How does building shape affect carbon neutrality in the early design stage? Sensitivity analysis and design optimization of office buildings in cold regions of China

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Abstract
Reducing carbon emissions and improving carbon offsets are effective ways to achieve Building Carbon Neutrality (BCN). However, in the early design stage, how the building shape affects the BCN and how to optimize the shape with the objective of the BCN have not been fully studied. In this study, a parametric model of typical photovoltaic (PV) office buildings below 50 meters is established for the Isolated Building Scenario (IBS) and the Urban District Scenario (UDS), respectively. A sensitivity analysis (SA) is then performed to identify the key shape variables that affect BCN related indicators, and based on this, design optimization is carried out. The results show that the number of floors, floor area, floor height, and shading PV overhang length are the key factors for both scenarios, and the south Window-to-Wall Ratio (WWR) also shows a certain impact on the BCN of IBS. However, the sensitivity of the number of floors and floor area to the PV carbon offsets in the two scenarios is significantly different. Furthermore, the above parameters show different effects on multi-rise and high-rise buildings for IBS. The number of floors can initially determine whether the BCN can be achieved and based on this, shape optimization can further improve the BCN. The design strategies discussed in this paper can provide a reference for the design of buildings driven by BCN.

Key Innovations
- SA of building shape variables on Life Cycle Carbon Emissions (LCCE), PV Carbon Offsets (PVCO), and Carbon Neutrality Levels (CNL).
- Revealing the different carbon neutral levels that can be achieved by different building shapes.
- Analysis and suggestions for building shape optimization design driven by BCN performance.

Practical Implications
The shape parameters that should be focused on to achieve BCN in office buildings in cold regions of China are extracted. The CNL that can be achieved in buildings with different number of floors are revealed. A series of suggestions for building form design are provided.

Introduction
The building sector accounts for approximately 40% of global greenhouse gas emissions (Ahmed et al., 2022). China pledged to reach its domestic carbon peak in 2030 and carbon neutrality in 2060 at the 75th United Nations General Assembly. In order to achieve carbon neutrality in the building sector, it is essential to reduce the carbon emissions emitted by buildings and to utilize various kinds of renewable energy. Many characteristics, such as the building shape, envelope, materials, and energy systems, have an impact on a building's energy and carbon emission performance (Evins, 2013). Among them, the building shape is determined at the early design stage and usually remains unchanged throughout the building's life cycle, which is crucial for improving the energy and carbon performances of buildings (Ostergard et al., 2016; Bhatta et al., 2020).

In the early design stage, combining sensitivity analysis (SA) with performance simulation becomes an effective method for performance-based design (Nembrini et al., 2014). SA can be divided into global and local approaches. Global SA is generally recognized for its ability to determine the effect of uncertain inputs on the entire input space. Many scholars use this method to identify the key parameters that affect building performance (Mechri et al., 2010; Ballarini and Corrado, 2012; Tian and Wei, 2013). To determine the optimal build variables, the performance-driven optimization method has become a research hotspot. This method improves the efficiency and accuracy of performance-based design and makes the decision-making process more autonomous (Fesanghary et al., 2012; Taehoon et al., 2017). However, the complexity of building simulation outputs and the expensive computational cost are the major challenges of this approach. To overcome these obstacles, alternative models for performance simulation engines have been developed, such as multiple regression, Artificial Neural Networks (ANN), and Support Vector Machines (SVM) (Zhao and Magoulès, 2012). Since 2017, there has been a great increase in the method for combining the ANN model with optimization algorithm to obtain the optimal design (Saryazdi et al., 2022).

At present, performance simulation, SA, optimization algorithms, and ANN have become effective methods for performance-driven building optimization design. The optimization of building variables with the objectives of energy consumption, carbon emission, and thermal comfort during the operation phase, however, is a common focus of previous studies; less attention has been paid to how building shape affects carbon emission from a life cycle perspective. On the other side, whereas previous studies have provided critical insights on passive
methods to reduce building carbon emissions, there is a lack of analyses of key shape factors for PV Carbon Offsets (PVCO). What shape variables should be taken into consideration, how should building design optimization be conducted out, and which shape can achieve Building Carbon Neutrality (BCN) when passive carbon reduction and PV carbon offsetting are applied simultaneously?

