

Article

Impact of Urban Morphology on High-Density Commercial Block Energy Consumption in Severe Cold Regions

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Abstract: In sustainable city development, urban form plays an important role in block energy consumption, and as different environmental contexts and block functions create differences in energy use, it is necessary to study the relationship between morphology and energy consumption under the dual constraints of special environments and special block functions. Urban high-density blocks have concentrated energy consumption, high energy intensity, and complex morphological layout, but the influencing mechanism of the block's morphology on its energy consumption remains unclear. Accordingly, this study focuses on the mechanism and evaluation method of the influence of morphology on the energy consumption of high-density commercial blocks in severe cold regions. Through Grasshopper model extraction, EnergyPlus performance simulation, Pearson correlation analysis, and linear regression analysis, this study extracts and classifies high-density commercial blocks in Harbin, China, into six basic layout types (Courtyard, Courtyard-T, Slab, Slab-T, Point, Point-T) according to their horizontal and vertical morphology, analyzes the energy consumption characteristics of each basic type, examines the relationships between energy use intensity (EUI) and building density (BD) and between floor area ratio (FAR) and building height standard deviation (BHSD), and constructs theoretical models by controlling variables to study the effect of a single form parameter on block EUI. The research findings are as follows: (1) The annual energy consumption of Point and Slab blocks is relatively low, whereas that of Courtyard and Courtyard-T blocks is higher due to the lack of open space in Courtyards and the poor ventilation in summer. (2) FAR is significantly correlated with the energy consumption of high-density commercial blocks in severe cold regions, while the effects of BD and BHSD are weaker than those of FAR. For every 0.1 increase in BD, every 1 increase in FAR, and every 1(m) increase in BHSD, the Winter Daily EUI of the Slab block changes by +0.87, −2.26, and −0.22 (kWh/m²), respectively, whereas that of the Slab-T block changes by −0.38, +0.68, and +0.08 (kWh/m²), respectively. (3) Controlling other variables, a large BD is theoretically beneficial to energy performance in the blocks, and increasing BD in the range of 0.4–0.55 has a significant effect on lowering energy consumption in Point blocks. EUI increases with the increase in FAR, while the change depends on different block types with the increase in BHSD. This study provides design strategies for high-density commercial blocks in severe cold regions. Under different layout types, though EUI shows different relationships with BD, FAR, and BHSD, Slab-T and Point-T blocks can achieve excellent energy performance by appropriately increasing BD and decreasing FAR, whereas Slab blocks need to decrease BD while increasing FAR. The patterns found in this paper can provide strategic help for policymaking and early urban design.



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Keywords: energy consumption; commercial block types; urban morphology; building performance; regression analysis

1. Introduction

1.1. Background

Carbon neutrality has become a common goal for all humanity. The total energy consumption of the building sector has grown by an average of 1% per year over the past 10 years, reaching 133 EJ (exajoules) in 2022, accounting for 30% of the world's total energy consumption [1]. According to the Global Carbon Project platform, China is the world's largest CO₂ emitter, accounting for 30.68% of global carbon emissions in 2022 [2]. Therefore, it has become urgent to study the mechanism of energy saving and emission reduction in the construction industry to reduce the energy consumption of buildings.

In China, cold regions account for about two-thirds of China's land area, and building energy consumption accounts for more than 50% of the national energy consumption [3]. Inhabitants of severe cold regions require a long heating period in winter to overcome the cold weather, and the percentage of energy consumption for heating in winter is much higher than that in other regions [4], as the temperature is one of the most critical microclimate factors in cold regions directly affecting the heating and cooling needs of buildings. Therefore, severe cold cities face greater challenges than other regions in terms of energy efficiency, and the extreme climatic conditions make the study of building energy consumption in severe cold regions an important issue [5].

High-density commercial blocks are the main venues for citizens' activities and the main economic core area of the city, characterized by high building density (BD), high floor area ratio (FAR), dense population, and rich crowd activities [6]. Due to their concentrated energy consumption, industrial agglomeration, and complex morphological characteristics [7], their energy saving and carbon emission problems are especially worthy of attention, making it vital to study their energy consumption impact mechanisms. The special climate of severe cold regions, such as obvious seasonal changes and large temperature differences between day and night, leads to more complicated energy saving and emission reduction problems in complex high-density commercial blocks.

Urban form can influence the carbon emission situation [8] and energy consumption [9] of a city, and due to the diversity of commercial building forms, their characteristics affect energy consumption to a greater extent than those of other types of buildings. There is thus an urgent need to quantify and analyze the energy consumption of high-density commercial blocks in severe cold regions to study the form–energy impact mechanism under the dual constraints of special environments and special types of buildings.

1.2. Literature Review

1.2.1. Research on Context of Form–Energy Relationship

Studies of urban morphology and building energy consumption are extensive, and researchers have primarily derived the relationship between morphology and energy consumption for different climatic conditions and environmental contexts. In cold regions, the extremely cold winter creates a large indoor–outdoor temperature difference; approximately 50% of the annual energy consumption for air conditioning and heating in public buildings is due to heat transfer between the interior and exterior of the building [10], and urban form has an important impact on energy consumption. For example, Arboit et al. found in their study of Mendoza, Argentina [11], that the building form and orientation of urban blocks are the most important variables affecting the potential of solar energy utilization for space heating. Youngsoo and Seahoon [12] reported that urban morphology can influence and determine the thermal efficiency of buildings through both physical and non-physical attributes. Physical attributes include spacing between houses, road widths, and building height, whereas non-physical attributes include land use, detailed building use, age, and the history of renovation, extension, and conversion. Leng et al. [13] analyzed the relationship between urban form parameters and building heating energy consumption in cold regions of China and found that for every unit increase in the perimeter and FAR, the building heating energy consumption was reduced by 6.76%. In hot regions, the urban heat island effect and humidity have important influences on building energy consumption.

For example, a study in Singapore [9] evaluated the impact of morphological parameters such as BD, height, and greenness on microclimate and found that they can cause a temperature change of 0.9–1.2 °C, which can reduce cooling energy consumption by 5–10%. Furthermore, Zinzi [14] pointed out that the urban heat island effect led to a 21% reduction in heating energy consumption in residential buildings. In hot-summer and cold-winter regions with sultry winters and humid summers, there is no heating system, but the heat and humidity load of air conditioning is high in summer. For example, Zhu [15] highlighted in his study of Nanjing that block building and green space forms can affect the total energy consumption of local settlements through coupling. Similarly, Xie and Wang [16] pointed out that the energy consumption of campus blocks in Wuhan is mainly affected by three morphological parameters, namely, the average length of the block, the shape factor, and the BD. It can be seen that under different kinds of climatic environments, building energy consumption is affected by morphology in different ways, and the mechanism of the effect of morphology on energy consumption is significantly affected by the climatic environment. Therefore, there is a need to conduct targeted research under the specific environment of severe cold regions.

Different functional types of buildings have differences in energy consumption due to different HVAC systems, occupant behaviors, and energy-using component requirements. Quan et al. pointed out [17] that most of the simulation studies chose case sites with residential, office, and mixed building functions, with only one study focusing on commercial building functions, whereas empirical studies extensively selected residential buildings as the focus of study. For example, Xia et al. [18] extracted the urban morphology characteristics of low-energy sustainable settlements through simulation analysis, multiple linear regression prediction, and nonparametric tests using a residential area in Hangzhou City. Tian et al. [19] evaluated the renewable energy potential of 36 residential communities located in Wuhan City, China, and proposed an optimal installation strategy for photovoltaic building integration in settlements. Leng et al. [13] studied the energy consumption of 73 office buildings and 7 urban morphology indices around these buildings through methods such as simulation and statistics and showed that larger building footprints, FAR, building heights, road height-to-width ratios, total wall areas, and lower green space ratios are conducive to the reduction in energy consumption in cold-land heating. However, the study showed in a comparison of the functional blocks in the cold region that the blocks with predominantly commercial functions are more diverse in form and more complex in layout than other blocks, and the annual heating energy consumption of retail buildings is among the highest, and the difference in energy consumption between retail buildings is greater than the difference in energy consumption between other buildings of the same type [20].

Due to the limited environmental context explored in the literature, the influencing mechanisms of morphology–energy consumption under specific environmental constraints are not clear, and some important building function types are rarely discussed in the literature, such as commercial blocks and hospitals. As building energy consumption in severe cold regions is severely affected by climate, and commercial buildings have high energy consumption and complex energy use, in-depth research on this subject is necessary.

1.2.2. Research on Mechanisms of Form–Energy Relationship

Building energy consumption can be effectively controlled by adjusting block morphology [21,22], which can affect 10–30% or even more of building energy consumption [23,24]. Urban morphology affects block energy consumption in two ways. On the one hand, there is a direct effect, where mutual shading between buildings affects the distribution and reflection of solar radiation, which in turn affects the energy consumption of lighting, cooling, and heating in buildings. On the other hand, urban morphology affects the internal energy balance of the area by changing the regional microclimate, such as air temperature, wind speed, and wind direction, which in turn affects the cooling and heating loads of buildings.

Researchers have quantified the relationship between urban form and block energy consumption by selecting different morphological indicators, among which the block layout type and overall construction intensity of the block are the most important. Block layout pattern is a concern in building typology. Martin and March [7] classified urban blocks into three categories: Point, Courtyard, and strip, and scholars have used different classifications based on this. Adjusting the block layout can change the block energy consumption: Shareef and Altan [25] carried out a study of the effect of meandering form on building energy consumption in Dubai, finding that building cooling energy consumption can be reduced by 4.9% when buildings are arranged alternately in an urban block; Bat et al. [26] investigated the relationship between the form of urban courtyards and building energy consumption, showing that in temperate climates, courtyards with small widths and medium depths can reduce energy consumption by 58%. The optimal layout pattern has been a focus of scholarly discussion: Zhang et al. [27] identified six prototypes in a tropical high-density city in Singapore and found that Courtyard and mixed-type blocks outperform tower-type and Slab-type blocks in energy use; Wang et al. [28] identified six block prototypes in Beijing based on the difference between the horizontal layout of the row type and enclosure type, as well as the difference in building height, and they found that low-rise building + tower-enclosed and low-rise building + tower-determinant blocks have the best energy efficiency; Vartholomaos [29] examined the effect of three types of buildings—Point, Slab, and Courtyard—on building heating and cooling energy consumption in the Greek Mediterranean city of Thessaloniki, and they concluded that compact layout, south-facing buildings, and Courtyard block forms are the most energy-efficient group layout patterns in the Mediterranean climate zone. It can be seen that the impact of block layout on energy consumption is unclear, and there is no definitive answer as to what the most energy-efficient block layout pattern is.

The impact of construction intensity on the energy consumption of a block has been a focus of scholarly research using indicators such as FAR, BD, open space rate, and average number of floors [30]. Some scholars quantified the extent to which construction intensity affects energy consumption, and their studies show that the effect is extremely significant: For example, Strømman-Andersen et al. [24] found that BD affects natural light and passive solar heat gain in buildings, which in turn affects lighting, cooling, and heating energy consumption by as much as +30% for office buildings and +19% for residential buildings. Additionally, Martins et al. [31] observed a 50% effect of building height on heating demand. Other scholars discussed the specific correlations between BD, FAR, and energy consumption, with some studies reporting a positive correlation and others either a negative correlation or a positive correlation within a certain range. For example, Pears et al. [32] argued that high density leads to high energy consumption, which is mainly due to heat loss, trade-offs between solar radiation and lighting, and the use of elevators and other amenities. Holden et al. [33] contended that there is a negative correlation between density and the energy consumption of buildings in compact residential areas, and Strømman-Andersen et al. [24] found that in higher-density areas, there is more public infrastructure and walls, which reduces heat gain/loss and energy consumption. Quan et al. [34] stated that energy consumption in urban blocks is negatively correlated with low density and positively correlated with high density and that energy consumption decreases with FAR up to a certain threshold and then starts to increase. Rode et al. [35] stated that building intensity has a more complex relationship with energy consumption. It can be seen that the relationship between a single construction intensity parameter and energy consumption is very complex and is affected by a variety of factors, and the conclusions of the studies are not uniform.

