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Correlation between Spatial Form and Carbon Emissions from Building Operations in Dense Low-rise Commercial Blocks in Beijing

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Abstract In the context of global warming and the in-depth advancement of China's dual carbon strategy, high-energy-consuming commercial blocks have emerged as critical breakthrough points for energy conservation and emission reduction in the urban architecture field. This study introduces the local climate zone (LCZ) theory and develops a parametric numerical simulation platform by selecting ten typical dense low-rise commercial blocks (LCZ3) within the central area of Beijing as case studies. Using Pearson correlation analysis and multiple linear regression models, the research quantitatively clarifies the regulatory effects and transmission mechanisms of spatial form factors on the carbon emission intensity associated with building operations. Research has indicated that the sensitivity of each factor decreases in the following order: building density (BD)>sky visibility factor (SVF)>building height-to-width ratio (H/D)>floor area ratio (FAR). Based on these findings, the study proposes differentiated low-carbon planning and design strategies across dimensions such as development intensity, surface coverage, three-dimensional geometry, and spatial permeability. These strategies offer scientific quantitative guidelines for the renewal of existing high-density urban blocks and for refined low-carbon governance in cold regions.

Keywords Spatial form, Carbon emissions from building operations, Dense low-rise commercial blocks, Microclimate
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In response to the challenge posed by global warming, the reduction of greenhouse gas emissions has emerged as a central impetus for reshaping urban development models. Currently, as the dual carbon strategy is advancing in depth, the low-carbon transition in the architecture field is especially critical. Relevant data indicate that carbon emissions from building operations account for over one-fifth of total societal emissions, highlighting this sector as a key area for achieving emission reduction targets[1].

In cold regions, the demand for winter heating is prominent. The spatial form of commercial blocks indirectly influences energy consumption for heating and cooling by regulating the local microclimate, thereby affecting carbon emission levels. To date, numerous studies have focused on residential and office blocks. Lian et al.[2] confirmed that the influence of spatial form on building carbon emissions reached 31.66%. Su et al.[3] identified a significant synergistic effect of spatial morphological differences on pollution mitigation and carbon emission reduction. Chen Wei[4] highlighted the considerable impact of street canyon morphology and building layout on the microclimate and building carbon emissions. Mo Linyu[5] advocated for the promotion of low-carbon transportation development within commercial blocks through the optimization of spatial forms.

Currently, the classification methods for block spatial forms remain relatively traditional and lack targeted response to the carbon emission characteristics of commercial blocks. Extensive geometric and topological classifications often overlook the heterogeneity in energy consumption arising from high-density building clusters, dense traffic flows, and diverse business types within these commercial areas. This disconnection in classification dimensions restricts the precise screening of morphological factors, leading many studies to suffer from index homogenization[6], thereby weakening the effectiveness of low-carbon strategies in commercial block applications. Furthermore, three-dimensional spatial morphological factors are mutually interwoven, collectively influencing the local microclimate and indirectly impacting carbon emissions. Nevertheless, there remains an insufficient quantitative characterization of their interactive and coupling effects[7].

As a typical example of megacities in cold regions, Beijing's commercial blocks demonstrate significantly higher energy consumption density and carbon emission levels compared to residential areas, attributable to their concentrated energy use and high-density spatial arrangement. Consequently, these commercial blocks become a critical focus for reducing emissions and enhancing efficiency[8]. In this context, the present study adopts the local climate zone (LCZ) theory, which transcends the limitations of traditional classification methods that rely solely on geometric indicators and lack environmental feedback. Originally proposed by Stewart and Oke, the LCZ theory systematically categorizes urban built environments into ten typical forms based on surface configuration as well as physical and thermal characteristics, thereby effectively addressing the ambiguities inherent in conventional classifications when describing microclimatic responses[9]. This system has been extensively adopted in reports by the World Meteorological Organization and the Intergovernmental Panel on Climate Change of the United Nations, serving as a methodological foundation for international climate observation programs[10]. The present study concentrates on the LCZ3 (dense low-rise building area) category, systematically investigating the quantitative relationship between morphological factors and carbon emissions from building operation. The objectives of this research are to: (1) identify the key morphological factors influencing carbon emissions in dense low-rise commercial blocks in Beijing; (2) rank the impact intensity of these core morphological factors and examine their correlation mechanisms with carbon emissions; and (3) propose strategies to regulate low-carbon emissions in commercial blocks by considering the combined effects of multiple factors.