To address the above problems and questions, a typical PV office building model below 50 meters in the cold region of China is established, and two environmental scenarios are provided. Indicators related to BCN are then defined from the life cycle perspective, and the effects of shape variables on different indicators are revealed. On this basis, the optimization algorithm and ANN are integrated to explore the CNL that can be achieved under different combinations of shape parameters and propose shape design suggestions driven by the BCN target.

Method

The workflow of this paper consists of three components. Among them, the parametric modeling part carries multi-dimensional information about the building's shape, materials, operation, and PV system. The sensitivity analysis part reveals the key shape variables for different BCN evaluation indicators. The shape design optimization part integrates ANN and optimization algorithms to optimize the identified variables with the objectives related to BCN.

Parametric modeling of a typical building

In the cold regions of China, office buildings are built in large quantities. As a result, there is great potential for passive carbon reduction and PV carbon offsetting. We establish a parametric model of a typical office building below 50 meters, located in Jinan, China. PV panels are installed on the building’s east, west, and south facades, as well as the shade. Since the layout of the roof PV array is not the focus of this study, the PV panels are idealized: the roof is fully installed, and the tilt angle of the panels is set to 0 degrees.

Two scenarios are established: the isolated building scenario (IBS, without surrounding building shading) and the urban district scenario (UDS, with surrounding building shading), which correspond to the building environment in low-density and high-density urban areas, respectively. The parametric model built on the Rhino-Grasshopper (GH) platform is shown in Figure 1. Ten shape variables are defined and constrained (Table 1), while the envelope (Table 2), simulation information (MHURDPRC, 2021), and PV system (Table 3) are quantitative and integrated into the parametric model through the GH-Ladybug and GH-Honeybee.

Table 1: Building shape variables.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Min</th>
<th>Max</th>
<th>Steps</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area</td>
<td>1000</td>
<td>1500</td>
<td>100</td>
<td>m²</td>
</tr>
<tr>
<td>Building aspect ratio</td>
<td>1.0</td>
<td>2.0</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>Floor height</td>
<td>3.3</td>
<td>4.5</td>
<td>0.3</td>
<td>m</td>
</tr>
<tr>
<td>Shading PV overhang length</td>
<td>0.4</td>
<td>1.2</td>
<td>0.1</td>
<td>m</td>
</tr>
<tr>
<td>Building orientation</td>
<td>-30</td>
<td>30</td>
<td>10</td>
<td>degree</td>
</tr>
<tr>
<td>Number of floors</td>
<td>1</td>
<td>15</td>
<td>1</td>
<td>floor</td>
</tr>
<tr>
<td>South WWR</td>
<td>0.15</td>
<td>0.7</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>North WWR</td>
<td>0.15</td>
<td>0.7</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>East WWR</td>
<td>0.15</td>
<td>0.7</td>
<td>0.1</td>
<td>-</td>
</tr>
<tr>
<td>West WWR</td>
<td>0.15</td>
<td>0.7</td>
<td>0.1</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 2: Information about the envelope.

<table>
<thead>
<tr>
<th>Name</th>
<th>Major initial Material</th>
<th>Average U-Value (W/m²K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exterior wall</td>
<td>Hollow concrete block</td>
<td>0.45</td>
</tr>
<tr>
<td>interior wall</td>
<td>Hollow concrete block</td>
<td>1.2</td>
</tr>
<tr>
<td>Interior floor</td>
<td>Reinforced concrete</td>
<td>1.2</td>
</tr>
<tr>
<td>Roof</td>
<td>Hollow concrete block, Rigid polyurethane board</td>
<td>0.35</td>
</tr>
<tr>
<td>window</td>
<td>Plastic-steel, Low-e glass</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Sensitivity analysis

Three BCN performance evaluation indicators are established, including Life Cycle Carbon Emissions (LCCE), PV Carbon Offsets (PVCO), and Carbon Neutrality Levels (CNL) to evaluate the impact of shape variables on the carbon neutrality target.