In summary, no clear conclusions have been drawn on how block layout and construction intensity affect the energy consumption of blocks. There is a lack of detailed comparative analysis of the energy consumption of different block layouts under specific environmental contexts. Additionally, the relationship between BD and FAR and energy

consumption is even more unclear, and the mechanism of their influence is even more complex, so there is an urgent need for an in-depth study of this issue.

1.3. Research Question Framing

Based on the above assessment, this study has the following research objectives: first, to propose a workflow for studying the relationship between morphology and energy consumption in complex blocks; second, in the first part of this workflow, to refine the morphological characteristics of severe-cold-region high-density commercial blocks; third, in the latter part of this workflow, to quantitatively analyze the influence of layout types and morphological indicators on the energy consumption of severe-cold-region high-density commercial blocks. The technology roadmap is shown in Figure 1.

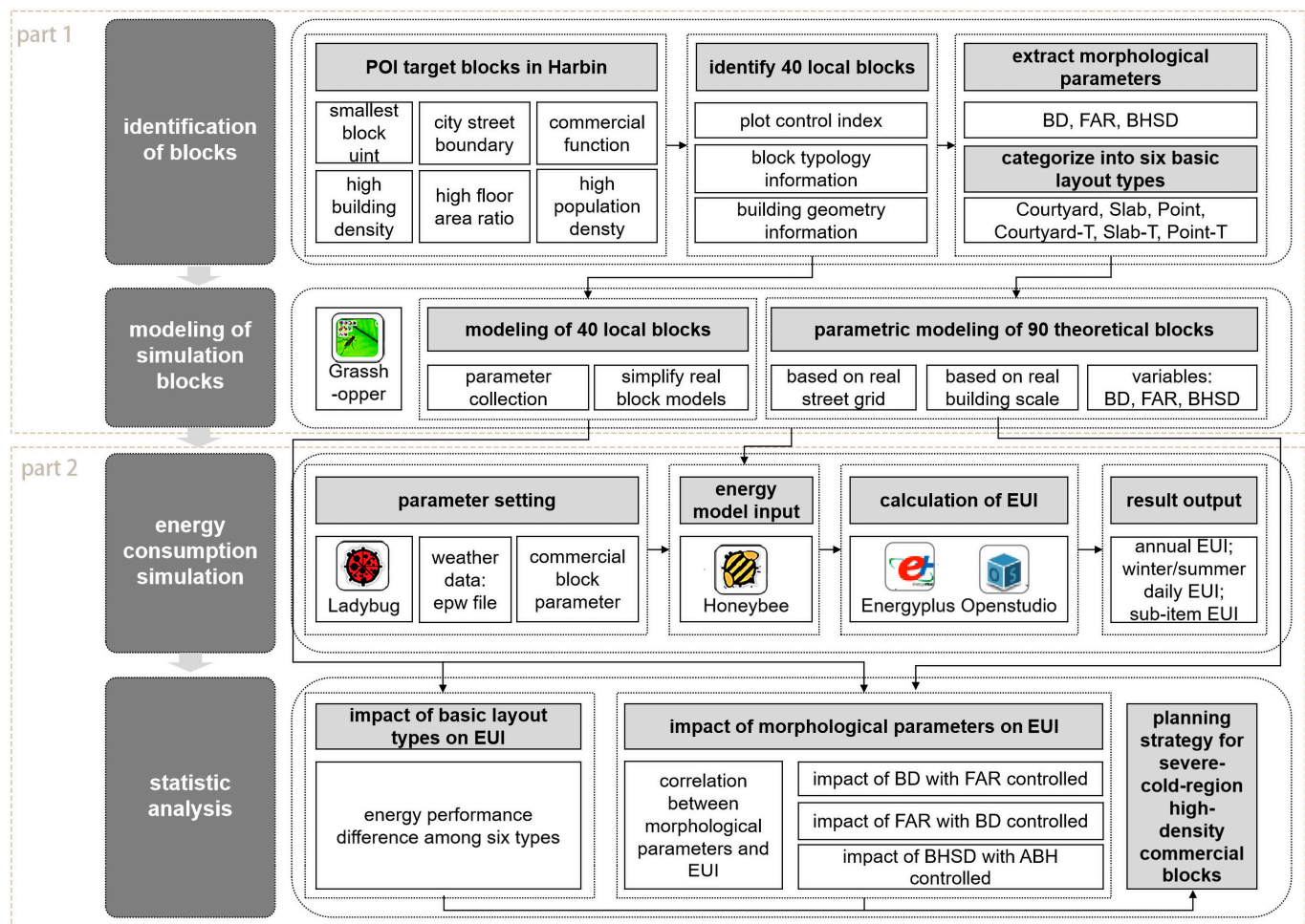


Figure 1. Research process diagram.

This study aims to discuss the following questions:

- (1) What is the difference in energy consumption among different layout types of high-density commercial blocks in severe cold regions?
- (2) What is the mechanism underlying the impact of major morphological indicators on the energy consumption of high-density commercial blocks in severe cold regions?

At the theoretical level, this study seeks to provide a methodology for the study of the relationship between complex urban form and energy consumption in high-density severe cold regions, and at the practical level, it tries to provide design strategies and recommendations for future energy-efficiency-oriented planning of high-density commercial blocks.

2. Materials and Methods

2.1. Case Study

2.1.1. Study Area

Harbin is located in Northeast China, between $125^{\circ}42'$ and $130^{\circ}10'$ E longitude and $44^{\circ}04'$ and $46^{\circ}40'$ N. Harbin belongs to the severe cold region of China, where the average temperature of the coldest month of the cumulative year is lower than or equal to -10°C .

In order to study the mechanism of the influence of the morphology of commercial buildings on energy consumption in severe cold areas, this study selects high-density commercial blocks in Harbin as samples, investigates their layout and morphology parameters, and analyzes them through theoretical and actual model simulation.

2.1.2. Selection of Measurement Points

Crawler technology was employed to capture Harbin's commercial Point of Interest (POI) on the Gaode map, and the spatial statistical data were transformed into a shapefile format in ArcGIS. The POI map shows that Harbin's commercial blocks are concentrated inside the second ring, so we limited our research scope to blocks situated inside the second ring of Harbin.

In order to select suitable cases of commercial blocks, the streets, building outlines, and number of floors were exported. We generated blocks by streets, numbered them, and then calculated the total base area and total floor area of buildings within the same number. The BD is obtained by dividing the total base area of buildings by the block area, and the FAR is obtained by dividing the total build-up area by the block area. The layers are colored, as shown in Figure 2.

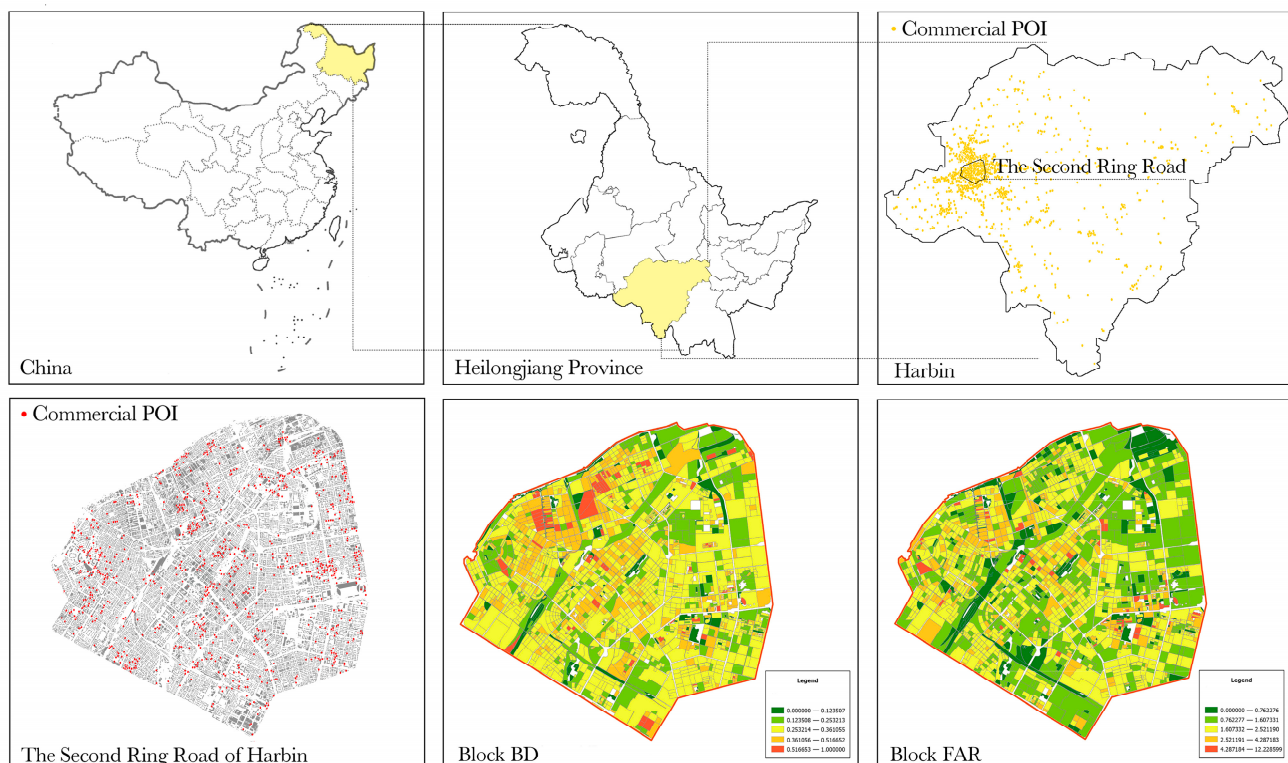


Figure 2. Selection of measurement points.

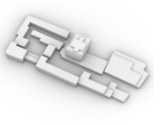
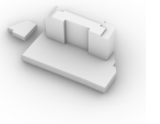
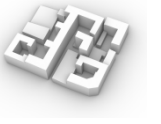
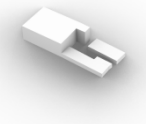
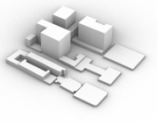
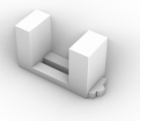
Figure 2 shows the screening of the samples of high-density commercial blocks from the second ring of Harbin with the following screening criteria:

- Functional orientation: with commercial functions, such as department stores, shopping malls, and pedestrian streets.

- BD: high density of buildings within the block.
- FAR: high intensity of building construction within the block.
- Population vitality: high population density.

Through the comprehensive evaluation of all aspects, 40 typical samples were screened out, listed in Table 1.

Table 1. Forty typical block samples selected from Harbin.

