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Planning Strategy for Urban Building Energy Conservation Supported by Agent-Based Modeling

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Abstract: As a systematic, preventive, and structural adjustment method of improving building energy conservation and carbon emission reduction, urban planning has received extensive attention. However, due to the insufficient interface between energy-saving technology and urban planning systems, urban planning has not properly played a role in building energy conservation. Scientific and innovative technical methods are urgently needed to explore the role of coordinating multiple effective planning elements in overall building energy conservation through urban planning means. Due to climate conditions, there is high demand for conserving building energy in severe cold regions, but research into this has not been thoroughly carried out. Harbin, located in the northeast of China, belongs to the Dwa zone of the Köppen–Geiger Climate Classification, and is also a typical city of severe cold regions where the daily average temperature is lower than 5 °C for more than 145 days in a year. This study takes Harbin as an example and uses agent-based modeling to establish an urban-scale building energy consumption simulation model. The model contains four types of agents (a global agent, building agent, residential agent, and household equipment agent) and two types of influence factor modules (an urban form module and a climate module). Three simulation scenarios were designed, including a baseline scenario, an urban form scenario, and a climate scenario. The baseline scenario provided an overview of the urban-scale building energy consumption distribution characteristics of Harbin and served as a reference group for the simulation results of other scenarios. The urban form scenario results show that when the elements with a highly significant impact change by 1 unit, the retail building block has the most obvious change in energy consumption, up to 44.7×10^6 kWh/10^5 m^2/year, while the office building block has the lowest change, with 34.5×10^3 kWh/10^5 m^2/year. The fluctuation of electricity is the most obvious, but the total change is lower than the heating energy consumption. The climate scenario shows that the energy consumption of residential land in urban centers will consistently rise in the next 50 years, up to 5.3×10^5 kWh/10^5 m^2/year. Based on these results, this study puts forward future building energy conservation planning strategies for Harbin, focusing on three aspects: the planning and control of urban form, the optimization and adjustment of the climate, and the building energy conservation planning system. These research results are expected to provide scientific support for transforming Harbin into a low-carbon city.

Keywords: urban energy efficiency planning; building energy consumption; agent-based model; severe cold regions

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1. Introduction

The building and construction sector is the primary focus of attempts to reduce greenhouse gas emissions. In 2018, it accounted for the largest share of global energy use (36%) and energy-related CO_2 emissions (39%) [1]. The impact of urban spatial planning on building energy consumption has been widely recognized. Creating an energy-efficient and low-carbon-oriented spatial environment through urban and rural planning is essential for optimizing and improving the overall low-carbon development of buildings [2]. Urban building energy conservation planning provides a platform for comprehensive consideration of the interaction between buildings and multiple urban environment elements, which is conducive to improving scientific and operational decision-making [3].

Planning for building energy conservation is a systematic task, and many factors need to be considered, including building monomer factors and urban planning elements that affect its energy consumption, as well as the interactions between the urban environment and building monomer thermal elements. Besides the physical condition of a building (the building type [4], the construction [5], the material, etc.); its heating, ventilation, and air conditioning system (the HVAC) [6]; and its energy consumption patterns (ECP) [7], urban form and climate are the two main aspects that are widely regarded as the influencing factors of building energy consumption at an urban scale. They are also factors that can be adjusted through urban planning [8]. The impacts of neighborhood building height [9], building density [10], aspect ratio [10,11], etc., on building energy consumption have been confirmed by several studies. Meanwhile, the effect of climatic conditions has also been widely discussed. Air temperature, wind speed, and relative humidity are the three main climate variables used in most models that investigate the potential impacts of climate change on the energy demands of heating and cooling buildings [12–15]. Existing studies have explored building energy conservation planning methods by optimizing the above factors [16]. However, most of these studies generally focus on one specific influencing factor. This is because the complexity of urban systems and the uncertainty of the interaction between multiple influencing factors limit traditional research methods in simulating the dynamic changes in multiple influencing factors [11,17]. A systematic review shows that many space-related building energy modeling methods have been developed recently. However, a comprehensive urban-scale building energy conservation planning framework has not yet been developed [18]. Currently, most methods have not integrated all stages of urban planning. That is, not all planning aspects have been considered. The main reason for this is that the formation of a complete urban building energy conservation planning model faces several obstacles. First of all, it needs to integrate a wide range of disciplines and needs to combine various different methods to deal with the correlations between different planning elements. Second, it requires high-level data and high analog computing capabilities. Large standardized databases and public data sources have limited availability and reliability at the local level. This problem is very challenging because data are not always open-source or up-to-date. Finally, a comprehensive and clear planning framework is necessary so that decision-makers can understand it. Therefore, it is essential to promote future research to develop more integrated technologies for various planning approaches related to the vision of sustainable urban planning.

In order to solve the above problems, the technology of urban system simulation has been constantly innovated in recent years. These models can be generally divided into top-down models and bottom-up models [19]. Among them, agent-based modeling (ABM), with its ability to synchronize and dynamically adjust multiple planning elements, has become one of the most popular technical tools for studying complex urban issues [20–22]. This kind of model is usually bottom-up or a combination of top-down and bottom-up. Compared with other models, it shows great advantages in simulating active and passive changes in the object of study in real-time and providing corresponding feedback to achieve dynamic equilibrium of the overall system [23]. The use of ABM has been widely explored by scholars in the urban planning field. It is used to build land-use planning models [24,25], urban space expansion models [26], models for public participation in urban planning [27], housing demand models, etc. [28,29]. In the study of building energy consumption, although ABM is more often used in research related to energy-use behavior [30,31], it has also been attempted in other areas in recent years, such as thermal energy transition in the built environment and energy feedback methods [32–34]. Relevant research results have confirmed that the application of this technique can effectively improve the simulation accuracy of urban systems. Considering the current knowledge, this study aims to explore a method to comprehensively consider various factors of urban-scale building energy consumption from the perspective of urban planning. The simulation results will support the formulation of energy efficiency planning decisions and facilitate planners. The technical advantages of ABM can provide support in solving the challenges of this study.