1 Research ideas and methods

1.1 Survey area

This study concentrates on four central

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districts of Beijing: Dongcheng, Xicheng, Haidian, and Chaoyang. Situated within the cold region of North China, this area experiences a high demand for heating in winter. It serves as a core area for the concentration of commercial buildings and the associated carbon emissions. Beijing's spatial texture is highly heterogeneous, characterized by an extremely high density of commercial activities, the coexistence of many dimensions, and a diverse array of samples. The LCZ3 blocks within the research sample are characterized by a dense combination of low-rise buildings, ranging from one to three stories, with surfaces mainly covered by extensive hard pavement. This type closely corresponds to the high-density, low-rise building texture commonly preserved in Beijing's older urban areas and historic traditional commercial districts. Accordingly, this study ultimately selected ten representative dense low-rise commercial blocks as the primary research samples.

1.2 Research methods

This study developed a technical framework for investigating carbon emissions from building operations at the block scale by integrating parametric simulation with statistical analysis.

(1) A volumetric model was constructed. Using the three-dimensional model of the commercial block generated on the Rhino platform as input, multi-module collaborative operations were performed through the Grasshopper parametric tool.

(2) The Urban Weather Generator urban canopy model was introduced to adjust local climate effects, with the objective of dynamically characterizing the complex microclimate environment of commercial blocks. Based on this model, standardized energy consumption parameters, including building envelopes, personnel behavior, and the operation of mechanical and electrical device, were integrated into the Energy Plus engine via the Honeybee module to perform hourly, all-terminal energy consumption simulations. By incorporating the energy carbon emission factor method, this approach enabled precise quantification of carbon emissions from building operations.

(3) The study integrated GIS-based geographic spatial data with morphological mathematical algorithms to calculate multidimensional morphological factors, including building density and shape coefficients, thereby establishing a database of block morphological characteristics.

(4) Through Pearson correlation analysis and multiple linear regression, the marginal effects of core morphological parameters on carbon emissions were quantified after eliminating redundant interference factors.

1.3 Data source

1.3.1 Building energy data. The study developed a multi-source data system covering geographic spatial information, meteorological and environmental data, and energy utilization parameters. Commercial plots within the core area of Beijing were identified using geographic information system (GIS) technology, and morphological information for ten typical LCZ3 blocks was extracted through the analysis of satellite imagery and POI data.

The meteorological data utilized in this study were obtained from the Chinese Standard Weather Data (CSWD) and included hourly measurements of temperature, humidity, wind speed and direction, as well as scattered radiation in Beijing. To ensure a close representation of actual microclimatic conditions, the data were calibrated and preprocessed accordingly. The thermophysical properties of the underlying surfaces, such as road reflectance, vegetation coverage and reflectance, were determined based on values reported in the literature, and anthropogenic heat emissions from traffic were incorporated into the analysis[11-12].

Energy parameters were established in accordance with the *Energy Efficiency Design Standard for Public Buildings* in Beijing and relevant commercial measurement rules[13], including lighting power density, personnel occupancy rates, device energy consumption, and heating and cooling power. Lighting power was determined based on the thresholds specified in the *Standard for Lighting Design of Buildings*[14]. Personnel occupancy rates were introduced into a commercial schedule curve and converted into hourly percentages[15]. Device energy consumption was coordinated with personnel occupancy rates, while the operation of air conditioning systems adhered to the legal heating and cooling nodes.