							
1. Central Mall	2. Biyot Plaza	3. Renhe Spring	4. Global Power Mall	5. McKellar General Store	6. Songlei Daoli Store	7. Zhuozhan Shopping Center	8. Hart Shopping Mall
							
9. Shangri-La Hotel	10. 14th Avenue West, Central Street	11. Turbot International Commodity City	12. Zhenlong Commercial Building	13. Xiu Long Commercial Building	14. Manhattan Commercial Building	15. Xin Sheng Long Commercial Building	16. Tian Di Metal Materials
							
17 Pacific Place	18. Jingyang Pedestrian Street	19. International Home Appliances City	20. Central Street Chinese Medicine Street	21. Harajuku Spring	22. Changyun Building	23. Central Classic	24. Life Insurance Company
							
25. Harvey Plaza	26. Gourmet Baroque	27. Hei Long Jiang Daily Group	28. Song Lei Nangang Store	29. Yuanda Shopping Center	30. Great World Mall	31. Provincial Finance Building	32. Green Sea Building
							
33. Orvis Business Plaza	34. Qiulin Company	35. Gangnam International Building	36. Xiangfang Wanda Store	37. Xiangfang Wanda 2	38. Songshan Chuangzhi Building	39. Pufa Building	40. Red Brick Street

Through GIS calculations, the block BD and block FAR were obtained, which were used as the horizontal and vertical coordinates of a matrix analysis (Figure 3). It can be seen

that the density of the selected cases is between 0.3 and 0.75, and the FAR is between 1.0 and 7.0. The blocks with small volume ratio and high BD are mainly ground-floor pedestrian streets, such as the Central Mall on Central Avenue; blocks with large plot ratios and low building densities tend to have high-rise buildings, such as Song Lei Nangang Store; and the blocks with both large volume ratio and high density are mostly a combination of low-rise commercial and high-rise offices or hotels, such as the Great World Mall.

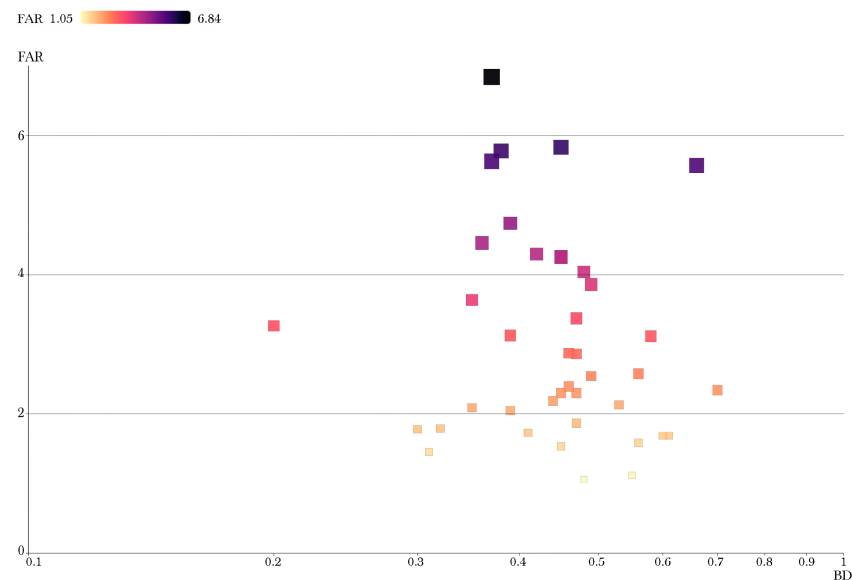


Figure 3. The BD and FAR distribution of the selected blocks.

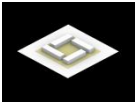
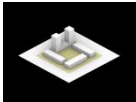
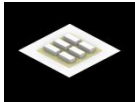
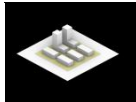
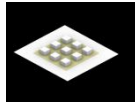
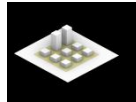
2.2. Prototype Analysis of Commercial Block Morphology

2.2.1. Classification of Basic Types

Summarizing the selected 40 commercial sites, it can be seen that the commercial streets within the second ring road of Harbin are dominated by multi-story buildings of 10–24 m in height, as well as a combination of multi-story and high-rise buildings. In terms of scale, most of them are building clusters, covering an area of 150 m × 150 m.

According to different plane forms, commercial blocks are divided into strip, Courtyard, and Point blocks. For example, International Home Appliances City is classified as strip and Songlei as Point. By their vertical forms, blocks are divided into multi-story and high-rise, whereby Pacific Place is multi-story and Songlei is a combination of multi-story and high-rise. Based on different planar and vertical forms, the blocks selected were divided into six basic types: Courtyard, Courtyard + tower (Courtyard-T), Slab, Slab + tower (Slab-T), Point, and Point + tower (Point-T), as shown in Table 2.

Table 2. Basic forms of commercial blocks.

	Courtyard	Courtyard-T	Slab	Slab-T	Point	Point-T
Basic type						
Commercial block	1, 10, 13, 17, 20, 21, 27, 34, 38	8, 14, 15, 16, 22, 24, 31, 32, 35	3, 13, 19, 20, 37	6, 9, 22, 23, 28, 36, 39	2, 7, 11, 26, 29	4, 5, 12, 15, 18, 25, 30, 31, 33

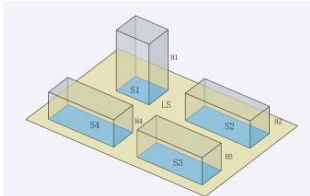
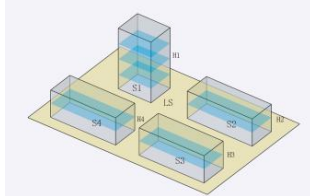
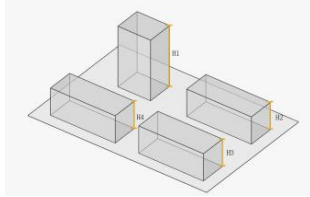
2.2.2. Morphological Analysis Based on Block Morphology Parameters

It has been found that different morphology indicators can be cited to quantitatively analyze urban morphology [36]. In this paper, after summarizing past literature experience and actual simulation analysis, BD and FAR were selected to describe the congestion

and openness of the parcel, and building height standard deviation (BHSD) to describe the height of the buildings in the block. ArcGIS calculations yielded 40 morphological indicators of real high-density commercial blocks.

The expressions and schematic diagrams of these variables are shown in Table 3. The values of the morphological parameters of the 40 selected blocks are shown in Table 4.

Table 3. Calculation of morphological parameters in study.

Name	Abbreviation	Formula	Schematic
Building density	BD	$BD = \frac{\sum_{i=1}^n S_i}{Ls}$	
Floor area ratio	FAR	$FAR = \frac{\sum_{i=1}^n F_i \times S_i}{Ls}$	
Building height standard deviation	BHSD	$BHSD = \sqrt{\sum_{i=1}^n (H_i - ABH)^2}$	

n is the number of buildings; Ls is the area of the block; F_i is the number of floors of building i ; S_i is the area of the ground floor of building i ; H_i is the height of building i ; ABH is the average building height.

Table 4. Morphological parameters of different blocks.

Block Code	BD	FAR	BHSD	Block Code	BD	FAR	BHSD
1	0.56	1.58	4.5	21	0.44	2.19	7.5
2	0.53	2.13	0.0	22	0.6	1.69	4.4
3	0.41	1.73	6.0	23	0.47	3.37	17.2
4	0.37	6.84	32.7	24	0.36	4.45	27.0
5	0.48	4.03	30.0	25	0.45	5.83	38.3
6	0.58	3.11	14.1	26	0.45	4.24	21.0
7	0.61	1.69	8.2	27	0.31	1.45	3.7
8	0.39	3.12	15.9	28	0.2	3.26	41.3
9	0.35	3.63	21.7	29	0.7	2.34	6.0
10	0.49	2.54	21.0	30	0.66	5.57	31.9
11	0.56	2.58	8.9	31	0.46	2.87	21.6
12	0.42	4.29	18.1	32	0.3	1.78	13.0
13	0.47	2.3	5.1	33	0.38	5.78	36.9
14	0.49	3.85	17.9	34	0.46	2.39	20.8
15	0.47	2.86	34.0	35	0.45	4.25	22.0
16	0.45	2.3	14.4	36	0.47	1.87	21.2
17	0.35	2.09	27.2	37	0.32	1.79	7.5
18	0.39	4.73	31.2	38	0.39	2.05	3.4
19	0.45	1.53	2.4	39	0.37	5.63	32.9
20	0.48	1.05	7.5	40	0.55	1.11	0.0

2.3. Simulation Workflow

After the typical actual cases of commercial blocks in Harbin were extracted and summarized, an energy consumption simulation was carried out for them. The simulation process includes the following four steps: (1) input the block model in Rhino and transform the geometric model into the Honeybee energy consumption model; (2) set the model parameters of the commercial block in severe cold regions and the climate and environment parameters of Harbin in winter and summer; and (3) use the EnergyPlus platform to carry out the energy simulation so as to obtain the annual energy use intensity (EUI), typical daily EUI, and itemized EUI in winter and summer for each model.

2.3.1. Generation of Simulation Models

The models used for simulation are divided into 40 actual block models and 90 theoretical block models. For the 40 actual blocks, the block boundaries are set by the city street network, the plane and height information of each block are obtained through the Baidu map, and the obtained (.shp.) vector file is used to generate a 3D model through Rhino.

As shown in Table 5, the theoretical models used for simulation are generated on the basis of the six basic types, and the BD, FAR, and BHSD are changed by Grasshopper, generating four groups of 90 models using parameter modeling. As blocks containing high-rise buildings can show various layout patterns under the same density or volume ratio, the effects of BD and FAR as variables are explored only for the three basic types (Courtyard, Slab, and Point), whereas the experiments with BHSD as a variable are aimed at deriving the effects of the vertical pattern of blocks on energy consumption, so it is explored for the six basic types.

Table 5. Theoretical model generation.

Basic Type	Spatial Types						Basic Type	Spatial Types	
	Group 1. Changes in BD, FAR = 4		Group 2. Changes in FAR, BD = 0.5		Group 3. Changes in BHSD, ABH = 20 m			Group 4. Changes in BHSD, ABH = 30 m	
	BD	Block Number	FAR	Block Number	BHSD (m)	Block Number		BHSD (m)	Block Number
Courtyard	0.4–0.6	C1–C9	3–7	C10–C18	0, 4, 8, 12	C19–C22	Courtyard-T	24, 28, 32, 36	C23–C26
Slab	0.4–0.75	S1–S15	3–7	S16–S24	0, 4, 8, 12	S25–S28	Slab-T	24, 28, 32, 36	S29–S32
Point	0.4–0.75	P1–P15	3–7	P16–P24	0, 4, 8, 12	P25–P28	Point-T	24, 28, 32, 36	P29–P32

The first group takes BD as a variable, controls FAR to be 4, and adjusts the BD in the block by changing the length and width of each single building according to a uniform ratio. Through the investigation and calculation in Section 2.1.2, it can be seen that for the vast majority of high-density commercial blocks in Harbin, BD is within the range of 0.3–0.75, those with BDs of 0.3–0.4 are mostly old blocks that need to be renovated, so their form parameters do not have reference values in future planning and construction, and there is no case of a Courtyard with a BD of more than 0.6. Therefore, in the establishment of the theoretical block models, BD is changed in the range of 0.4–0.6 for the Courtyard block and 0.4–0.75 for the Slab and Point blocks.

