than the front row

Figure 10. Design strategy for Strip layout.
3.5. Courtyard layout

3.5.1. Characteristics
1) It is suitable for the scheme of office buildings in low rise and high density covering a large floor area.
2) For large planes, the scattered courtyard is conducive to enhancing the uniformity of lighting.
3) Compared with enclosed layout, it has greater flexibility and variability, and can be combined with the terrain, slope and other site conditions to form several groups of courtyard spaces in different shapes, sizes and heights so as to become an integral whole with the environment.

3.5.2. Design strategy.
Similar to problems of the enclosed layout, the spatial organization between the courtyards and the entities is the focus the courtyard layout design, and the optimal depth-width ratio should be able to guarantee natural lighting and natural ventilation around the courtyard. In the design, we can combine the design methods of the open ground floor and air garden, and form a three-dimensional courtyard system with the horizontal courtyard to enhance the ventilation effect. Meanwhile, in order to increase the effect of passive heat gain, the effect of local set-back can be formed to increase the lighting area to the south (Figure 11).

3.6. Uniform layout

3.6.1. Characteristics
1) Unlike the horizontal extension of the integral layout, the uniform layout is extended in the vertical direction.
2) The rules of shape are beneficial to seismic resistance and windbreak design, and it is also easy for the organization of vertical traffic.
3) The same podium can connect several groups of high-rise buildings to increase the utilization rate of the space.

3.6.2. Design strategy.
Under the condition that the overall volume of the building remains unchanged, the way of forming the recess through the openings on the façade can effectively shorten the actual depth of the building to make the building become thinner and more transparent and reduce the demand for artificial lighting. High-rise buildings can be broken up into parts through vertical segmentation, to divide the building into several small-scale buildings in vertical direction. When the distance between the vertical blocks is large enough, the natural lighting can be organized without blocking each other. If combined with lighting atrium, it can solve the problem of the entry of natural light in vertical and horizontal directions simultaneously. The natural ventilation of high-rise buildings doesn’t mainly rely on exterior windows, and it can consider combining the vertical atrium and the podium space to organize the mixed ventilation mode due to the great impact of wind environment (Figure 12).
3.7. Set-back layout

3.7.1. Characteristics

1) The overall space form shows the relationship of a big bottom and a small top.
2) Each floor can form an outdoor platform, which can be used as a balcony and an outdoor courtyard.
3) The plane area of the low-rise buildings is always large.

Table 6. Carbon emissions in a building of set-back layout with different opening orientations (in the case of medium-sized and multi-storey buildings; Unit: 10^3 kg/m^2).

| Orientation | East  | South | West  | North | South-east | North-west | South-west | North-east |
|-------------|-------|-------|-------|-------|------------|------------|------------|------------|
| Carbon emissions | 133.6 | 133.5 | 133.6 | 133.7 | 134.7      | 134.7      | 134.7      | 134.7      |

3.7.2. Design strategy. The orientation of the set-back layout and the excessive depth at the bottom are the design problems of the set-back layout. The overall spatial situation of the upward contracture is suitable to form the atrium in the shape of the inverted funnel internally, which is prone to applying the effect of thermal pressure ventilation. The step-like volume and form may create good interpenetration and connection between the floors and the outdoor garden terrace can be set on each floor. The space of large depth at the bottom can connect with the urban space to form an interactive sharing hall. For set-back buildings, when the set-back is facing the south, it is beneficial to heat gain in winter and building carbon emission is smaller (Table 6). When the set-back is facing the north, it will have smaller impact on the natural lighting of adjacent buildings (Figure 13).
3.8. Cantilever layout

3.8.1. Characteristics

1) Huge grey space can be formed below the cantilever to form good indoor and outdoor transition, which is suitable for the deployment of the base by the street or by the square.

2) The overall shape is favorable for the ventilation and form self-shading.

3) The large and smooth roofs are beneficial to the deployment of wind power and solar energy systems.

4) The spatial layout of a big top and a small bottom is unstable in structure, and it is also difficult for the design of vertical traffic.

Table 7. Carbon emissions in a building of cantilever layout with different opening orientations (in the case of medium-sized and multi-storey buildings; Unit: 10^3kg/m^2)

| Orientation         | East | South | West | North | South-east | North-west | South-west | North-east |
|---------------------|------|-------|------|-------|------------|------------|------------|------------|
| Carbon emissions    | 112.5| 114.2 | 112.5| 113.2 | 113.9      | 113.7      | 114.0      | 113.6      |

3.8.2. Design strategy. It can form a covered semi-outdoor space at the bottom to form self-shading. When the cantilever is east-west, it is conducive to low carbon and energy saving on the whole (Table 7). In addition, when the upper part is too deep, the inner courtyard and skylight are designed partly for lighting, and the ventilation effect of the shape is combined with the outer grey space to organize the natural ventilation. When the condition is limited, the vertical opening is too deep to make the lower grey space and the surrounding office space form natural lighting, and the light guiding system or the reflecting system can be used (Figure 14).

![Figure 14. Design strategy for Cantilever layout.](image)

4. Conclusion

This paper compared and discussed the characteristics of heating, refrigeration, lighting energy consumption and carbon emission of the office buildings in eight types of spatial layout in Shanghai, and put forward the potential of low-carbon design strategy for their morphological characteristics.

1) Among types of horizontal spatial layout, the integral layout has the smallest shape coefficient, the courtyard layout has the largest coefficient, the values of the strip, enclosed and semi-enclosed layouts are between the two. Among the types of vertical spatial layout, the cantilever layout has the largest shape coefficient.

2) The heating energy consumption and refrigeration energy consumption of each type are opposite to the law of change of architectural form. There is no space layout type which can reduce heating and refrigeration energy consumption simultaneously when the form changes (floor height or plane area).

3) The change of the floor number has less effect on energy consumption and carbon emissions per unit area, while the building depth plays a decisive role. Among types of horizontal spatial layout, the semi-enclosed and courtyard layouts have higher carbon emissions and the integral layout has the lowest emissions. Among the types of vertical spatial layout, the cantilever layout has slightly higher...
carbon emissions than the uniform layout and the set-back layout.

4) In terms of lighting performance, the courtyard and the enclosed layouts are the best, followed by the semi-enclosed and strip layouts, and the integral, uniform, set-back and cantilever layouts are worse.

5) We should conduct passive and active designs according to the morphological characteristics of the overall layout of architectural space to make best use of the advantages and bypass the disadvantages. For different types of layout, designers should consider problems including: internal ventilation and lighting of large-scale integral space; reasonable depth-width ratio of the courtyard in the enclosed layout; the orientation selection of the semi-enclosed layout; the orientation selection and spacing control of the strip layout; reasonable organization of the courtyard in the courtyard layout; lighting and ventilation of the bottom space in the set-back layout and the utilization of grey space in the cantilever layout.

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