1.3.2 Selection of morphological factors. To ensure that each factor remains mathematically independent and can collectively form a multi-dimensional complementarity within the external spatial representation, while accurately reflecting the physical interaction processes between the microclimate environment of the block and building energy consumption, this study selected two complementary variables for each of four dimensions: development intensity, surface coverage, three-dimensional geometry, and spatial permeability. This framework not only regulates macroscopic energy consumption concentration and heat dissipation boundaries through development intensity and surface coverage but also influences heat transfer and air duct obstruction of the building envelope via three-dimensional geometry and spatial permeability.

1.4 Simulation and calculation methods

1.4.1 Simulation of building energy consumption. Full-cycle hourly simulation of energy consumption was conducted using the Energy-Plus open-source engine[16]. The topologically corrected three-dimensional model of the commercial blocks was converted into a thermal calculation zone. Additionally, local microclimate meteorological data of Beijing, adjusted by the urban weather generator, along with energy consumption parameters compliant with energy-saving standards for public buildings in cold regions, were incorporated[17]. The simulation process encompassed the four primary categories of terminal energy consumption, including heating, cooling, lighting, and device, and produced detailed hourly energy consumption data for the entire year, thereby accurately capturing the seasonal and operational fluctuations in energy use within commercial buildings.

1.4.2 Calculation of carbon emission. Based on the carbon emission factors associated with different energy types released by Beijing in 2025, the terminal energy consumption coupling summation method was employed to perform the calculation[18]. The formula used is as follows:

$$CEI=\frac{\sum_{i=1}^{n}=(E_{h,i}+E_{c,i}+E_{l,i}+E_{e,i})\times EF_i}{A}$$

where CEI represents the annual carbon emission intensity per unit of building area, expressed in $kg\cdot CO_2/(m^2\cdot a)$; $E_{h,i}$, $E_{c,i}$, $E_{l,i}$, and $E_{e,i}$ denote the annual cumulative energy consumption for heating, cooling, lighting, and device, respectively, corresponding to the i-th type of energy; EF_i refers to the carbon emission factor associated with the i-th type of energy; and A signifies the gross floor area of the block[19].

Calculation of morphological factors. The eight preliminary indicator systems consisted of floor area ratio (FAR), gross floor area (GFA), building density (BD), pervious surface fraction (PSF), building shape coefficient (S), building height-to-width ratio (H/D), sky visibility factor (SVF), and open space ratio (OSR). To ensure the independence of these indicators and eliminate redundancy, this study employed Origin software to quantitatively assess the significance of the relationships between each factor and carbon emissions from building operations using Pearson correlation analysis.

2 Results and analysis

2.1 Calculation results of carbon emission simulation and morphological factors

Fig.1 shows the annual carbon emission intensity per unit area for ten samples across four categories: heating, cooling, lighting, and device. Among these, heating and cooling carbon emission intensities accounted for the largest proportions across all samples, exhibiting considerable variability. Given that the programs of this type of commercial blocks were consistent during the building energy consumption simulation, modeled uniformly as retail spaces, the annual carbon emission intensities for lighting and device remained relatively stable. Notably, the carbon emission structures varied among different samples. Table 1 summarizes the calculated values of eight primary morphological factors for the ten samples.

2.2 Correlation analysis between morphological factors and carbon emissions

The Pearson correlation coefficient was employed to assess the degree of linear association between two variables, with values ranging from −1 to 1. A significance threshold of $P<0.05$ was established to identify variables with strong explanatory power. Table 2 presents the correlation data between morphological indicators and carbon emissions. This approach was utilized to develop the logical relationships between physical spatial factors and carbon emissions from building operations[20]. Through Pearson correlation analysis, a comprehensive evaluation was performed on eight morphological indicators of the LCZ3 dense low-rise commercial blocks in Beijing. Four key factors, namely FAR, BD, H/D, and SVF, were initially identified as significantly correlated with total carbon emission intensity.

As shown in Fig.2, the FAR exhibited a significant positive correlation with BD, suggesting that high-intensity land development is associated with concentrated energy consumption and serves as a primary spatial determinant of carbon emission growth. The OSR and SVF demonstrated either a negative correlation or complex microclimatic constraints, indicating that three-dimensional form indirectly influences energy consumption by modifying solar radiation and airflow[21]. Following the removal of highly collinear and redundant parameters through correlation analysis, FAR, BD, H/D, and SVF were selected as the core input variables for multiple regression analysis.