The second group uses FAR as the variable, controls BD to be 0.5, and changes FAR by uniformly adjusting the heights of single buildings within the block. From Section 2.1.2, it can be seen that the vast majority of high-density commercial blocks in Harbin have FARs distributed in the range of 1–7, of which those with FARs in the range of 1–3 are mostly low-rise historic blocks, such as the historically protected buildings on Central Street, and

in subsequent urban planning, such low-FAR blocks are difficult to replicate. Therefore, in the establishment of the theoretical block models, FAR is varied in the range of 3–7.

The third and fourth groups use BHSD as the variable, take the blocks with no towers (ABH = 20 m) and the block with towers (ABH = 30 m) as the basic model, respectively, and adjust BHSD to the values in Table 5. The range of variation in BHSD is similarly derived with reference to the results of the investigation of actual cases. Parameter modeling of the prototypes is generated under the constraint that the locations of the highest and lowest buildings in each block remain unchanged.

2.3.2. Parameter Setting for Simulation

As shown in Tables 6 and 7, for the characteristics of the commercial block in severe cold regions, the personnel indoor rate, window-to-wall ratio, heat transfer coefficient of construction, and human-related parameters are taken from the “Design standard for energy efficiency of public buildings” GB50189 [37].

Table 6. Values for hourly indoor occupancy rates of commercial buildings.

Computational Moment	1	2	3	4	5	6	7	8	9	10	11	12
Room occupancy rate (%)	0	0	0	0	0	20	0	20	50	80	80	80
Computational moment	13	14	15	16	17	18	19	20	21	22	23	24
Room occupancy rate (%)	80	80	80	80	80	80	80	70	50	0	0	0

Table 7. Values of relevant parameters for commercial buildings in severe cold regions.

Parameters		Values for Commercial Buildings in Severe Cold Regions
Window-to-wall ratio		South 0.3, east 0.2, west 0.2, north 0.1
Heat transfer coefficient of construction W/(m ² ·K)	Roof	0.35
	Walls	0.45
	Transparent material (window)	2.5
Person-related parameters	Heat dissipation (W)	Apparent heat 75, latent heat 106
	Dissipation of moisture (g/h)	158
	Floor space occupied per capita (m ²)	8
HVAC system	Heating period	20 October–20 April
	Cooling period	15 June–15 July
Simulation period	Annual energy consumption simulation	1 January–31 December
	Daily energy consumption simulation	Winter/summer peak energy use day

For the climate parameter setting in the severe cold region, this paper selects Harbin as the research background; the severe cold region has a large indoor–outdoor temperature difference in winter and a long heating period, and the heat loss from the indoor–outdoor temperature difference in heat transfer during the heating period is dominant. The heating period in winter is set from 20 October to 20 April of the following year, and the outdoor meteorological data are obtained from the National Meteorological Information Center of China, which comprises the corresponding hourly meteorological station data of the heating period [38]. The simulation period was set for the whole year. In addition, although the analysis of cumulative energy consumption is important, the peak energy intensity of each phase is also critical in the actual energy use management, and in order to explore the influence of various factors on block energy consumption in different seasons and time periods, the peak energy consumption days in summer and winter were selected for simulation studies and comparative analyses.

2.3.3. Simulation of Block Energy Consumption

EnergyPlus is a new generation of international building energy simulation software supported by the U.S. Department of Energy [39], with higher accuracy than other energy simulation software such as DOE-2 and DeST. In terms of energy consumption calculation, EnergyPlus first adopts the state-space method to solve the thermal characteristics of a single-side enclosure, taking into account the long-wave mutual radiation heat transfer between the internal surfaces of the enclosure and the convection heat transfer with the indoor air, which constitutes the heat balance equation of the surface of the enclosure structure and strictly ensures the heat balance of the room, thus ensuring the accuracy of the results of the energy consumption. In terms of user interface settings, EnergyPlus can define specific parameters such as glass, air, and film layer by layer, as well as related parameters such as wind speed and temperature difference. It can take into account the changes in each time step in the calculation of solar radiation, and there are various algorithms to choose from so as to facilitate the detailed setup of the basic parameters of the building. EnergyPlus's visualized user interface, Open Studio (version 2.5.0) [40], allows the visualization of the energy flow values on the building surface [41,42], which is useful for analyzing the distribution of energy consumption of single buildings in the block.

In order to measure the level of energy consumption in buildings, most studies use the concept of EUI, which refers to the annual energy consumption per unit area of a building. In this study, EnergyPlus is used to calculate EUI at the block scale, which is divided into annual EUI and typical Winter and Summer Daily EUI according to the time period of analysis, and it also calculates the EUI of the sub-items that make up the total energy consumption. The formula for calculating EUI is as follows:

$$\text{Total EUI} = \frac{\text{TEC}}{S} \quad (1)$$

Total EUI = Heating EUI + Cooling EUI + Interior Lighting EUI + Electric Equipment EUI + Water Systems EUI

EUI: energy use intensity ((kWh/m²)/year or (kWh/m²)/day).

TEC: block total energy consumption (kWh/year or kWh/day).

S: block total building area (m²).

2.4. Correlation Analysis

Using SPSS statistical analysis software, correlation analysis and linear regression analysis were carried out to explore the relationship between urban form factors and block energy consumption. The Pearson correlation test (two-tailed) was conducted to find the strength and significance of the correlation between urban form factors and energy consumption. The significance correlation test between the variables was carried out using the *p*-value, such that the lower the *p*-value, the higher the correlation. The confidence levels at *p*-values of 0.1, 0.01, and 0.005 are 0.9, 0.95, and 0.99, respectively. In linear regression analysis, the correlation coefficient *r* is used to determine the degree of linear correlation between the variables, where the larger the *r*-value, the stronger the correlation, and a positive *r*-value means a positive correlation; *r* is calculated as follows:

$$r = \frac{\sum_{i=1}^n (xi - \bar{x})(yi - \bar{y})}{\sqrt{\sum_{i=1}^n (xi - \bar{x})^2} \sqrt{\sum_{i=1}^n (yi - \bar{y})^2}} \quad (2)$$

x: the value of the independent variable, which is substituted for the values of the blocks BD, FAR, and BHSD, respectively, in the regression analysis later (i.e., the variables shown in the horizontal coordinates).

y: the value of the dependent variable, which is substituted for the value of EUI in the regression analysis later (i.e., the variable shown in the vertical coordinate).

3. Results

3.1. Energy Performance Analysis of 40 High-Density Commercial Blocks

3.1.1. Overall Energy Consumption Statistical Analysis

As shown in Figure 4, the energy consumption of different blocks varies greatly: Block 4 of the Point-T group has an annual energy consumption of 845.00 kWh/m², and it contains high-rise buildings with large standard floor area and the vertical density concentrated in the corner of the block; Block 39 of the Slab-T group has an annual simulated energy consumption of 788.96 kWh/m², and it has four strip high-rise buildings arranged horizontally to form several short block canyons with high plot ratio; Block 35 of the Courtyard-T group has an annual simulated energy consumption of 730.35 kWh/m², and it consists of two high-rise buildings and a semi-harmonized multi-story complex, whereas Block 32 is similar but has an annual energy consumption of only 194.91 kWh/m² due to the relatively low level of high-rise buildings, different locations of high-rise buildings, and different degrees of openness of the Courtyard. Comparing Blocks 12, 14, and 16, it can be seen that Block 14 has an annual energy consumption of only 142.29 kWh/m² due to the fact that the high-rise buildings are located in the center of the Courtyard block and the layout of the block is compact, whereas the high-rise buildings in Blocks 12 and 16 are located beside the streets and their rows are dispersed, which results in a higher annual energy consumption.

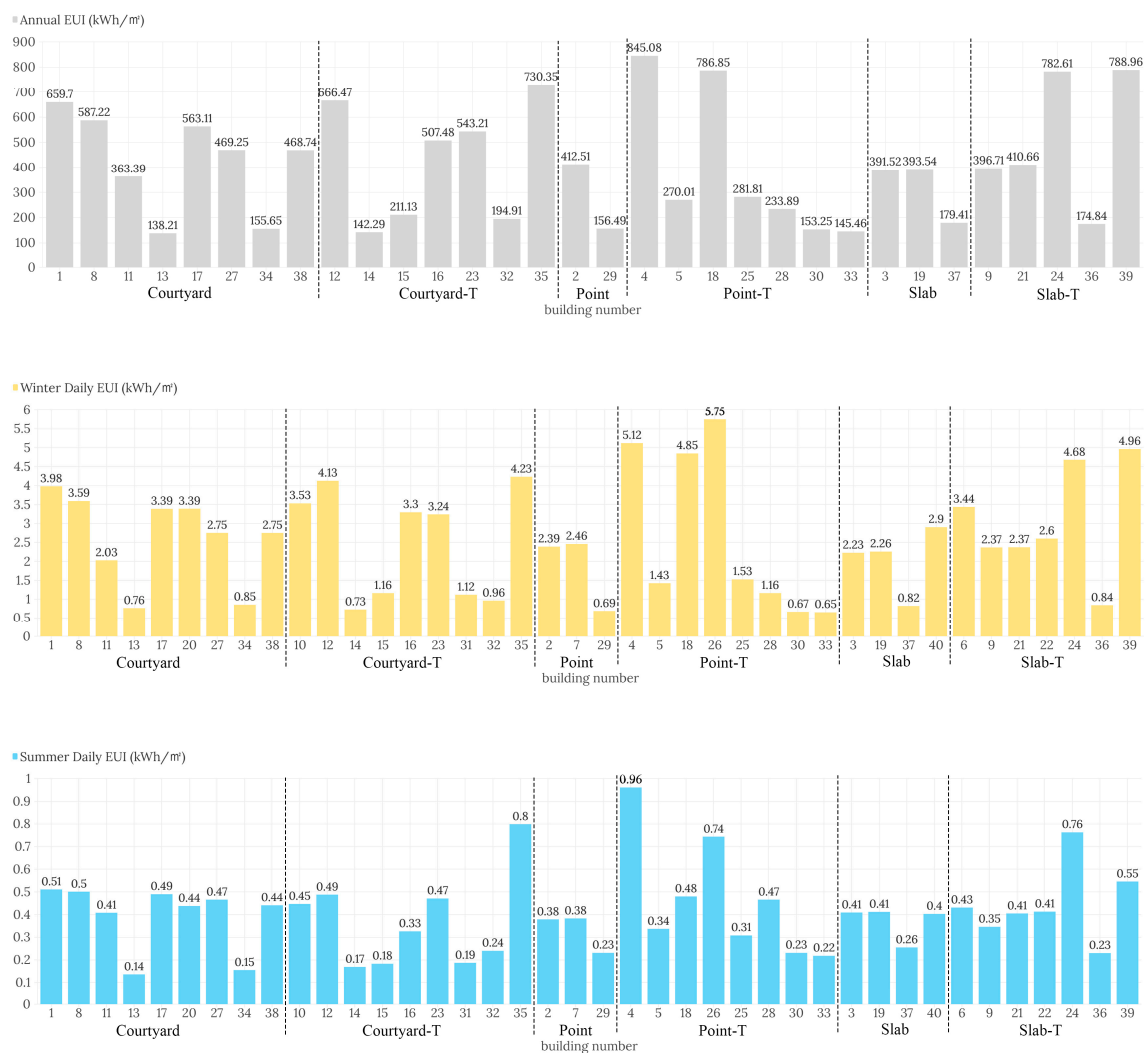


Figure 4. EUI performance of selected blocks (annual, winter, and summer).