In the existing research on macro-level urban energy conservation planning, cities in severe cold regions are not the main focus. However, due to the current climate, cities in severe cold regions usually face the complex issue of heavy energy-saving and emission-reduction tasks caused by the high building energy demand [35]. The term "severe cold region" usually refers to an area where the daily average temperature is lower than 5 °C for more than 145 days in a year, and it is also one of the five different climate regions in China. However, the research on building energy conservation from a planning perspective in this area is insufficient. Most research on building energy consumption in severe cold regions focuses on the design and thermal performance of a single building. Building materials [36] and reconstruction and optimization methods of single buildings [37,38] are usually the focus of such research. These research results and methods are more convenient for engineers and architects than for urban planners. Although some studies have begun to pay attention to the impact of urban planning elements on building energy consumption, most focus on hot summer and cold winter areas with a strong dependence on air conditioning, or are general studies that do not consider climate zoning. Urban planning elements that significantly affect energy consumption related to air conditioning [39], and a general energy-system planning-evaluation simulation research framework [40], have been proposed. These studies can provide a reference for cities in severe cold regions, but they cannot be entirely suitable for these regions. The heating demand for urban buildings in severe cold regions is far higher than the demand for electricity throughout the year. Climate protection in urban planning is essential for building energy consumption. In summer, the residents' cooling method is still the use of natural ventilation rather than air conditioning [22]. These differences lead to the need for extra attention being paid to severe cold regions, rather than solely general research.

Based on the above research background, this study took Harbin, a typical city in the severe cold region of China, as the research object and built an agent-based simulation model by integrating the influencing factors of building energy consumption at an urban scale. We referred to our previous quantitative research on influencing factors as the parameters of the model [41]. This paper takes the influencing factors identified in [41] as the basic variables under the influence module of the model, and model programming is conducted based on the quantitative influence relationship calculated in [41]. Finally, the strategies for building energy conservation planning in severe cold regions are proposed based on the scenario simulation results. The model and the strategies are supposed to provide a scientific basis and quantitative support for transforming Harbin into a low-carbon city.

2. Materials and Methods

In general, the ABM method has the following advantages over other methods that have been confirmed in many studies [42,43]: (1) ABM has the characteristics of modularization, flexibility, large-scale expressiveness, and parallel execution and can naturally describe complex adaptive systems in reality. (2) Unlike traditional modeling methods, which directly describe the system behavior, ABM starts from the description of behavior at the micro-level of the system, taking into account the autonomy and heterogeneity of the agents. (3) The idea of "bottom-up" modeling is adopted to effectively establish the relationship between the behavior of micro-agents in the system and the macro-attributes of the system, which is conducive to the study of system emergence. (4) This method is suitable for hypothesis testing, and the model has good reusability. (5) It can be combined well with other methods, such as discrete methods or system dynamics. Based on the above characteristics and advantages, our research selects this method to establish an urban-scale building energy consumption simulation model. The application is based on Harbin, China. This section provides a detailed description of the basic data, system construction and functional design of the model.

2.1. Study Area and Data

Harbin is the political, economic, and cultural center of northeastern China and a typical representative of cities in the severe cold region [44]. Since building electricity and heating energy are the most critical aspects of building energy consumption [45], this study focuses on the impact of urban planning on these two types of energy consumption at an urban scale.

The database of building energy consumption used in this study was obtained from the Harbin Municipal Leading Department of Building Energy-Saving Wall Material Reform. This came from a monitoring project on building energy consumption in Harbin in 2017. The electricity consumption information was provided to the government by the State Grid Corporation of China. Some heating energy consumption data were obtained from the National Energy Monitoring System for large public buildings, and the heating company provided the rest. Most cities in severe cold regions in China use central heating systems, also known as district heat supply; these use steam or hot water as the medium to supply domestic and production heat to users throughout the city or one of the regions through the heating pipe network. The heating company is the primary department responsible for adjusting the central heating system to supply heat to buildings according to the external temperature and heating standards. For example, in Harbin, the indoor heating standard of a residential building is 20 °C. In the original database, the unit of building electricity data is kWh/year, while the unit of heating is kJ. In order to facilitate the comparison and calculation of total energy consumption, the unit of heating energy consumption is converted into kWh/year in subsequent research. Energy-use intensity (EUI) is used as the measurement index, which is usually expressed as the total amount of energy consumed per unit of building area in one year (kWh/m^2/year) [46]. In addition to the energy consumption data, the database also records the physical information of each building, including the location, floor numbers, height, function, and build time. After the initial selection of the sample buildings, we determined the cooling and heating methods of the buildings through field surveys, such as consulting the community managers and a questionnaire survey of residents. In addition, some building characteristic values were revised using the field surveys, such as the number of floors, the floor height and whether there is a basement.

In order to study the influencing factors at the macro-level of the city, we set some conditions for the selection of sample buildings to control the physical variables of individual buildings and avoid any difference in energy consumption caused by these micro-factors. (1) Location: Four administrative districts in the central urban area were selected as the study area, and the distribution of building samples were uniform and scattered. (2) Building age: The "JGJ26-1986 Standard for Energy Efficiency Design of Civil Buildings (Heating Residential Buildings)" was issued to regulate the design standards related to the heating of buildings. Therefore, buildings built after 1986 were selected to ensure unity of the design standards, structure, and materials, ensuring relatively consistent thermal performance of buildings with the same function. (3) Building type: Building types were used whose energy consumption is significantly affected by the external urban environment, including residential buildings, retail buildings, medical buildings, education buildings, hotel buildings, and office buildings. (4) Building form: The possible building forms of various building types, such as bungalows, low-rise, mid-rise, and high-rise buildings, were comprehensively considered. (5) Heating method: This mainly included buildings with a centralized heating system in winter to ensure a consistent statistical caliber of heating data. For public buildings with independent heating, the statistical value of heating energy consumption was converted into the unit of urban central heating.