2.3 Impact of morphological factors on carbon emissions

Multiple linear regression analysis is used to examine the linear relationship between a single dependent variable and multiple independent variables. This study introduced the model and utilized the ordinary least squares method for parameter estimation to quantitatively assess the contribution of each morphological factor to carbon emission intensity[22]. By comparing the magnitudes of standardized regression coefficients, the primary morphological factors influencing variations in the energy efficiency of commercial blocks were identified.

Within the control network of total carbon emission intensity, sensitivity was observed to follow the order BD>SVF>H/D>FAR (Fig.3). In cold regions characterized by prolonged winters, heating-related carbon emissions dominate throughout the year, thereby causing the overall carbon emissions to be heavily influenced by the thermal characteristics of winter. The BD determines the scale of the horizontal base and the heat transfer boundary of the building envelope. The SVF affects the radiation balance by modulating three-dimensional openness. The H/D alters the canyon outline and disrupts the near-surface

Table 1 Calculation results of morphological factors

Sample No.	Sample name	GFA	FAR	BD	PSF	H/D	S	SVF	OSR
S1	768 Creative Industry Park	58,000	0.84	0.41	0.63	0.24	0.26	0.81	0.90
S2	Longhui 1910 Cultural and Creative Industrial Park	53,200	0.80	0.44	0.31	0.16	0.26	0.74	0.97
S3	Dashilan	63,294	1.38	0.63	0.02	0.32	0.37	0.67	0.22
S4	Langyuan Vintage	30,000	1.30	0.56	0.27	0.63	0.24	0.53	0.36
S5	Liulichang West Street	42,606	0.97	0.54	0.18	0.30	0.38	0.73	0.76
S6	Nanluogu Lane	32,490	1.04	0.60	0.39	0.27	0.57	0.72	0.29
S7	Courtyard No.4, Sanlitun Machinery Institute Compound	35,585	1.09	0.50	0.16	0.28	0.23	0.66	0.46
S8	Wudaoying Hutong	35,536	0.98	0.49	0.20	0.22	0.41	0.73	0.33
S9	Yandai Xiejie	18,216	1.19	0.54	0.06	0.26	0.43	0.67	0.30
S10	Friendship Store	20,620	1.17	0.55	0.23	0.48	0.33	0.52	0.51