- Life cycle carbon emissions
  The life cycle consists of building material production and transportation, construction, operation, and demolition
The number of building floors. where (DHURDGP, 2022). The calculation is shown in Eqs. (4) simplified method provided by the Chinese criteria demolition stages are calculated according to the The carbon emissions during the construction and life expectancy. life cycle as PV systems in China generally have a 25-year modules are replaced once during the building’s 50-year is complex, and we regard PV panels as a single material should be mentioned that the processing of PV materials The calculation program is developed within the GH. It parameters are shown in Table 5. The major building materials, such as steel bars, concretes, blocks, and PV panels, are selected to participate in the carbon emission calculation at the production and transportation stages due to the difficulty to figure out the amount of each building material in detail at the early design stage. The calculations are shown in Eqs. (2) and (3):

\[
CE_{\text{prod}} = \sum_{i=1}^{n} M_i \cdot F_i 
\]  

(2)

where \( n \) is the total number of material types, \( M_i \) is the consumption of type \( i \) material, \( F_i \) is the CO₂ emission factor of type \( i \) material (Table 4).

\[
CE_{\text{cons}} = \sum_{i=1}^{n} D_i \cdot T_i 
\]  

(3)

where \( D_i \) is the average transportation distance (TD) of type \( i \) material, \( T_i \) is the CO₂ emission factor of type \( i \) material’s transportation carrier. The relevant transportation parameters are shown in Table 5.

Table 4: CO₂ emission factors of materials.

<table>
<thead>
<tr>
<th>Construction material</th>
<th>CO₂ emission factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete</td>
<td>295kgCO₂/m³</td>
</tr>
<tr>
<td>Steel bar</td>
<td>2050 kgCO₂/t</td>
</tr>
<tr>
<td>Hollow concrete block</td>
<td>327 kgCO₂/m³</td>
</tr>
<tr>
<td>Rigid polyurethane board</td>
<td>5220kgCO₂/t</td>
</tr>
<tr>
<td>Plastic-steel window</td>
<td>121 kgCO₂/m³</td>
</tr>
<tr>
<td>PV module</td>
<td>160.86kgCO₂/m²</td>
</tr>
</tbody>
</table>

Table 5: Parameters of material transportation.

<table>
<thead>
<tr>
<th>Parameters Name</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>TD of concrete</td>
<td>40km</td>
</tr>
<tr>
<td>TD of other materials</td>
<td>500km</td>
</tr>
<tr>
<td>( T_i ) for diesel trucks (load 18t)</td>
<td>0.129kgCO₂/(t·km)</td>
</tr>
</tbody>
</table>

The calculation program is developed within the GH. It should be mentioned that the processing of PV materials is complex, and we regard PV panels as a single material with a carbon emission factor of 160.86 kgCO₂/m² according to scholars’ research (Zhao et al., 2020). PV modules are replaced once during the building’s 50-year life cycle as PV systems in China generally have a 25-year life expectancy. The carbon emissions during the construction and demolition stages are calculated according to the simplified method provided by the Chinese criteria (DHURDGP, 2022). The calculation is shown in Eqs. (4) and (5):

\[
CE_{\text{cons}} = A \cdot (X + 1.99) 
\]  

(4)

\[
CE_{\text{demol}} = A \cdot (X + 1.99) 
\]  

(5)

where \( A \) is the total floor area of the building and \( X \) is the number of building floors. The \( CE_{\text{opera}} \) can be estimated as shown in Eqs. (6):

\[
CE_{\text{opera}} = (EC_{\text{cool}} + EC_{\text{heat}} + EC_{\text{light}} + EC_{\text{equip}}) \times F_e 
\]  

(6)

where \( EC_{\text{cool}}, EC_{\text{heat}}, EC_{\text{light}}, \) and \( EC_{\text{equip}} \) are the electricity consumption of heating, cooling, lighting and electrical equipment of the building calculated by the simulation software respectively. \( F_e \) is the factor of electricity emissions for the region where the building is located, which takes the value of 0.7921 kgCO₂/kWh (MEEPRC, 2020).

The electricity consumption is calculated by EnergyPlus called by GH-Honeybee. It should be noted that the effect of the efficiency of air conditioning and coal-fired boiler on heating and cooling electricity consumption is considered according to the Chinese criteria (MHURDPRC, 2021).

- PV system carbon offsets
- The PV system carbon offsets (PVCO) can be obtained as shown in Eqs. (7):

\[
PVCO = E_{\text{gener}} \times F_e 
\]  

(7)

where \( E_{\text{gener}} \) is the total electricity generated by the PV panels, calculated by EnergyPlus called by GH-Ladybug.