Finally, 609 civil buildings in the central area of Harbin were selected as samples, including 242 residential buildings, 48 hotel buildings, 50 retail buildings, 35 medical buildings, 107 educational buildings, and 127 office buildings. These six types of buildings are considered to be the ones whose energy consumption is more affected by the urban environment. Table 1 shows the range of physical information for each type of building in this study. Gross floor area refers to the total area of each floor of a building. Footprint area refers to the area of land occupied by the building.

Table 1. Range of physical information for different types of sample buildings.

Building Type	Building Height (m)	Gross Floor Area (m^2)	Footprint Area (m^2)
Hotel	5.92–108.73	941.13–6036.59	172.00–4018.23
Retail Business	6.00–97.00	1536.6–238,437.16	269.12–101,453.12
Medical	3.29–57.42	810.65–76,286.13	223.51–3632.20
Education	3.49–57.00	503.04–85,500.63	174.10–6276.32
Residential	11.39–111.84	158.06–45,679.20	158.06–5279.00
Office	4.00–115.25	941.61–106,209.65	50.30–5373.42

2.2. Model System

The identification results of the influencing factors quantitatively describe the relationship between the urban form, climate factors, and energy consumption of different types of buildings in Harbin. Based on this relationship, the agent-based modeling technique will mainly solve the following two problems: First, to realize the integration of multiple influencing factors within the same simulation system and to accurately simulate the influence mechanism of specific influencing factors on the overall building energy consumption. Second, to propose planning strategies that can meet the building energy-saving targets based on the energy-saving prediction results of different planning scenarios.

Based on the above objectives, the design idea of the model is to first build a framework of urban-scale building energy consumption simulation system, and set the buildings, residents, and household equipment as agents at different levels. Each agent interface will contain its own parameters and environmental parameters. This study converts local influencing factors and their quantitative influence relationships into model parameters. The model operation environment and rules are set as the action of the parameters, and urban form and climate are set as condition modules. During simulation, the household equipment agent in the building agent can automatically call the parameter values in the condition module and the characteristic values of the residents to calculate their individual energy consumption, summarize them in the building agent, and finally, output the overall or regional total building energy consumption value through the calculation function on the main panel. The study takes systematic thinking as the starting point, fully considers the operability and scalability of the model, and relies on the AnyLogic software platform to complete the model construction. The general idea of the model design is shown in Figure 1.

2.2.1. Classification of Agents

The design of agents for the urban-scale building energy consumption simulation model includes a "global agent", "building agent", "resident agent", and "household equipment agent".

The global agent is the overall control area of the model, including the group of building agents and variables at the macro-level of the city, such as climate factors, socioeconomic factors, population, policies, and guidelines related to building energy conservation.

The building agent includes physical information, such as the building number, function, location, resident agent, and household equipment agent within the building. In addition, it also includes the urban form parameters within the neighborhood where the building is located, such as building density, floor area ratio, aspect ratio, building height, and shape factor (Figure 2).

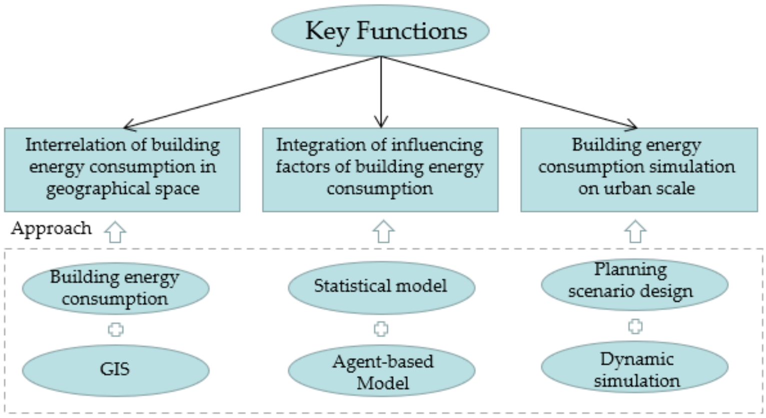


Figure 1. The general idea of the model design.

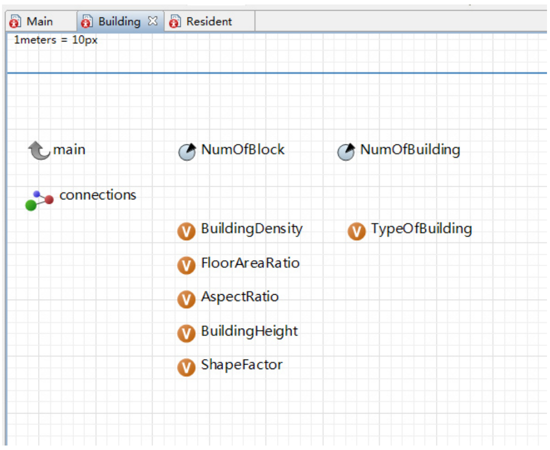


Figure 2. Urban form variable settings on building agent.

The resident agent contains all information related to energy users, including their age, gender, education level, income level, energy-saving awareness level, and daily energy-use habits (Figure 3). In this agent, the residents' energy-use behavior is quantified by the probability values obtained from the questionnaire survey. Although each agent has its own parameters, the overall behavior exhibited by its group can represent the general rules of residents' energy-use patterns at the city scale.

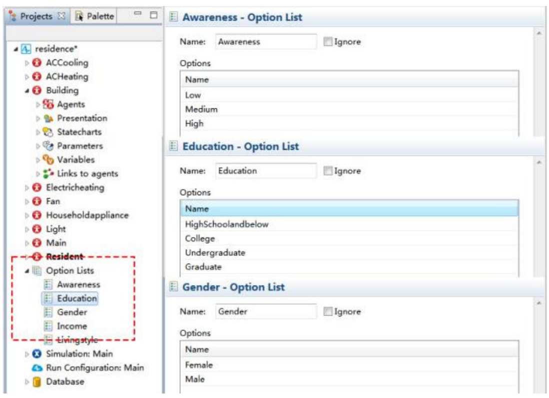


Figure 3. Personal characteristic option settings of resident agent.