The better energy performance results are found in Blocks 29 and 37, with annual EUIs of 156.49 and 179.41 kWh/m², respectively. The form of 29 presents a concentration of construction intensity in a single volume, which helps to reduce heat loss in winter, and 37 is a typical low-rise block of a strip, which creates good ventilation corridors in spite of the dispersed volume. In a similar vein, Block 34 employs a large-volume podium, and although the overall EUI is higher in the Courtyard group, this block also presents a better energy performance of 155.65 kWh/m² for the whole year.

As can be seen from Figure 5, the heating EUI largely determines the energy performance of high-density commercial blocks in severe cold regions; the distribution of annual cooling EUI is similar to that of summer, but the gap within each group is very large and not similar to the distribution of annual total EUI. Therefore, in the design of high-density commercial streets in cold regions, the heating energy consumption of the building should be primarily controlled, and other sub-items should be secondary.

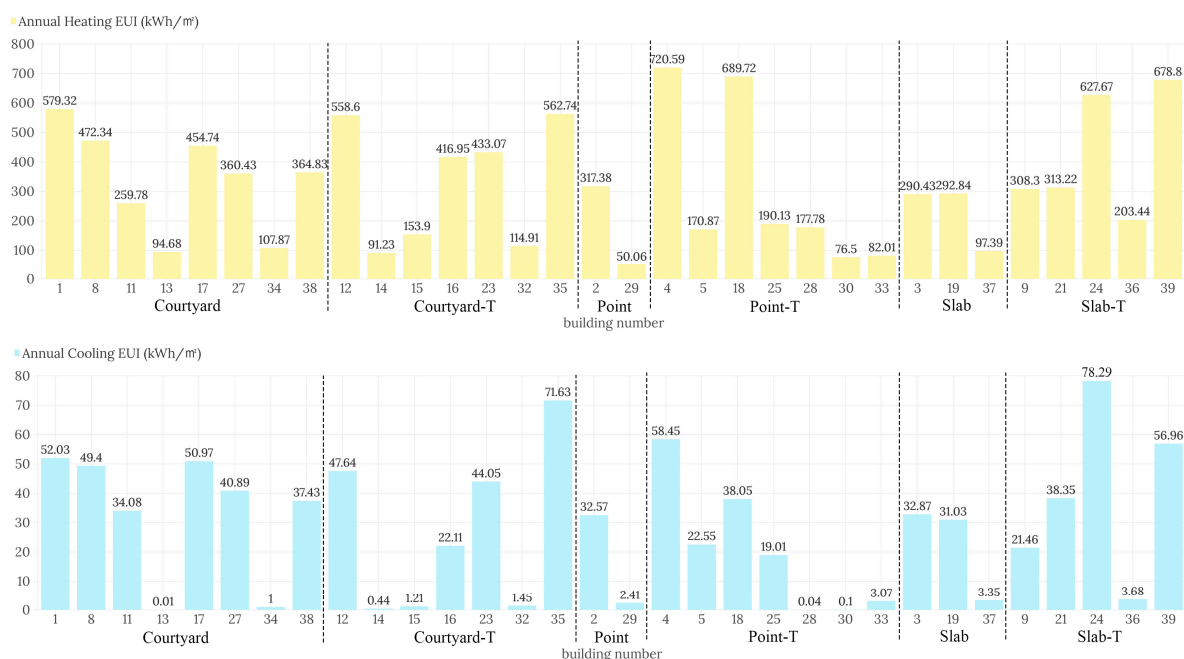


Figure 5. Annual heating EUI and cooling EUI performance of selected blocks.

3.1.2. Impact of Basic Layout Types on EUI

The energy consumptions of the six basic types of blocks were compared, and significant differences were found, as shown in Figure 6. In the simulation of total energy use over the year, the Point and Slab groups have relatively low energy use, and some blocks in the Point-T and Slab-T groups have relatively high energy use, but overall, the Courtyard and Courtyard-T groups have higher average energy use. In winter, the relative energy use of the different block types is very similar to that of the whole year, but the within-group differences in the Point-T group are significant, indicating that the overall shading of the blocks from solar radiation varies due to the relative positional relationship between the upper floors and podiums within the blocks. However, in summer, the Courtyard group of blocks shows higher EUI, which may be due to the fact that the low-rise blocks of the Courtyard are unable to form smooth ventilation corridors, whereas the high-density, high-floor urban form, with rational design, can save energy in summer, as it has a significant shielding effect on buildings from solar radiation.

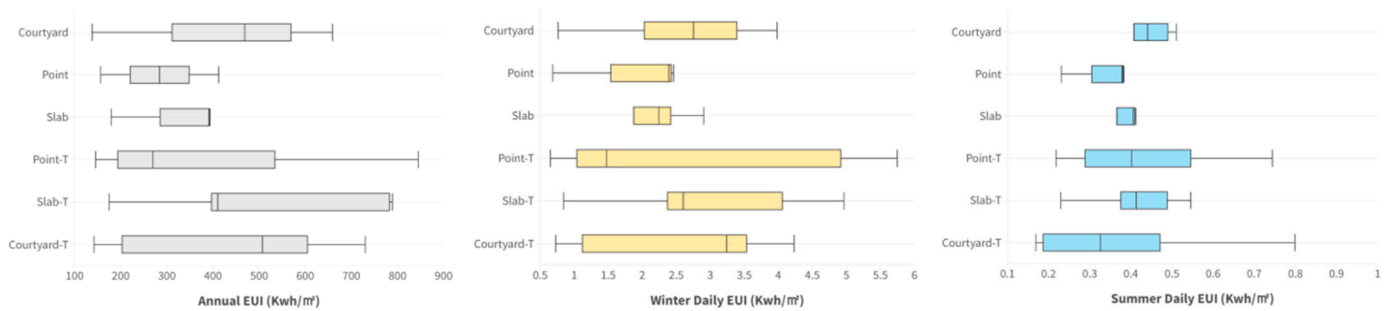


Figure 6. EUI distribution range of different block basic types.

3.2. Correlation between Morphological Parameters and EUI

3.2.1. Correlation Analysis

To further study the relationship between EUI and the three morphological parameters (BD, FAR, and BHSD), Pearson correlation analyses were performed. As shown in Table 8, EUI is negatively correlated with BD and positively correlated with FAR and BHSD. Winter Daily EUI shows a significant correlation with FAR at the $p \leq 0.01$ level, and Summer Daily EUI is significantly correlated with FAR at the $p \leq 0.005$ level.

Table 8. Pearson correlation analysis of the morphological parameters and EUI.

		BD	FAR	BHSD
Winter Daily EUI	Pearson's r	−0.135	0.370	0.036
	p -value	0.406	0.010 *	0.826
Summer Daily EUI	Pearson's r	−0.234	0.444	0.120
	p -value	0.146	0.004 **	0.459

* Two-tailed significance test, 0.01 level. ** Two-tailed significance test, 0.005 level.

3.2.2. Impact of Morphological Parameters on EUI

As shown in Figure 7, for the linear regression analysis of EUI and BD, no overall correlation trend was obtained due to the complexity and variety of the morphology of the forty commercial blocks, but certain influencing patterns can be obtained through the analysis of different block categories.

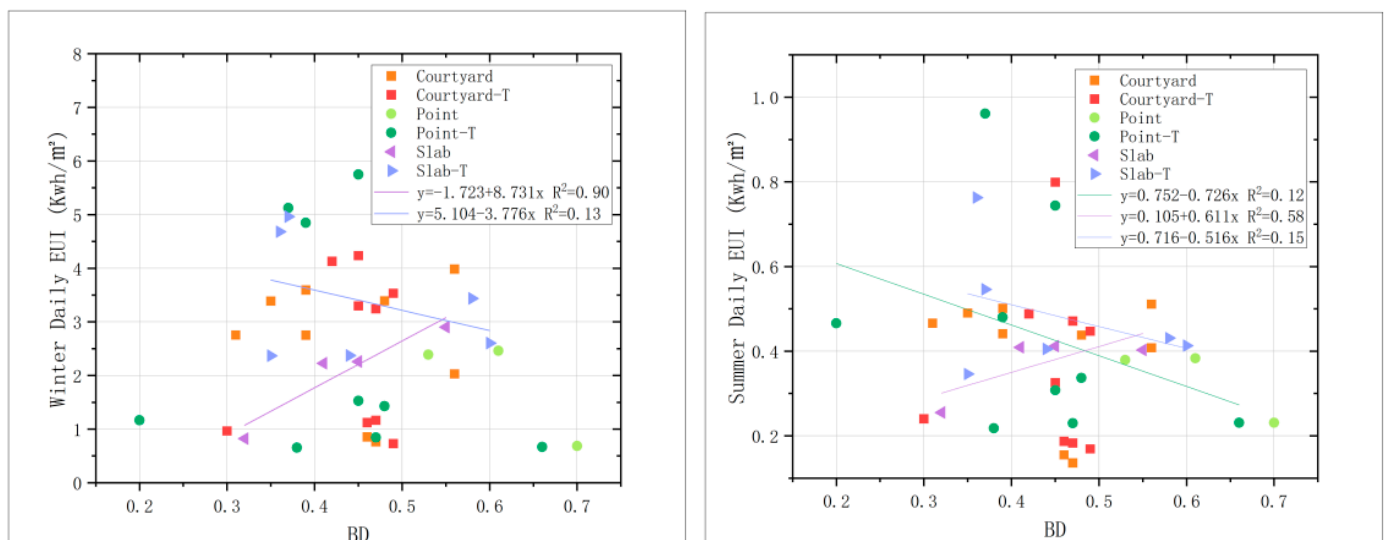


Figure 7. EUI-BD relationship linear regression analysis.

The winter EUI and BD of the Slab and Slab-T blocks show a linear relationship whose R^2 values are 0.90 and 0.13, respectively. For every 0.1 increase in the BD of the Slab block, the Winter Daily EUI increases by 0.87 (kWh/m²), and for every 0.1 increase in the BD of the Slab-T block, the Winter Daily EUI decreases by 0.37 (kWh/m²). Summer EUI in the Point-T, Slab, and Slab-T blocks displays a linear relationship with BD, with R^2 being 0.12, 0.57, and 0.15, respectively, and for every 0.1 increase in BD in the Point-T block, Summer Daily EUI decreases by 0.07 (kWh/m²). In comparison, for every 0.1 increase in BD in the Slab block, the Summer Daily EUI increases by 0.06 (kWh/m²), and for every 0.1 increase in BD in the Slab-T block, the Summer Daily EUI decreases by 0.05 (kWh/m²).

As shown in Figure 8, the EUI and FAR of commercial blocks show a more obvious linear relationship; overall, the winter and summer EUI of the 40 blocks are positively correlated with FAR, with $R^2 = 0.14$ and 0.20, respectively, and there are also more types of blocks that show a linear relationship with energy consumption. For winter, in the regression analysis of Courtyard-T, Point-T, Slab, and Slab-T blocks, R^2 is 0.17, 0.31, 0.63, and 0.71, respectively, and for every increase of 1 in FAR, the Winter Daily EUI of the four types of blocks increases by 0.68, 0.79, -2.26 , and 0.67 kWh/m², respectively, which shows that Slab blocks are more significantly affected by FAR and have a negative correlation. For summer, the Courtyard-T, Point-T, Slab, and Slab-T blocks still show a linear relationship with FAR, with R^2 being 0.27, 0.42, 0.26, and 0.33, respectively, and for every increase of 1 in FAR, the Summer Daily EUI of the four types of blocks increases by 0.12, 0.11, -0.12 , and 0.06 kWh/m², respectively.