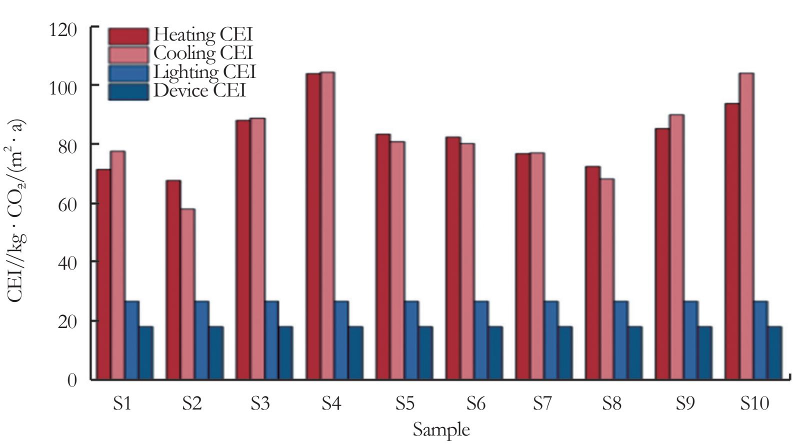

Fig.1 Carbon emission intensities for ten samples across four categories

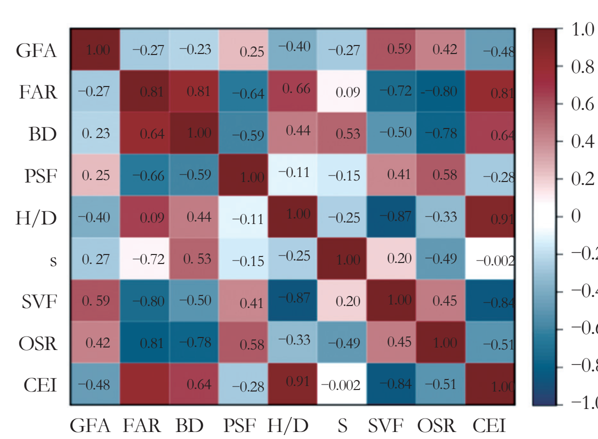

Fig.2 Pearson correlation analysis

wind field. The relatively low influence of the FAR suggests that, within a dense low-level context, the capacity of volumetric expansion to affect total carbon emissions is weaker than the microclimatic feedback mechanisms associated with horizontal coverage and sky openness reshaping.

The sensitivity ranking of carbon emissions related to heating was as follows: BD>SVF>H/D>FAR. The high temperature difference between indoor and outdoor environments, combined with high building density, results in an extensive horizontal envelope contact surface area, which causes a linear increase in heat transfer losses proportional to the base area. Dense individual shading significantly reduces the SVF, thereby obstructing the block's capacity to capture passive solar radiation and consequently reducing solar heat gains. An increased H/D increases the convective heat transfer coefficient of the envelope structure.

The sensitivity of cooling carbon emissions exhibited the following trend: SVF>BD>H/D>FAR. Summer carbon control primarily involves suppressing the interception of short-wave radiation during daytime and enhancing the dissipation of long-wave radiation at night. A low SVF hinders the release of long-wave radiation during nighttime, resulting in a pronounced heat retention effect that raises the microclimate base temperature and consequently increases the cooling load sharply. High BD contributes to the formation of a huge heat storage body on the high-density underlying impervious surfaces. The H/D restricts near-ground wind speeds.