The household equipment agents are located within the building agent, representing the energy-use pattern and intensity of the equipment in the building. The types of equipment are not identical in each building and are set based on the holding data obtained from the survey. The equipment use pattern is associated with the resident agent and controlled by the individual characteristic parameters and climate conditions. For example, Figure 4 shows a state diagram of the heating behavior of the air conditioner and the settings of key process nodes.

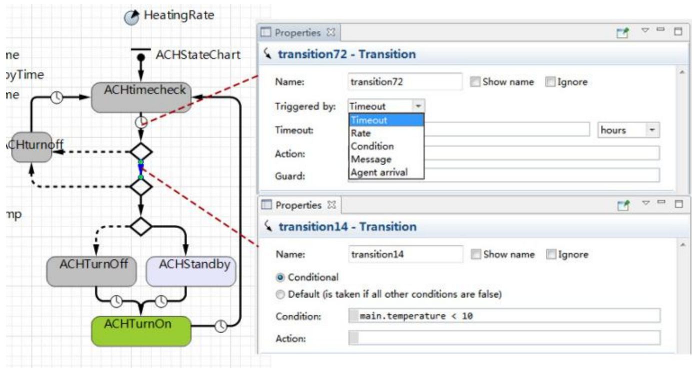


Figure 4. Behavior transformation of air conditioning for heating.

2.2.2. Influence Modules

The agent-based model in this study operates via the feedback mechanism of building energy consumption on influence factors. Therefore, it is essential to integrate the main influencing factors into the same simulation system. According to the existing research, the influencing factors of building energy consumption at the urban scale can be divided into urban form and climate. This study designs two different functional modules to realize the integration of multiple parameters. Each module has its own relatively independent parameters, which are related to each other through temporal or spatial variables. The interaction between different agents and the dynamic changes between agents and the environment are realized through the code settings of the actions ("Entry Action" and "Exit Action").

The urban form module exists at two positions in the model. The first position is within the global agent, also referred to as the main panel. Through the pre-processing of the ArcGIS software, the central area of Harbin is divided into blocks, with the effective influence radius of the external environment on building energy consumption set at 340 m [47]. The land-use types of each block are categorized to form a table function named "TypeOfBlock". The second location of the urban form module is within the building agent. Following pre-processing through ArcGIS software, five types of urban form factors of 77,637 buildings in the central area were obtained, including building density, floor area ratio, aspect ratio, building height, and shape factor, which were set as "variable" in the model. The building density refers to the proportion of the total building footprint area to the total land use area. The floor area ratio is calculated by dividing the gross floor area by the total land use area. The aspect ratio is calculated as the ratio of building height to the width of the distance between buildings. The shape factor reflects the ratio of the external surface area of a building in contact with the outdoor atmosphere and the volume enclosed by it. The urban form variable of each building will be assigned according to the building serial number, and the data type is set as "double" in the model. Figure 5 is an example of a coding window for building height variables. The building type parameter is retrieved from the database during the simulation process according to the agent number of each building.

In the climate module, all parameters are set as global variables within the global agent since they represent the macro-climate environment in the central area of Harbin. The three types of climate parameters in the database are set as the table functions "TEMP", "WSP", and "RH", respectively. In addition, the climate variables "monthlytemp", "monthlywsp", and "monthlyrh" are also set for the model simulation. For example, the command to assign a value to the temperature is "monthlytemp = TEMP (MonthOfYear)". In most urban-scale building energy consumption modeling studies, the climate module usually adopts the urban climate mathematical model at the source-code level or the pre-processed meteorological data in the meteorological database. Most studies use the latter method [48]. For example, CitySim software uses pre-processed urban macro-, meso-, and urban canopy climate data to modify the climate input values of other sub-models [43]. In order to ensure the calculation capacity of the model at the current stage, the climate module in this study also uses pre-processed climate data, which are set on the main panel of the model in the form of table functions. The climate value is captured in 24 h, and the updated rule settings are shown in Figure 6. The energy consumption simulation calculation function is also set on the main panel, and the command set is shown in Figure 7.

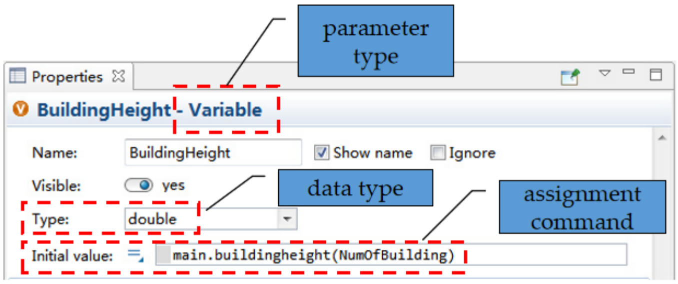


Figure 5. Example command for assignment of building height variable.

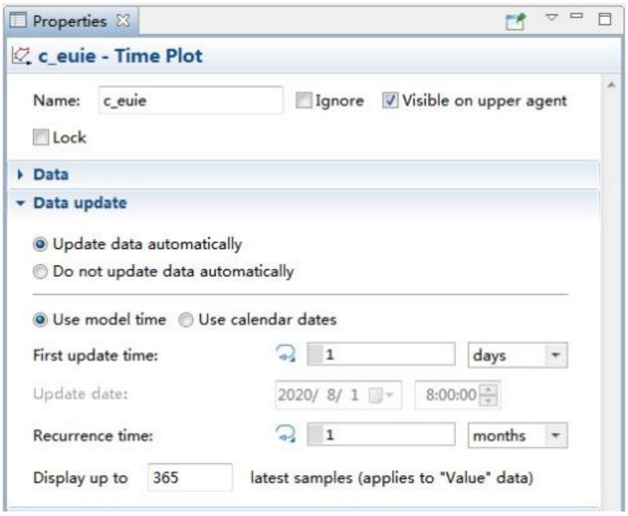


Figure 6. Updated settings of climate module data.