- Carbon neutrality level

The CNL represents the degree to which the building is achieving its carbon neutrality target. An indicator less than 1.0 means that the building is not carbon neutral, while an indicator greater than 1 means that the building can achieve carbon neutrality and has the ability to neutralize carbon emissions from other sectors. The total CNL can be given as follows:

\[
CNL = \frac{PVCO}{LCCE} 
\]  

(8)

After the definition of the above three BCN performance evaluation indicators, we use Sobol, a global SA method, to analyse the sensitivity of each shape variable to the indicators. Firstly, 352 random samples are sampled by the Sobol sampling method, and then the simulations of the indicators are performed, and finally, the first order index and total effect index of the variables are calculated. The total effect index explains the sensitivity of the variables to the evaluation indicators under the interaction with other variables. If the index is greater than 0.1, it means the parameter is highly sensitive, greater than 0.01 and less than 0.1 means sensitive, and less than 0.01 means insensitive (Tang et al., 2007). Based on the key shape variables identified by the Sobol method, the trend of their influence on different indicators was analysed using the control variables method.

Shape design optimization

The building shape variables are optimized by using an optimization algorithm to investigate the CNL that can be achieved by different combinations of shape parameters and to decide on the optimal design. The variables to be optimized are selected from the previous Sobol SA, and the objectives of the optimization are to minimize LCCE and maximize PVCO. The Hypervolume (HypE) algorithm integrated within the GH-Octopus is used for optimization, which is a HypE estimation algorithm for multi-objective problems (Bader and Zitzler, 2011). In addition, we use the Latin
hypercube sampling method to obtain 100 sets of shape parameters and then simulate their LCCE and PVCO data using GH-HB. The obtained data are used to train the ANN model to solve the time-consuming problem of performance computation relying only on simulation software. The training of ANN is performed using the GH-LunchBox plug-in. Finally, the ANN model is combined with the optimization algorithm to improve the efficiency of the optimized design.

Result

Sensitivity analysis and variable screening

To reveal the effects of shape on the BCN, SA is performed for each performance indicator in both scenarios, and the results are shown in Figure 2.

The results of the carbon emissions SA for the two scenarios are similar. The highly sensitive parameter for LCCE is the number of floors; the sensitive parameter is the floor area; and the other parameters are insensitive. The same characteristics are also observed in the life cycle sub-stages, including operation, construction, and demolition. However, the SA results in the stages of material production and transportation differ from this, and besides the number of floors and floor area, the floor height also shows a certain sensitivity. It can be observed that the sensitivity coefficient of the number of floors is significantly greater than the other variables, implying that it is a key factor affecting carbon emissions.

As can be seen from the SA of PVCO, there is a dramatic difference in the sensitivity ranking of the two scenarios. Four sensitive parameters are obtained for the IBS. Among them, the sensitivity coefficients of the number of floors and floor area are 0.78 and 0.21, respectively, which both show high sensitivity, and the floor height and shading PV overhang length are sensitive parameters. However, for the UDS, the floor area exceeds the number of floors and becomes the most sensitive parameter, with sensitivity coefficients of 0.47 and 0.36, respectively, and the ranking of the two sensitive parameters, floor height and shading PV overhang length, is reversed.

The sensitive parameters of PVCO on different facades are different. For IBS, the highly sensitive parameter of the south facade PVCO is the number of floors, and the...
south WWR, shading PV overhang length, aspect ratio, floor height, and orientation are sensitive parameters. Compared with the south facade, the shading PV overhang length becomes a highly sensitive parameter for PVCO on the east and west facades. Moreover, for the facade PVCO of UDS, the most obvious difference from the IBS is that the sensitivity of the WWR of the east and west facades is significantly improved, while the sensitivity of the number of floors is reduced. Overall, consistent with LCCE, the number of floors is the most important factor affecting the PVCO of each facade.

The number of floors is the most influential parameter for the CNL in both scenarios. In IBS, the floor area, floor height, and shading PV overhang length, which affect LCCE or PVCO, do not show sensitivity to CNL, while the south WWR becomes a highly sensitive parameter with an index of 0.15. Differently, for UDS, the sensitivity of south WWR is significantly decreased, and only the number of floors shows sensitivity with an index of 0.95.