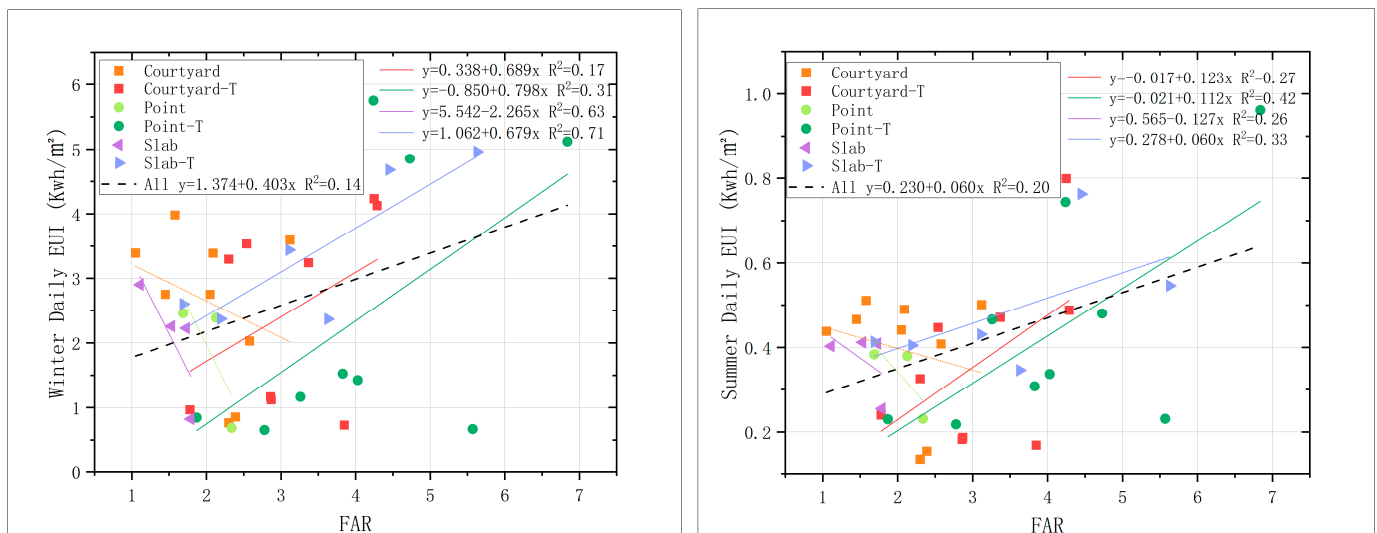


Figure 8. EUI–FAR relationship linear regression analysis.

As shown in Figure 9, the overall analysis of the 40 blocks found no significant linear relationship between EUI and BHSD due to the fact that the average heights of different types of blocks are different and BHSD is more affected by the average height, so the overall analysis is not that meaningful. The Winter Daily EUIs of Point-T, Slab, and Slab-T blocks show a certain linear relationship with BHSD, with R^2 being 0.13, 0.74, and 0.64, respectively, and for every 1 m increase in BHSD, the Winter Daily EUI of the three types of blocks increases by -0.11 , -0.22 , and 0.08 kWh/m², respectively. The summer EUIs of the Slab and Slab-T blocks show a somewhat linear relationship with BHSD, with R^2 being 0.45 and 0.34, respectively, and for every 1 m increase in BHSD, the Slab block Summer Daily EUI decreases by 0.02 kWh/m², whereas for the Slab-T block, it increases by 0.01 kWh/m².

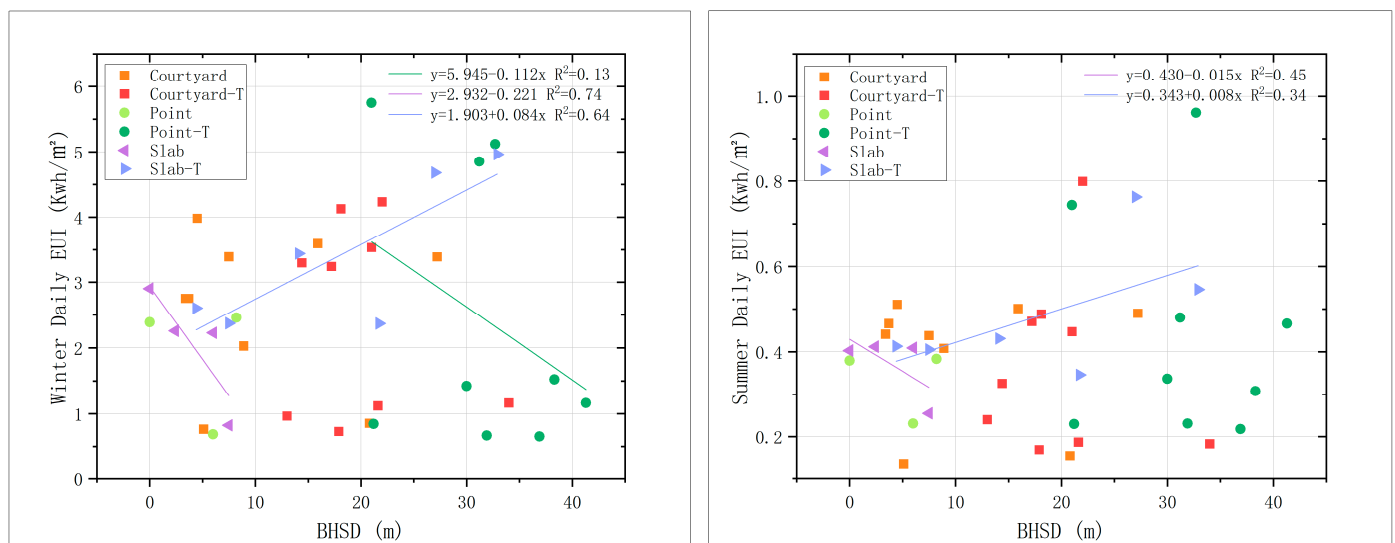


Figure 9. EUI-BHSD relationship linear regression analysis.

3.3. Analysis of Effect of Single Morphological Parameter on EUI

3.3.1. Simulation of BD Interference with EUI

As shown in Figure 10, the study of the singular effect of BD on EUI is based on the energy performance result of Group 1, consisting of C1–C9, S1–S15, and P1–P15. Overall, the building energy consumption of the commercial blocks decreases with BD, and the rate of decrease slows down gradually. Point blocks are more easily affected by BD than the others. The trend of annual EUI and Winter Daily EUI is basically the same; when BD is in the range of 0.4–0.55, the annual EUI of the Point block is more easily affected by BD. The annual EUI of the Point block is more influenced by BD, but when $BD > 0.53$, the rate of change in EUI slows down. While C1–C9 show higher energy intensity in summer, there is little difference in energy consumption between S1–S15 and P1–P15; the Summer Daily EUI of the Point block is larger than that of the Slab block when BD is in the range of 0.4–0.63, whereas the Summer Daily EUI of the Slab block fluctuates when $BD > 0.63$, appearing higher than that of the Point block in some cases.

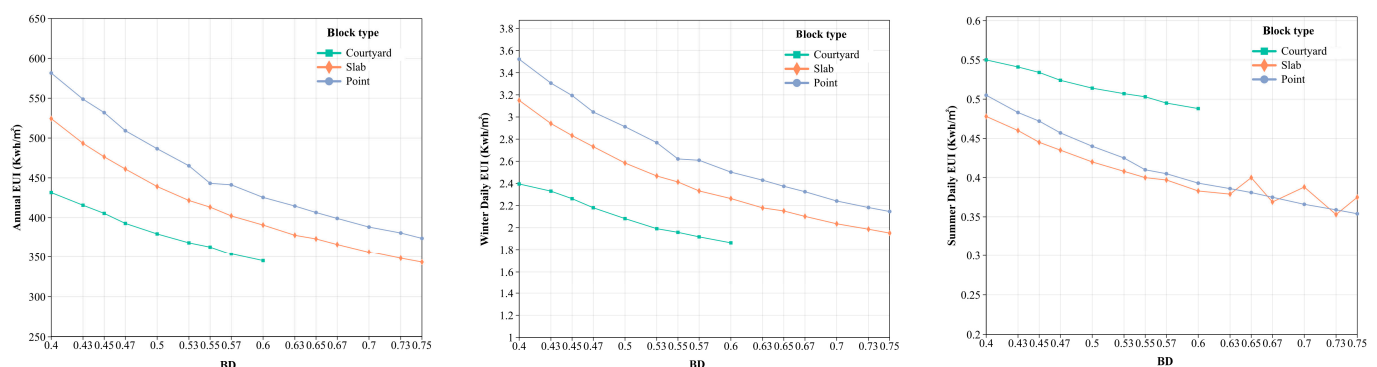


Figure 10. The simulation results of EUI when BD is a variable and FAR controlled (annual, Winter Daily, Summer Daily).

In winter, for every 0.05 increase in BD, the daily EUI decreases by about 0.30 kWh/m² in the Point block and 0.10–0.20 kWh/m² in the Slab and Courtyard blocks, and the change in daily EUI in winter for the three types of blocks is less than 0.10 kWh/m² and nearly flat when BD transitions from 0.55 to 0.6. In summer, the energy consumption of the three types of blocks is much less affected by BD than in winter: The change in daily EUI in summer is about one-tenth of that in winter throughout the change in BD, and for every 0.05 increase in BD, the EUI of the blocks decreases by less than 0.03 kWh/m².

As shown in Figure 11, the comparative analysis of the impact of BD on the energy consumption of sub-categories shows that in winter, the heating energy consumption accounts for 87–94% of the total energy consumption, and the heating energy consumption gradually decreases with the increase in BD, whereas the energy consumption of the other sub-categories has no relation with BD. In the case of FAR = 4, the heating energy consumption appears in the order P1–P15 >> S1–S15 > C1–C9, which is the main reason for the difference in total energy consumption of those three types of blocks. When BD = 0.4, the three types of blocks have the largest gap in heating EUI; P1 is 1.16 kWh/m² larger than C1, and the gap gradually decreases with the increase in BD, whereas when BD = 0.6, P9 is only 0.67 kWh/m² larger than C9. While the lighting, electrical equipment, and water system energy consumption are not affected by BD, lighting energy consumption is ranked Point > Slab > Courtyard, electrical equipment energy consumption is ranked Courtyard > Point > Slab, and water system energy consumption is ranked Courtyard > Slab > Point. The difference between different block types is less than 0.05 kWh/m².