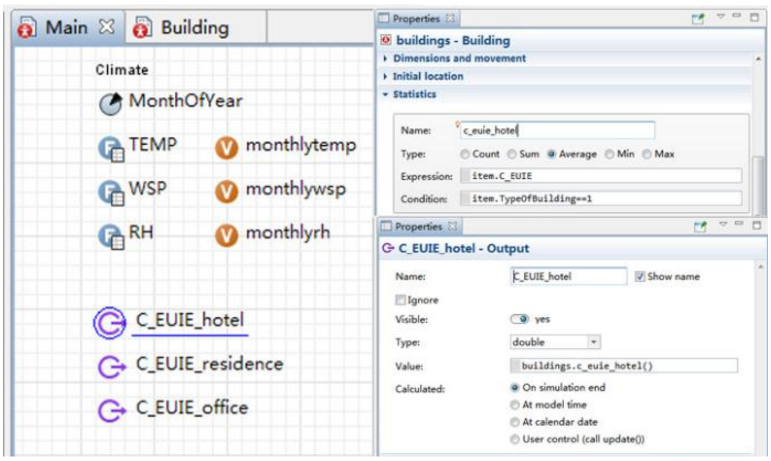


Figure 7. Simulation output of energy consumption under the climate module on the main panel.

2.2.3. Parameter Values

Urban form influences building energy consumption levels by changing the thermal performance of buildings, including the building density, aspect ratio, floor area ratio, building height, and shape factor [49–53]. The climate is mainly composed of temperature, wind speed, and relative humidity. In order to remain consistent with the actual database of building energy consumption, this model is temporarily constructed using climate data for the year 2017. According to a previous study by our team, the quantitative relationship between building energy consumption and various impact parameters at the urban scale is shown in Tables 2 and 3 [41]. That study used the same research area, sample buildings, and basic data as this paper. Therefore, the identified influencing factors and quantitative relationships in [41] are applicable to the parameters required for the model built in this study. Correlation, regression, and sensitivity analyses are widely used in current research on the factors that play a leading role in building energy consumption. This study chose stepwise regression to solve the problem of multicollinearity among elements and ensured that influence relationship determination was carried out at a highly significant level. The study followed a standard statistical analysis process. Firstly, correlation analysis was conducted to select the factors that preliminarily impact building energy consumption. Then, the variance inflation factor (VIF) was used to determine whether there was multicollinearity between the impact factors [54]. This was calculated by taking the ratio of the variance of all of a given model's betas divided by the variance of a single beta if it were fit alone. Following this, the stepwise regression method was used to quantify the influence level between the factors and energy consumption. In the end, an independent two-sample *t*-test was performed to examine whether the independent variable in the regression model was correlated to the dependent variable. In this study, the identified influencing factors were used as the "variables" and "parameters" set on the agents' panel. The constant and denormalization coefficient results obtained from each stepwise regression will be used as the input information of the model. The denormalization coefficient is the slope of the regression equation, indicating that each independent variable changes by one unit, and the dependent variable changes by a number of units. The coefficient is related to the unit taken by the independent variable, so it can be used for prediction and calculation. In order to avoid repetition of the previous article's content, this article will not repeat the detailed data and theoretical analysis process.

Table 2. Stepwise regression results of urban form factors and building EUI.

Building Type	Electricity EUI (kWh/m^2/Year)		Heating EUI (kWh/m^2/Year)	
	Variable	Denormalization Coefficient	Variable	Denormalization Coefficient
Hotel	/	/	(Constant)	192.037
	/	/	Building Height (m)	−0.601
Retail	(Constant)	21.081	(Constant)	105.508
	Shape Factor	357.346	Aspect Ratio	51.45
	/	/	Shape Factor	239.71
Medical	(Constant)	−17.89	/	/
	Building Density (%)	2.514	/	/
Education	(Constant)	50.964	(Constant)	170.211
	Building Height (m)	−0.775	Building Height (m)	−0.65
Residence	(Constant)	−18.732	(Constant)	99.013
	Shape Factor	266.632	Floor Area Ratio	9.516
	/	/	Shape Factor	217.762
Office	(Constant)	51.519	(Constant)	179.642
	Building Height (m)	−0.279	Building Height (m)	−0.369

Table 3. Stepwise regression results of climate factors and building EUI.

Building Type	Electricity EUI (kWh/m^2/Year)		Heating EUI (kWh/m^2/Year)	
	Variable	Denormalization Coefficient	Variable	Denormalization Coefficient
Hotel	(Constant)	6.669	(Constant)	−1.074
	Wind Speed	−1.264	Wind Speed	6.856
	Temperature	0.087	Temperature	−1.003
Retail	/	/	(Constant)	57.233
	/	/	Wind Speed	−10.281
Medical	/	/	(Constant)	23.458
	/	/	Temperature	−0.639
Education	/	/	(Constant)	43.923
	/	/	Wind Speed	−7.303
Residence	(Constant)	10.231	(Constant)	0.553
	Wind Speed	−0.598	Wind Speed	−7.187
	Relative Humidity	−0.073	Temperature	0.627
	/	/	Relative Humidity	0.792
Office	(Constant)	42.605	(Constant)	44.302
	Wind Speed	−8.686	Wind Speed	−2.342
	Temperature	0.382	Temperature	−1.060
	Relative Humidity	−0.183	Relative Humidity	−0.315

2.2.4. Model Validation

Model testing and validation are essential aspects and the most challenging and controversial issues in agent-based modeling. Usually, an agent-based model includes multiple non-associated variables and attributes to express factors' heterogeneity, which verify such models based on their construction principle and structure. Considering that this model is built based on mathematical statistics, we refer to the method of Ciulla G [55]. To assess the stability of the model parameter values and whether the model can be used in ranges other than the sample observations, this study compared the simulated values with the standardized residual analysis of the actual energy consumption dataset. The results show that the standardized residual values are within ±2 for both the simulated data values and the actual energy consumption data (Figure 8), indicating that the data are reliable.