Based on the results of the above global SA, the sensitive parameters of LCCE, PVCO, and CNL are extracted as the key factors to achieve the BCN target. To reveal the trend of the influence of these factors on the BCN-related performance objectives, controlled variable experiments are performed, and the results are shown in Figure 3.

As the number of floors increases, the change in each evaluation indicator is significantly greater than the changes caused by the other parameters, which again proves to be an critical factor. For IBS, the increase in the number of floors leads to an increase in both LCCE and PVCO. However, the former increases much more than the latter, resulting in a gradual decrease in CNL. Similar variation are observed in the UDS, but all three metrics are smaller than those in the IBS, and it is worth noting that the CNL reduction of the UDS is small at 1 and 2-floors, implying that the effect of surrounding buildings on PV is small under conditions where the surrounding buildings are low in the number of floors.

Interestingly, the PVCO and CNL change abruptly when the number of floors is 7 in UDS. The reason is that the height of the 7-floor building exceeds 24 m and the interval of the surrounding buildings expands (Figure 1), resulting in a sudden reduction of the shading to the central building.

Different from the number of floors, the increases in LCCE and PVCO caused by floor area are similar; therefore, the decrease in CNL is more stable for both scenarios. A further novel finding is that the effect of floor height on the CNL of the two scenarios is opposite. In addition, the building height of this model exceeds 24 m when the floor height is 4.1 m, resulting in an abrupt change in the PVCO and CNL of the UDS.

The shading PV overhang length shows a positive correlation with each evaluation indicator, which means that increasing their values appropriately can improve the CNL. Furthermore, the increase of south WWR will lead to a decrease in CNL.

Design optimization for IBS

In low-density urban areas in cold regions of China, unshaded scenarios around buildings are common, especially for buildings below 50 meters; therefore, we explore the shape design optimization of IBS. The SA result demonstrates that achieving the BCN target depends significantly on the number of floors. To reveal the achievable CNL under different shape variables, we first take the number of floors as the dominant variable to initially limit the CNL and then integrate ANN and optimization algorithms to optimize the floor area, floor height, shading PV overhang length, and south WWR with the objectives of LCCE and PVCO. Finally, the Pareto solutions are obtained, and the achievable CNL for different numbers of floors is calculated (Figure 4).

The CNL in the optimal solutions tends to decrease as the number of floors rises, as shown in the median and mean distributions in figure 4. Furthermore, the decrease in the indicator gradually becomes smaller. The CNL range for 1-floor buildings is 1.18-1.91, which means that not only all buildings can achieve BCN, but even the PV of some buildings can offset almost two times the LCCE. It should
be noted that in the boxplot, the longest and overall skewed distribution of the box at 1 floor indicates that its CNL fluctuates the most. At 2-floor buildings, the range of CNL is 0.82-1.18, with the median and mean reaching 1.0 and the lower quartile approaching 0.95, implying that most optimal solutions can achieve BCN. Starting from 3-floor buildings, all CNL values are below 1.0. In addition, starting from the 6-floor, the upper and lower truncation line spacing is significantly smaller than before the 6-floor, suggesting a more centralized and stable CNL.

Figure 4: Domains of CNL values achievable by shape optimization under different numbers of floors.

Figure 5 shows the specific optimization results for a typical 6-floor building. The X-axis in the figure is the LCCE, the Y-axis is the 1/PVCO, and the brown points are the Pareto optimal solutions. It can be seen that the optimal solutions can be clustered into 6 groups. The floor area in which the groups' differences are most noticeable. The floor areas of the optimal solutions in the leftmost clusters are all 1000m$^2$, and they increase by 100m$^2$ for each cluster from left to right. This verifies that the floor area is the most important factor affecting LCCE and PVCO compared to the floor height, shading PV overhang length, and WWR under the condition that the number of floors is determined. Furthermore, the decreasing number of design solutions in each cluster means that the smaller the floor area, the more design possibilities are available to the decision-maker.

The similarity within each cluster is that the shading PV overhang length of the optimal solutions is 1.2m, and from left to right, the south WWR of the optimal solution decreases and the floor height increases. This implies that the combination of a smaller south WWR and a higher floor height results in higher LCCE and PVCO when other parameters remain unchanged.