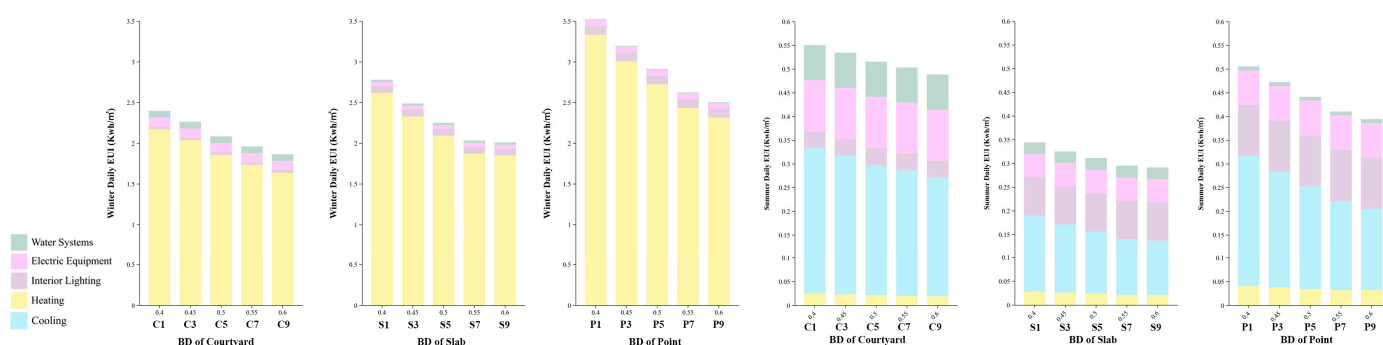


Figure 11. The simulation results of sub-item EUI when BD is a variable and FAR controlled (Winter Daily, Summer Daily).

In summer, the cooling energy consumption accounts for 39–56% of the total energy consumption, with C1–C9 > P1–P15 > S1–S15, consistent with the trend of the total energy consumption: for every 0.05 increase in the BD, the cooling EUI of the Courtyard and Slab blocks decreases by 0.01 kWh/m² on average, whereas it decreases by 0.02 kWh/m² on average for the Point block. Lighting energy consumption accounts for 21–27% of the total for the Point block, and electrical equipment energy consumption accounts for 19–22% of the total in the Courtyard block, both due to the sharp drop in heating energy consumption compared to winter.

3.3.2. Simulation of FAR interference with EUI

As shown in Figure 12, the study of the singular effect of FAR on EUI is based on the energy performance result of Group 2, consisting of C10–C18, S16–S24, and P16–P24. Overall, there is a good linear relationship between EUI and ABH when FAR is in the range of 3–7. In winter, for every 0.5 increase in FAR, the daily EUIs of C10–C18 and S16–S24 all increase by 0.16 kWh/m² on average, and the daily EUIs of P16–P24 increase by 0.22 kWh/m² on average. In summer, the energy consumption of the three types of blocks is much less affected by BD than in winter, and there is little difference in the extent of the effect of FAR among different types of blocks, with an average increase of 0.01 kWh/m² in daily EUI for each block for each 0.5 increase in FAR.

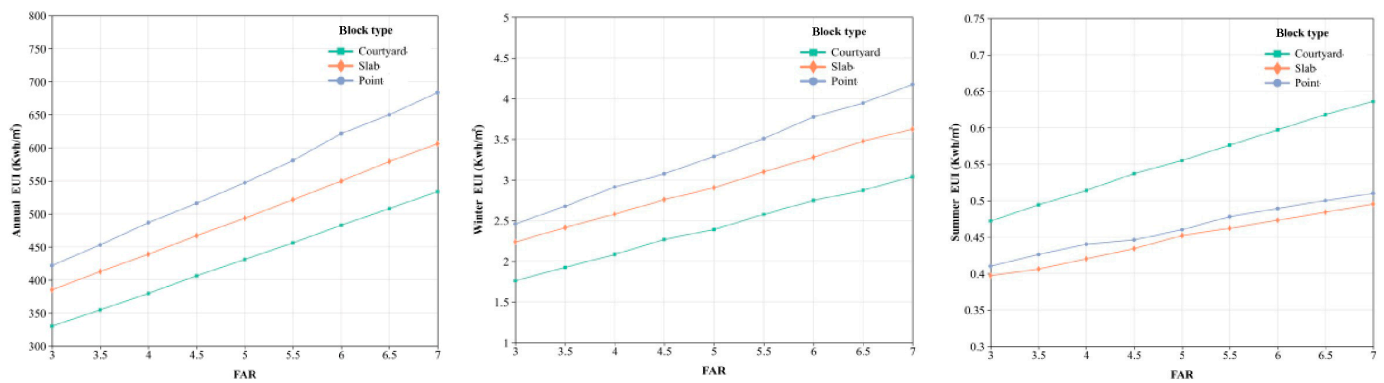


Figure 12. The simulation results of EUI when FAR is a variable and BD controlled (annual, Winter Daily, Summer Daily).

As shown in Figure 13, for the analysis of itemized energy consumption, in winter, the daily heating EUI is 1.86–2.52 kWh/m² for C12–C16, 2.10–2.74 kWh/m² for S18–S22, and 2.72–3.58 kWh/m² for P18–P22. S16 has a value 0.24 kWh/m² higher than C10's daily heating EUI when FAR = 4, whereas P16 and S16 have 0.63 and 0.22 kWh/m² higher daily heating EUI than C10 when FAR = 6, and P16 has 0.84 kWh/m² more than S16. These results show that as FAR increases, the demand for heating increases more significantly in the Point blocks than in the other two types of blocks.

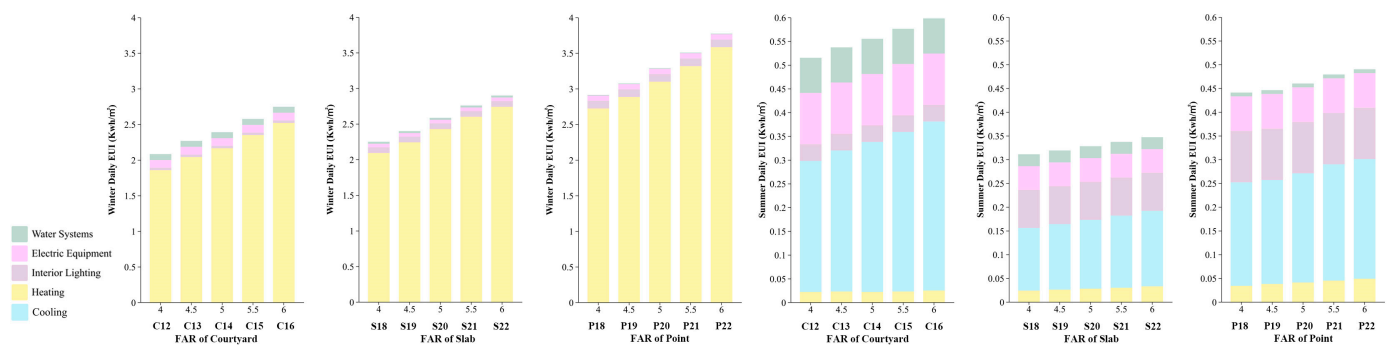


Figure 13. The simulation results of sub-item EUI when FAR is a variable and BD controlled (Winter Daily, Summer Daily).

In summer, the effect of FAR on the cooling energy consumption of the Courtyard block is greater than that of the Slab and Point blocks. The daily cooling EUI of the Courtyard block increases by an average of 0.02 kWh/m² for every 0.5 increase in FAR, which is much smaller than the extent of the effect of FAR on heating energy consumption in winter. The changes in other sub-items of energy consumption are even smaller and, therefore, will not be analyzed specifically.

3.3.3. Simulation of BHSD Interference with EUI

As shown in Figure 14, the study of the singular effect of BHSD on low-rise block EUI is based on the energy performance result of the two groups. For Group 3, consisting of C19–C22, S25–S28, and P25–P28, the impact on blocks without towers is examined, whereas for Group 4, consisting of C23–C26, S29–S32, and P29–P32, the impact on blocks including towers is further explored.

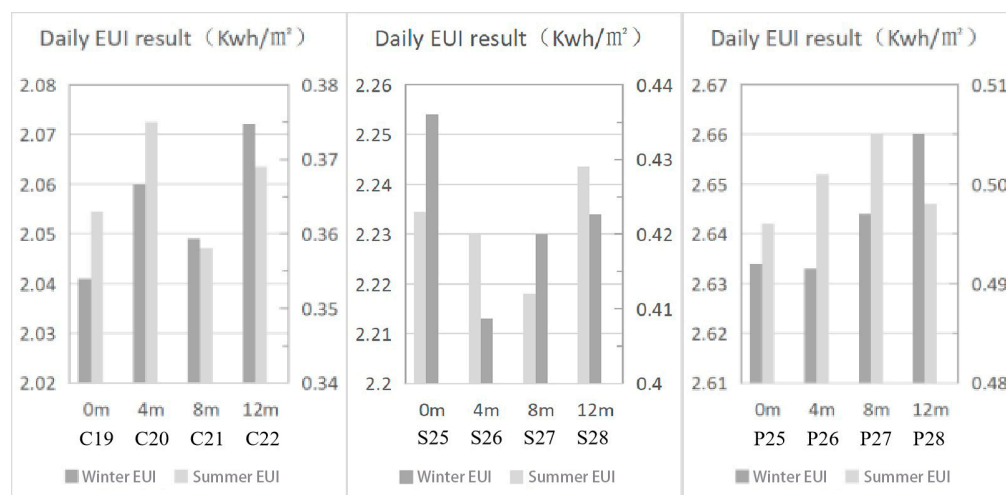


Figure 14. The simulation results of EUI when BHSD is a variable and ABH controlled (Winter Daily, Summer Daily, for blocks without towers).

In general, for Point blocks, the lower the BHSD, the more energy-efficient it is in winter, as it is more conducive to reducing the heat loss inside the block, thus reducing the heating energy consumption. The situation is more complicated in summer, in which different types of blocks affect the degree of penetration of natural winds by varying the height distribution, thus influencing the cooling energy consumption.

The winter EUI distribution of the Courtyard block ranges from 2.04 to 2.07 kWh/m², and the summer EUI distribution ranges from 0.36 to 0.38 kWh/m², which displays the best yearly energy performance when BHSD = 8 m. The winter EUI distribution of the Slab block ranges from 2.21 to 2.25 kWh/m², and the summer EUI distribution ranges from 0.41 to 0.43 kWh/m², whereas the lowest total energy consumption in the whole year appears when BHSD = 12 m. The winter EUI distribution ranges from 2.63 to 2.66 kWh/m² for the Point block, and the summer EUI distribution ranges from 0.49 to 0.51 kWh/m², whereas the total energy consumption appears the lowest in the whole year when BHSD = 0 m. These values present a better energy consumption scenario.

As shown in Figure 15, a comprehensive analysis of the 12 block prototypes containing towers shows that winter block energy consumption in the case with towers is more significantly affected by BHSD than in the case without towers, showing a clear positive or negative correlation with BHSD.

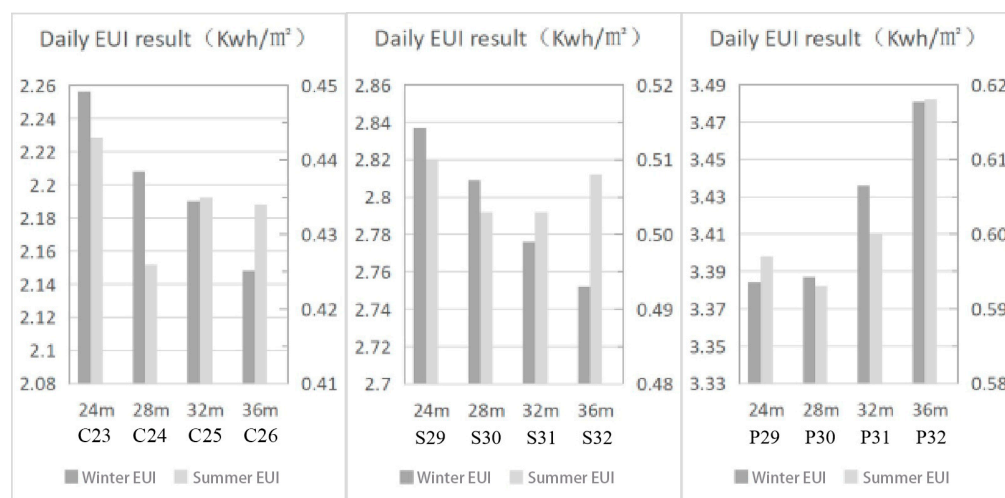


Figure 15. The simulation results of EUI when BHSD is a variable and ABH controlled (Winter Daily, Summer Daily, for blocks containing towers).