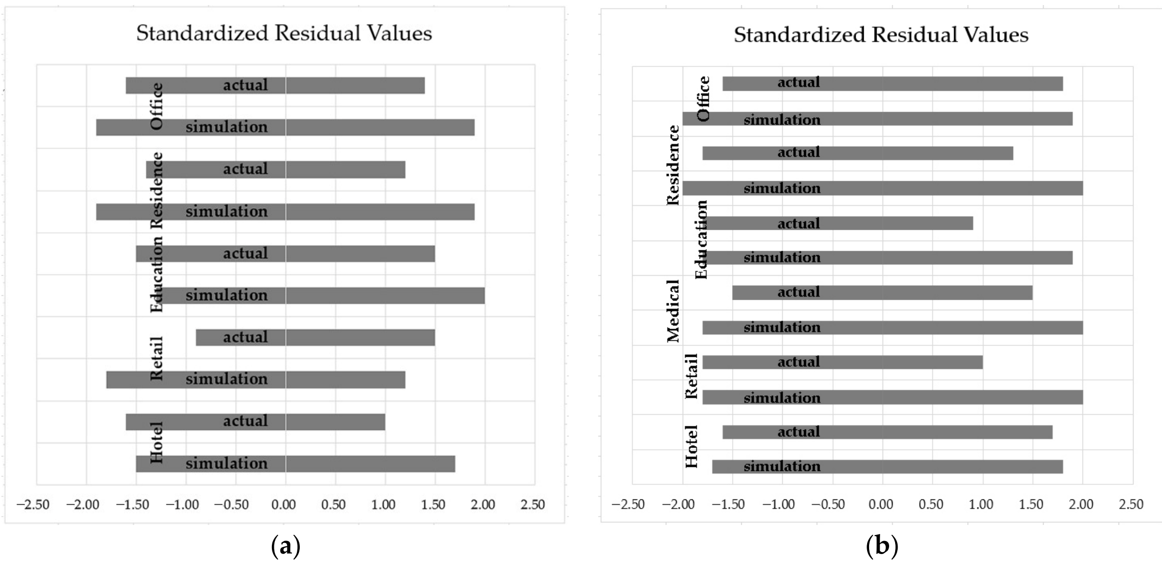


Figure 8. The standardized residual values for validation. (**a**) Electricity EUI; (**b**) heating EUI.

2.3. Simulation Scenario

The simulation scenarios designed in this study can be cataloged as the baseline, urban form, and climate scenarios, which are set up mainly through the global parameters in the main panel of the model and the setting and conversion of the parameters of each influence module. Since cities in the severe cold regions of China mainly adopt centralized heating systems, the daily electricity consumption and the winter heating energy consumption of buildings are different in terms of pathways and statistics. The model calculates electricity and heating energy consumption separately, then, calculates the block's total building energy consumption (Equation (1)).

$$E = \sum_{i=1}^{n} [(EUI_{e,i} + EUI_{h,i}) * A_i)] \quad (1)$$

where E is the total building energy consumption of the block (kWh/year), n is the number of buildings in the block, $EUI_{e,i}$ is the electricity use intensity of the building i (kWh/m^2/year), $EUI_{h,i}$ is the heating energy-use intensity of the building i (kWh/m^2/year), and A_i is the gross floor area of the building i (m^2).

Baseline Scenario: The building EUI level in the baseline scenario is the standard reference group for the simulation results of all scenarios. The design of the baseline scenario should conform, as far as possible, to the reality of urban zoning, economic and social development, climate, and other factors. In this study, the Monte Carlo method is used to estimate the total annual building EUI using the actual EUI value of the sample buildings, and then, determine the benchmark building energy consumption in the central area of Harbin.

Urban Form Scenario: As the current development of the central area of Harbin is relatively stable, it is unreasonable to take energy conservation as the only goal to design urban form indicators that are divorced from the actual situation. The results of this scenario are expected to support the planning strategy related to the urban form indicators; they should identify the area of building energy consumption most sensitive to urban form factors, which will be focused on first, and how much of an energy-saving effect this area may produce. Therefore, the simulation parameters are designed according to the significant influencing factors and their impact on each type of building. The value is a 1-unit increase or decrease in the initial value under the baseline scenario (Table 4). During the urban form scenario simulation, the initial parameter is each block's current urban form factor value. The parameter values of the influence factors that significantly impact building energy consumption are updated according to the settings of the scenario. Climate parameters and residents' daily life patterns remain unchanged under this scenario.

Table 4. Parameter settings for urban form scenario.

Building Type	Adjusted Parameters	Value Changes from Baseline
Hotel	Building Height (m)	+1.00
Retail Building	Aspect Ratio	−0.10
	Shape Factor	−0.10
Hospital	Building Density (%)	−1.00
Educational Building	Building Height (m)	+1.00
Residential Building	Floor Area Ratio	−0.10
	Shape Factor	−0.10
Office Building	Building Height (m)	+1.00

Climate Scenario: The main objective of the climate simulation scenario is to predict the trend of urban-scale building energy consumption under future climate change conditions. This study uses the BCC_CSM1.1 climate model from the National Meteorological Center of the China Meteorological Administration climate system to analyze the climate change projection results in the northeast region of China under the background of RCP2.6 CO_2 emissions. The BCC_CSM1.1 climate system model has reached the world's most advanced level of prediction and testing accuracy after a long time-series of climate experiments [56]. The RCP2.6 CO_2 emission scenario is one of the four greenhouse gas concentration scenarios proposed in the Fifth IPCC Assessment Report [57]. RCP represents the Representative Concentration Pathways, and the figure represents the radiation force level of 2.6 Wm^2 in the year 2100. RCP2.6 is the most ideal of the four scenarios. It assumes that human beings will use more positive methods to reduce greenhouse gas emissions. By the end of this century, greenhouse gas emissions will become negative. In this scenario, the temperature will not rise by 2 °C.

This study uses a climate projection scenario for the next 50 years to create a long-term projection of building energy consumption in the central city of Harbin.

3. Results

3.1. Characteristics of Energy Consumption of Sample Buildings

Building function determines how the building is used, as well as the energy-use patterns within the building. The electricity EUI and heating EUI of six types of buildings in Harbin show relatively similar patterns (Figure 9). The overall level and median of electricity EUI in the hotel, educational, residential, and office buildings do not differ significantly, indicating that these four types of buildings have some similarities in terms of electricity demand. The difference in electricity consumption EUI for retail buildings of different sizes and types is more pronounced. Medical buildings have higher heating demand in winter than other building types. Retail, medical, and residential buildings have higher total EUI than others. In general, retail and medical buildings consume the most energy per unit area of all six types.