Discussion

Variable screening and design suggestions

The number of floors is the most significant factor affecting the LCCE of both scenarios, and the LCCE of UDS is smaller than that of IBS due to the shading effect of surrounding buildings. The expansion of building scale increases the amount of material, transportation and construction equipment usage, and operation energy consumption, which leads to an increase in carbon emissions in all stages of the life cycle. Therefore, the number of floors and floor area, as shape variables that directly determine the gross floor area, show high sensitivity to LCCE. Nevertheless, it can be seen from their sensitivity coefficients that the number of floors is the decisive factor. Moreover, operation-stage carbon emissions account for most of the LCCE, so its sensitivity factors are highly similar to the LCCE, which explains why operation-stage are mostly studied in the previous literature (Feng et al., 2022). It is worth mentioning that the floor height shows a certain sensitivity only in the production and transportation stages. In summary, from a life cycle perspective, it is recommended that the number of floors and floor area be the primary concerns for carbon reduction, and the adjustment of floor height can be considered secondarily.

The number of floors and the floor area are the major parameters affecting the PVCO, as they determine the installable area of the PV panels. A notable difference is that for IBS, the influence of the number of floors is significantly greater than the floor area, while for UDS, the sensitivity of the number of floors decreases due to the shading of the surrounding buildings, and the floor area becomes the most influential factor. Furthermore, the integration of shading panels with PV is a recommended way, as shading PV not only reduces the carbon emissions by shading from solarization but also offsets part of the carbon emissions through PV generation. An effective way to increase the PVCO on facades is to increase the shading PV overhang length. It should be noted that the above-extracted factors affecting PVCO are based on the premise of including roof, south, east, and west facade PV. However, when only a single facade PV panel is applied for carbon offsetting, the influence of floor area on facade PVCO is weakened, and the role of WWR is enhanced, especially in UDS. Therefore, it is suggested that the
shape variables be adjusted according to the installation location of PV panels.

BCN can be achieved by PVCO, and the CNL depends primarily on the number of floors. The higher the number of floors, the more challenging it is to achieve BCN in both scenarios. The experiments also reveal that for IBS, expanding the floor height can increase the CNL, while for UDS, the opposite effect occurs. Therefore, the floor height should be adjusted according to the presence or absence of surrounding buildings. In addition, for IBS, the expansion of the south WWR increases carbon emissions, reduces the installation area of PV panels on the south facade, and leads to a decreasing level of BCN. Therefore, in low-density urban areas with less shading around buildings, reducing the south WWR is a reasonable way to achieve BCN under the premise of satisfying the lighting. In general, we suggest that the number of floors should be the primary parameter to control the building CNL, and on this basis, detailed optimization of other variables should be carried out. It should be noted that this strategy is premised on gross floor area as the dependent variable for number of floors and floor area, and that the sensitivity of the number of floors may be reduced when building scale is limited to a certain range.

Carbon neutral building shapes for IBS

For IBS in cold regions of China, most design solutions for PV office buildings below 50 meters are difficult to achieve BCN through passive carbon reduction and PV carbon offsetting. We found that the 1-floor buildings are completely carbon neutral, and the PV can still neutralize emissions from other sectors. The majority of 2-floor buildings also achieve BCN, with a minimum of 0.82 CNL. Starting with 3-floor buildings, it is difficult to neutralize the building's carbon emissions through PV alone. This indicates that blindly reducing the number of floors to achieve BCN is contradictory to the current design conditions of land constraints in China and that various methods of energy conservation and carbon reduction must be investigated for application in buildings.

The decrease in CNL becomes gradually smaller as the number of floors rises, and the decrease is particularly obvious in buildings with fewer than 6 floors. In China, 24 meters is used to distinguish multi-rise buildings from high-rise buildings. Therefore, 6 floors are generally the demarcation between a multi-rise and a high-rise. This implies that although the number of floors determines the building's CNL, the influence is gradually decreasing, and the impact of it is significantly greater for multi-rise buildings than for high-rise buildings. The reason for this phenomenon is that the roof PV panels account for a larger proportion of PVCO in lower-floor buildings and have the highest solar energy utilization, which becomes the major way to offset carbon. As the number of floors increases, the area of roof PV panels remains the same while the area of facade PV panels increases, and the focus of PVCO shifts from the roof to the facade. Therefore, it is suggested that multi-rise buildings should focus on the maximum utilization of roof PV, while high-rise buildings should pay more attention to facade PV.