3 Discussion

3.1 Transmission mechanism of carbon emissions from building operation driven by spatial form

3.1.1 Intrinsic impact of morphological factors on carbon emissions in LCZ3 commercial

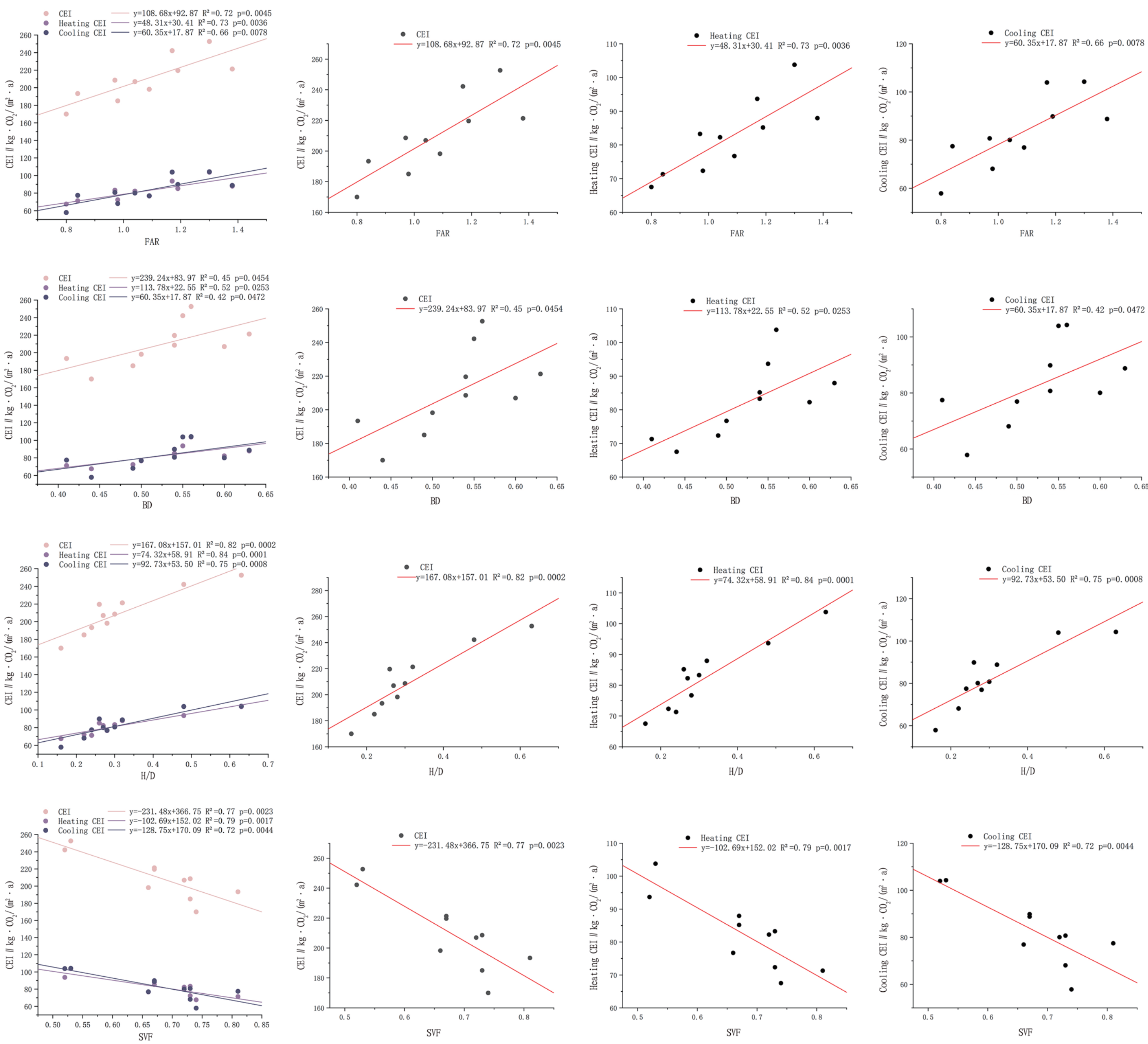

Fig.3 Linear regression models of morphological factors and carbon emission intensity

Table 2 Correlation between morphological indicators and carbon emissions

Architectural form factor	Correlation and significance	Carbon emission intensity
GFA	Correlation	−0.475 9
	Significance	0.164 4
FAR	Correlation	0.810 0
	Significance	0.004 5
BD	Correlation	0.641 9
	Significance	0.045 4
PSF	Correlation	−0.277 8
	Significance	0.437 2
H/D	Correlation	0.914 5
	Significance	0.000 2
S	Correlation	−0.002 0
	Significance	0.995 7
SVF	Correlation	−0.841 8
	Significance	0.002 3
OSR	Correlation	−0.507 3
	Significance	0.134 5

blocks. The model analysis revealed that BD, categorized under the surface coverage dimension, was the predominant influencing factor. An increase in the lateral expansion of the base area directly increased the base carbon emission boundary. Specifically, for every 0.1 unit increase in BD, the CEI increased by 19.06 kg·CO_2/(m^2·a). SVF exhibited a strong negative correlation with carbon emission intensity, with its contribution rate ranking second only to BD. A 0.1 unit decrease in SVF (reflecting a reduction in sky openness) resulted in a significant surge in CEI, identifying SVF as a critical negative control variable. The H/D demonstrated a positive effect on carbon emission intensity, whereas the FAR had the least influence among the variables considered.

This intrinsic connection at the quantitative level profoundly indicates that, within the specific spatial context of dense low-rise commercial blocks, the intensity of carbon emissions from building operations does not solely depend on the absolute expansion of three-dimensional building volume. Instead, it is primarily influenced and jointly determined by horizontal coverage density and the degree of sky openness.

3.1.2 Indirect impact of morphological factors on carbon emissions in LCZ3 commercial blocks. In addition to the direct quantitative relationship, spatial form also exerts a complex indirect influence on carbon emissions by shaping the microclimate at the block scale. High BD and extensive impervious surfaces create huge heat storage body and reduce the openness of the sky, leading to intense radiation trapping during summer. This phenomenon hinders heat dissipation at night, increases local baseline temperatures, and consequently increases energy demand for cooling. In cold regions during winter, densely arranged building units obstruct passive solar radiation pathways, diminishing natural heat gains. Additionally, deep street canyons tend to induce turbulence and downdrafts within the wind field, which significantly enhance convective heat transfer losses and result in a marked increase in carbon emissions associated with heating.