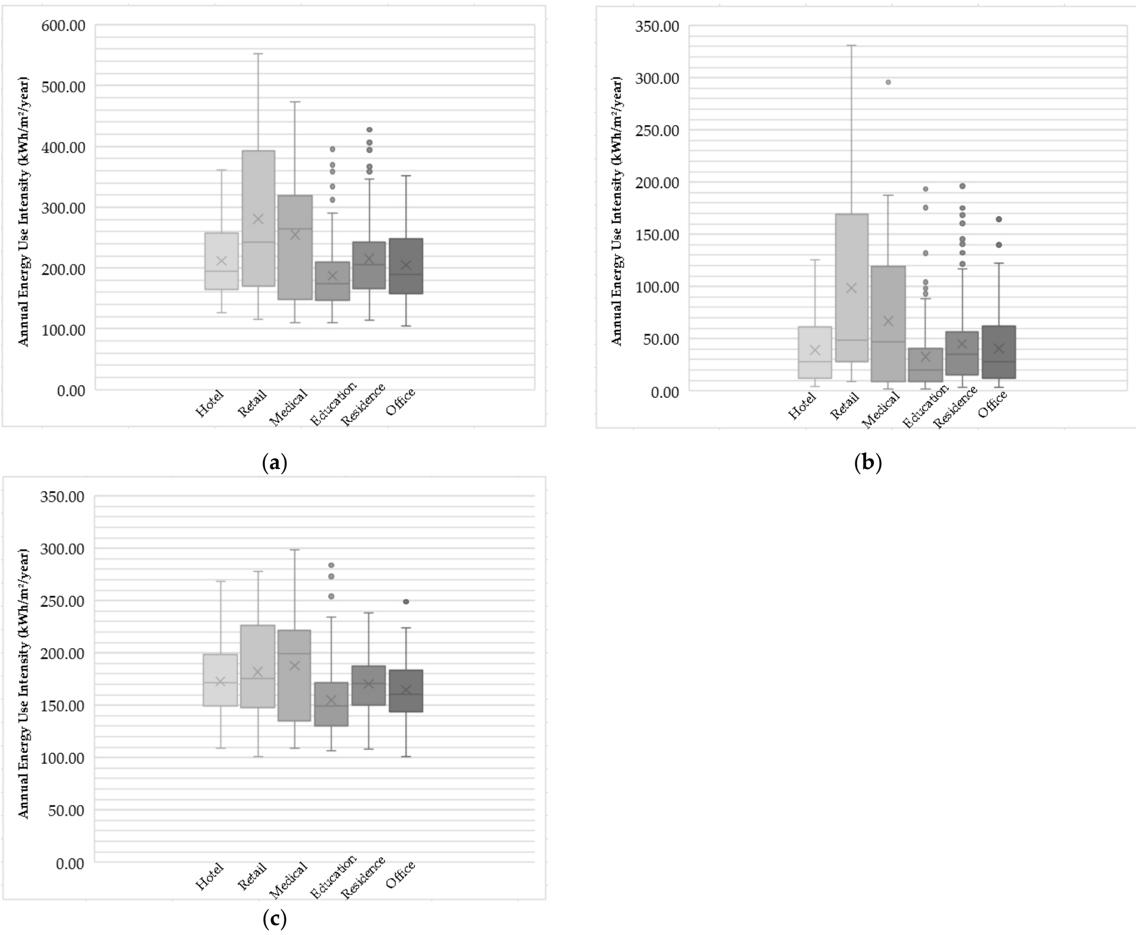
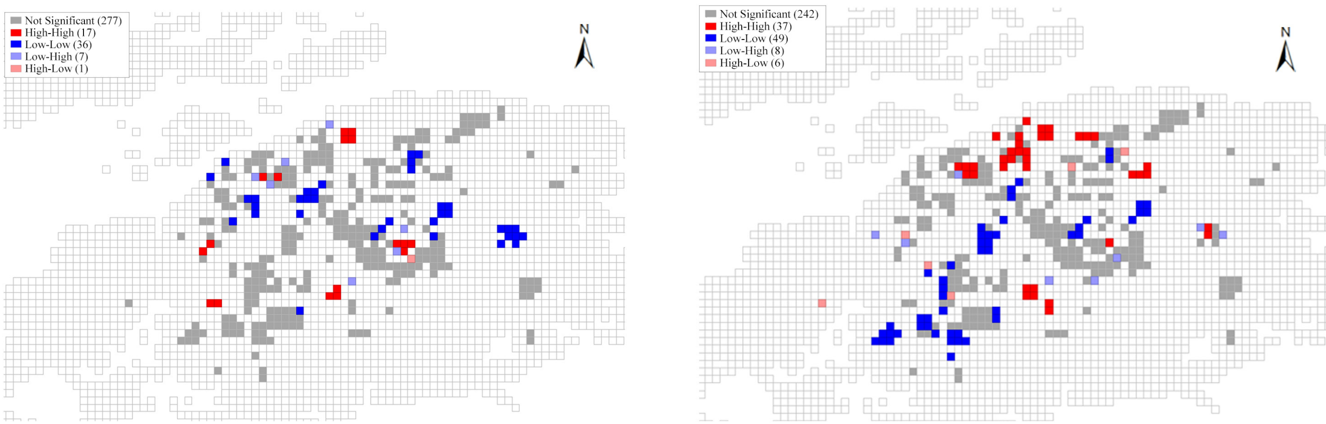


Figure 9. Boxplot of EUI of sample buildings. (**a**) Total EUI; (**b**) electricity EUI; (**c**) heating EUI.