The winter EUI of the Courtyard-T block decreases with increasing BHSD, with a distribution range of 2.15–2.25 kWh/m², and the summer EUI distribution ranges from 0.42 to 0.44 kWh/m². As winter energy consumption has a larger impact on the value for the whole year, the best energy-saving performance for the Courtyard-T block occurs when BHSD = 36 m. The winter EUI of the Slab-T block also decreases with the increase in BHSD, with the distribution range of 2.75–2.83 kWh/m², and the distribution range of summer EUI is 0.50–0.51 kWh/m². Due to the small difference in energy intensity in summer, the annual energy consumption of the Slab-T block also reaches the lowest when BHSD = 36 m. The winter and summer EUIs in the Point-T block basically correlate positively with BHSD, with the distribution of Winter Daily EUI ranging from 3.38 to 3.43 kWh/m² and the distribution of summer EUI ranging from 0.59 to 0.62 kWh/m². Two prototypes, P29 and P30, present better energy-saving performances in comparison with others, so the lowest energy consumption is achieved when BHSD = 24 m and 28 m.

4. Discussion

4.1. The Main Findings of This Study

- (1) We determine a methodology applicable to studying the relationship between complex urban form and block energy consumption. In this study, the relationship between the layout form and energy consumption of high-density commercial blocks in severe cold regions, as well as the overall and individual impacts of BD, FAR, and BHSD on the energy consumption of blocks, are derived through the classification, simulation, and linear regression analyses of real blocks, as well as the analysis of control variables of theoretical block models. This study finds that there are differences in the mechanism of the impact of a single form parameter on energy consumption when controlling and not controlling other parameters, and the simulation results for the theoretical blocks in this study are used to explore the impact of the form parameters on energy consumption in detail, and they should not be used for a comparative analysis of the differences in energy consumption between actual blocks. Previous studies had similar paths [43,44] but did not establish a theoretical model on the basis of real blocks to analyze in depth the role of a morphological parameter on energy consumption, and they also analyzed the differences between their theoretical and practical models less thoroughly.
- (2) We summarized the basic types of high-density commercial blocks in severe cold regions. In terms of classifying high-density commercial blocks in cold regions, this study established a set of method streams for screening target blocks. According to the concept of high-density blocks, POI was carried out to distinguish BDs and FARs. Moreover, according to the layout of the block, six basic block types were determined: Courtyard, Courtyard-T, Slab, Slab-T, Point, and Point-T. Pan et al. [45] summarized four basic morphological patterns, namely, Point, linear, Courtyard, and mixed pattern, by refining the morphological patterns of building clusters in cold cities, and the proportion of each morphological pattern was different in different cities. In this paper, the way of categorizing blocks is similar to previous research, but the difference is that the analysis and summary were conducted from both vertical and horizontal levels, which captures the characteristics of high-density blocks in a more in-depth way.
- (3) The relative energy use characteristics of the severe-cold-region high-density commercial blocks under different layout types were derived. The simulation results for real blocks show that Point, Slab, and some Point-T blocks have lower energy consumption throughout the year, which is due to the fact that they have compact massing layouts and smooth ground-floor ventilation corridors or they only consist of high-rise buildings with fewer podiums, which is more energy-efficient. However, some Point-T blocks consume more energy in winter due to the severe mutual shading between high-rise buildings, which reduces solar heat gain. In contrast, Courtyard-T blocks consume more energy in summer due to the fact that high-rise buildings are

located on the four sides of the blocks or on the corners of the streets. The blocks that are low in the middle with high buildings on the periphery cannot attain good ventilation performance.

- (4) The relationship between urban form parameters and energy consumption of severe-cold-region high-density commercial blocks was derived.
 - (a) The situation of the influence of BD on energy consumption in high-density commercial blocks in severe cold regions is complicated. When the confounding interference of other variables is not considered, BD and the energy consumption of the three types of blocks without towers are negatively correlated, which is different from the results of the positive correlation between energy consumption and BD in the real Slab blocks, indicating that the BD of Slab blocks affected by other factors has a different impact on energy consumption than its own impact. For blocks with towers, increasing BD is a good method to save energy. In a study of office buildings in severe cold regions, Leng et al. [13] pointed out that larger building footprints are conducive to lower heating energy consumption of office buildings, which is partially consistent with the findings of this study, as the complex morphological characteristics of severe cold commercial blocks cause the effects of BD on energy consumption to vary by block layout type.
 - (b) There is a strong correlation between the FAR and energy consumption of high-density commercial blocks in severe cold regions. Comparing the results of the simulation of real blocks and theoretical blocks, it can be noted that when FAR is in the range of 1–2, increasing FAR is conducive to energy savings, whereas when FAR is set to be 2–7, increasing FAR is very unfavorable for energy saving. Wang et al. [28] derived a negative correlation between FAR and energy consumption from their study in cold regions; Quan et al. [34] analyzed the simulation of energy consumption in some real blocks in Shanghai and found that blocks with high FAR have a negative correlation with energy consumption before a specific inflection point and a positive correlation after that point. The findings of this study are similar to theirs, especially for the three types of blocks with towers, for which increasing FAR is not an energy-efficient development mode, and the value of the optimal FAR is a matter of trade-off.
 - (c) The energy consumption of high-density commercial blocks in severe cold regions is less easily affected by BHSD than by construction intensity. The energy consumption of Slab blocks is negatively correlated with BHSD, whereas Slab-T is positively correlated. The energy performance of real blocks is different in terms of their average heights, and the unevenness of blocks' heights has a greater relationship with their average heights. For theoretical blocks varying the BHSD while controlling the average height, it was found that their energy consumption was less affected by BHSD. The results of previous studies [46,47] have also shown that the energy consumption of the block is greatly influenced by its average height, whereas the influence of BHSD is smaller, but attention should be paid to the height arrangement of the buildings within the block, since forming certain ventilation corridors and shading relationships through controlling the staggering of building heights could reduce the overall energy consumption of the block.

4.2. Implications of This Study

- (1) Although Courtyard and Courtyard-T blocks are the layout types usually adopted in severe cold regions, this study found that for high-density commercial blocks, these two layouts tend to present intricate volumes with high-rise buildings located around them, which makes their energy consumption higher than the other layout types. For the blocks without towers, this study suggests using Point and Slab blocks as the block layout options and choosing compact multi-story Point-type massing or separated strip-type small massing, which presents the best energy-saving effect. For

the blocks with towers, it is recommended to use Point-T blocks as the options, setting independent high-rise massing and not adding too many multi-story buildings and podiums to the blocks. Overall, the energy-saving performance of a block without towers is better than that of a block with towers.

- (2) For Slab-T and Point-T blocks, it is recommended to choose a BD within the range of 0.6–0.7. For Point and Courtyard blocks, a higher BD is recommended if the plot ratio is certain, but with the increase in BD, the energy consumption is gradually less affected, so the optimal BD still needs to be weighed. For Slab blocks, a lower BD is recommended within the range of 0.3–0.4.
- (3) For blocks without towers, a low FAR in the range of 2–3 is recommended, and it is not advisable to adopt too large an FAR when the BD is certain. Conversely, for blocks with towers, a low FAR of 1–2 can be selected.
- (4) For the Slab and Point-T blocks, staggered building placement is recommended to give the blocks a high BHSD, whereas a reduced BHSD is recommended for the Slab-T block. BHSD values of 8 m, 12 m, and 0 m are recommended for Courtyard, Slab, and Point blocks, respectively, when the average height of the block is 20 m, and values of 36 m, 36 m, and 24–28 m are recommended for Courtyard-T, Slab-T, and Point-T blocks, respectively, when the average height of the block is 30 m. Also, for an average block height of 30 m, a BHSD of 36 m, 36 m, and 24–28 m is recommended for Courtyard-T, Slab-T, and Point-T blocks, respectively.

4.3. Limitations and Future Work

In terms of form indicator selection, this study focuses on BD, FAR, and BHSD for detailed analysis, mainly to explore the impact of the construction intensity of high-density commercial blocks on energy consumption. Future research can explore the effects of more morphology indicators on the impact mechanism of energy consumption and conduct a more in-depth study of the morphology impact pathway on energy consumption at the block scale, such as how morphology affects the energy consumption of the block through the intermediary of microclimate and human behavior.

In terms of the classification of blocks, this study obtained models of actual blocks by means of field research and map information acquisition and classified them into six basic layout types in a traditional way. Future research could use the clustering method to classify block types more precisely.

In terms of experiments, this study simulated the energy consumption of both real blocks and theoretical blocks using controlled variables, and the results of the two types of blocks complemented each other to form the final conclusions. Future research should increase the sample size of these two types of blocks to reach a more comprehensive conclusion.

5. Conclusions

This study explores the mechanism of the influence of the morphology of high-density commercial blocks in severe cold regions on their energy consumption through simulation and quantitative analysis. A workflow is proposed to study the morphology and energy consumption of blocks. The morphological features and macro-level energy consumption characteristics of high-density commercial districts in severe cold regions are derived through the classification, simulation, and linear regression analysis of real blocks, and theoretical models are established to quantitatively analyze the influence of the BD, FAR, and BHSD of high-density commercial blocks on their energy consumption by means of controlling variables. The following conclusions are drawn:

- (1) By analyzing the energy consumption of typical block layout patterns, it is found that there are significant differences in energy use between blocks due to the difference in layouts, where Point and Slab blocks have the best energy performance and the Point-T block without large podiums can also have better energy performance. In contrast, the energy performance of Courtyard and Courtyard-T blocks is relatively poor.

- (2) The morphological parameters are correlated with energy consumption. FAR has a greater impact on block energy consumption than BD and BHSD. For every 0.1 increase in BD, every 1 increase in FAR, and every 1(m) increase in BHSD, the Winter Daily EUI of the Slab block changes by +0.87, −2.26, and −0.22 (kWh/m²), respectively, whereas that of the Slab-T block changes by −0.38, +0.68, and +0.08 (kWh/m²), respectively.
- (3) Increasing BD is theoretically beneficial to energy performance in the block, but for a real Slab block in the specific environment studied, a low BD is instead energy-efficient, and increasing BD in the range of 0.4–0.55 has a significant effect on lowering energy consumption in Point blocks.
- (4) FAR is significantly correlated with EUI (winter $r = 0.37$, summer $r = 0.44$). When FAR is in the range of 1–2, increasing FAR is conducive to energy savings for real Slab blocks, whereas when FAR is set to be 2–7, increasing FAR is very unfavorable for energy saving. The optimal FAR is a matter of trade-off.
- (5) The relationship between BHSD and energy consumption varies across blocks, and different types of blocks have different influence mechanisms. Slab block energy consumption is negatively correlated with BHSD, whereas Slab-T block energy consumption is positively correlated with it.

The workflow adopted in this study can be utilized for similar studies in other areas to provide strategies for urban energy efficiency planning and contribute to sustainable development.

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