Furthermore, it can be seen from figure 4 that, compared with high-rise buildings, multi-rise buildings have a larger domain of CNL and a less steady distribution, indicating again that these parameters have a greater impact on multi-rise buildings than high-rise ones.

A solution is selected from the Pareto solutions of a 6-floor building (Figure 5). The comparison (Table 6) with the unoptimized building shows an 15.2% reduction in LCCE, a 1.7% rise in PVCO, and a 19.0% increase in CNL. This proves that with a fixed number of floors, optimizing the floor area, building height, shading PV overhang length, and south WWR is an effective way to achieve the BCN. Therefore, a staged performance-based process is suggested for the design of PV office buildings, in which the designer first determines the number of floors based on the design requirements to initially define the achievable range of building CNL, and then utilizes an algorithm to carry out a shape optimization driven by the performance related to BCN.

Table 6: Comparison of before and after optimization of 6-floor building.

<table>
<thead>
<tr>
<th>Information for comparison</th>
<th>Before optimization</th>
<th>After optimization</th>
</tr>
</thead>
<tbody>
<tr>
<td>Floor area</td>
<td>1200m²</td>
<td>1000m²</td>
</tr>
<tr>
<td>Floor height</td>
<td>3.3m</td>
<td>3.8m</td>
</tr>
<tr>
<td>Shading PV overhang length</td>
<td>0.6m</td>
<td>1.2m</td>
</tr>
<tr>
<td>Number of floors</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>South WWR</td>
<td>0.40</td>
<td>0.58</td>
</tr>
<tr>
<td>LCCE</td>
<td>2.82×10^7 kgCO₂</td>
<td>2.39×10^7 kgCO₂</td>
</tr>
<tr>
<td>PVCO</td>
<td>1.18×10^7 kgCO₂</td>
<td>1.20×10^7 kgCO₂</td>
</tr>
<tr>
<td>CNL</td>
<td>0.42</td>
<td>0.50</td>
</tr>
</tbody>
</table>

Conclusion

In this paper, SA is utilized to reveal the shape-influencing factors of LCCE, PVCO, and CNL for typical PV office buildings below 50 meters for two scenarios in cold regions of China, and a performance-driven approach is used to optimize the shape.

The number of floors, floor area, floor height, and shading PV overhang length are the key variables for both IBS and UDS, and the south WWR shows sensitivity to CNL for IBS. Furthermore, the factors mentioned above have a significantly higher impact on multi-rise buildings than on high-rise buildings below 50 meters. In IBS, the number of floors is the most important factor, followed by the floor area, and the number of floors directly determines the achievable CNL of the building.

Compared to IBS, the impact of the number of floors on PVCO is reduced in UDS, and the floor area becomes the most critical factor. Therefore, when buildings are in high-density urban areas, the focus of PV efficiency improvement should be on floor area.

In low-density urban areas with large building intervals, roof PV has a significant impact on the CNL of multi-rise buildings, and the way of facade PV carbon offsetting should be more concerned for high-rise buildings. Besides, increasing the shading PV overhang length and the floor height are effective ways to increase the total PVCO. The
east and west facades’ PVCOs are more affected by orientation and shading PV overhang length than the south facade's PVCO.

Under the conditions that only PV is used and there is no shading around the building, BCN can be achieved for buildings of only 1 floor and some 2 floors, and buildings higher than 3 floors should try to apply more renewable energy forms. Furthermore, when the building is located in a high-density urban area, the CNL is reduced due to the reduction of solar energy utilization of the facade PV, especially for buildings with more than 3 floors, making it more essential to utilize other renewable energy. In the end, the study suggests a staged performance-based design process, which can effectively improve the performance related to BCN.

The limitations of this paper are that the selected objects are office buildings in the cold region of China, and only IBS is considered in the optimization stage; the carbon emission calculation process is simplified, which has some impact on the experimental precision. Therefore, the optimized design of BCN for a wider range of climate zones, building types, and urban scenarios, as well as more precise calculation methods, are the directions to be studied. In addition, the SA in this paper is conducted under the premise that the total floor area is not restricted, and when the building scale is limited, the relevant analysis is naturally the next step.

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References