3.2 Low-carbon design strategies for dense low-rise commercial blocks in Beijing

Given the absolute dominance of BD to carbon emissions, the design should, while ensuring commercial capacity requirements are met, strategically regulate the extent of continuous horizontal base coverage by incorporating discontinuous forms such as point and staggered designs. To improve the SVF, priority should be accorded to the design of north-south oriented streets and alleys, as well as south-facing building setbacks. Expanding north-south pedestrian corridors and implementing stepped setbacks can optimize the passive solar heat gains within the block. Furthermore, the spatial contour should be designed to mitigate exposure to the northwest wind, which is the prevailing winter wind direction, to minimize convective heat loss, thereby achieving a dual objective of reducing heat loss during winter heating periods and enhancing nocturnal heat dissipation in summer.

The relatively low ranking of FAR within the energy consumption network offers strategic flexibility for achieving low-carbon objectives. An effective approach should focus on the non-uniform redevelopment of three-dimensional space, enabling the dilution of thermal disturbance loads associated with FAR through targeted local height modifications, three-dimensional greening initiatives, and the use of high-reflectivity materials, all while maintaining control over BD and ensuring adequate SVF.

4 Conclusions

This study examines typical dense low-rise commercial blocks in Beijing to systematically and quantitatively clarify the driving principles and internal mechanisms by which spatial form factors influence the carbon emission intensity associated with building operations.

(1) Research indicates that the sensitivity of each factor to the overall carbon emission intensity generally follows a decreasing order: BD>SVF>H/D>FAR. This pattern effectively reflects the climatic conditions characteristic of cold regions, including prolonged winters and significant temperature differences between indoor and outdoor environments.

(2) The sensitivity ranking of carbon emission factors influencing heating is as follows: building density BD>SVF>H/D>FAR. High BD directly restricts the extensive horizontal envelope heat transfer area, while the significant reduction in SVF resulting from the mutual shading of high-density individual buildings is the primary cause of significant losses in natural solar heat gains and the consequent sharp increase in carbon emissions during winter heating.

(3) The sensitivity ranking of carbon emission factors affecting cooling is as follows: SVF>BD>H/D>FAR. This hierarchy reflects the fundamental physical mechanisms underlying summer carbon control, which primarily aims to reduce the interception of short-wave radiation during daytime and enhance the dissipation of long-wave heat at night. The pronounced heat retention effect resulting from a lower SVF, combined with the heat storage capacity of hard surfaces under high BD, along with the significant suppression of near-surface wind speed caused by a deep H/D, constitute the principal factors that hinder timely convection and diffusion of local heat and induce the increased intensity of carbon emissions during the summer cooling period.

(4) There are clear quantitative thresholds for low-carbon planning control strategies applicable to dense low-rise commercial blocks. It is recommended that the FAR of existing dense low-rise commercial blocks in Beijing should be maintained between 0.80 and 1.10, while the BD should be set within the range of 0.44 to 0.50 to achieve an optimal balance of efficiency. This recommendation is derived from a reverse analysis of low-carbon benchmark

samples (e.g., S2, S7, and S8), indicating that such interval not only preserve commercial capacity and economic vitality but also effectively mitigate heat dissipation losses associated with indiscriminate horizontal expansion of the base.

The limitations of this study stem from its exclusive focus on dense low-rise building types, without encompassing diverse spatial structures such as high-rise or open structures. The scope of analysis is confined to the energy consumption associated with building operations, lacking a systematic integration of carbon emissions related to block-level traffic and landscape carbon sinks. Future research should aim to broaden the sample coverage across various local climate zones and advance carbon studies that transition from solely examining energy consumption to addressing a bidirectional balance between production capacity and energy use. This approach is essential for achieving comprehensive carbon regulation at the block scale.

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