In order to observe the distribution of building energy consumption in urban space, this study uses GeoDa software for spatial clustering analysis. GeoDa is a free and open-source software tool that serves as an introduction to spatial data science [58]. The software can perform many kinds of spatial data analysis, such as spatial autocorrelation statistics of aggregated data and basic spatial regression analysis of point and polygon data. The distance weight is set using the k-nearest neighbor algorithm (KNN), and the value is set to 4. Local Moran's I is used to identify the relationship between energy consumption at a specific location and its surrounding energy consumption, that is, the type of clustering or outliers. Based on the calculation results of Local Moran's I, we drew a LISA (Local Indicators of Spatial Association) cluster map of the annual building EUI. We introduced the method for this in detail in previous research (ref. [41]) and will not repeat it in this paper to avoid repetition. The distribution of building EUI in the study area is low in the center and high in the periphery (Figure 10). The possible reason for this is that Harbin is vulnerable to the cold air from northern Siberia, resulting in lower temperatures in the outskirts than in the central areas. Additionally, the city's heat island effect can make the central area slightly warmer than the fringe area. During the transition season at the beginning or end of the heating period, the use of electric heating equipment in the edge zone is higher than that in the central zone, increasing the EUI of buildings in the edge zone. The northern and eastern parts of Harbin's central area are prone to high-heating-EUI clusters, while the central and southwestern parts are mostly low-heating-EUI clusters. The spatial distribution shows that building heating EUI decreases from northeast to southwest.



(**a**) (**b**)

Figure 10. LISA cluster map of the EUI of sample buildings. (**a**) Annual electricity EUI; (**b**) annual heating EUI [41].

3.2. Baseline Scenario

Figure 11 shows the building EUI simulation results in different blocks under the baseline scenario. The EUI results show obvious differences across the blocks, which may be caused by differences in land use and urban form. The building energy consumption in the central area shows an aggregated spatial distribution pattern. The high-energy-use areas are located primarily in clusters, mainly in the northern part of the neighboring river and the periphery of the central area of the main city. Most of these areas are new development zones built in the main urban area of Harbin in recent years. The low-energy-consumption areas are mainly distributed in the central area of the main city, which is also the old area of the city. The building energy consumption of the blocks adjacent to both river banks is generally higher than that of the non-river-adjacent area.

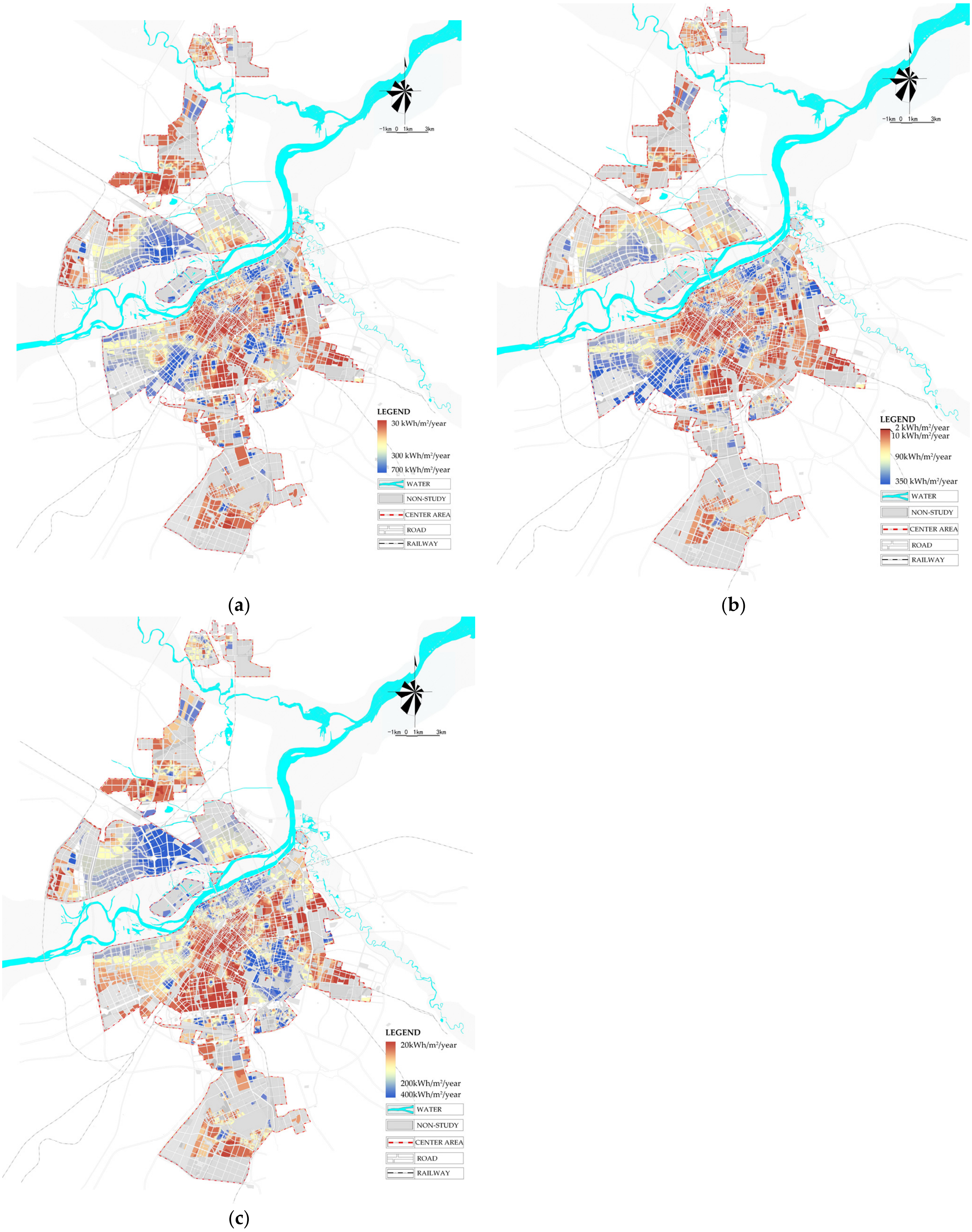


Figure 11. EUI of the central urban area under the baseline scenario. (**a**) Total EUI; (**b**) electricity EUI; (**c**) heating EUI.

The spatial distribution of the electricity and heating EUIs is similar but different. The difference mainly lies in the distribution of high-EUI areas. The high EUI of electricity and heating is mainly distributed in the central area to the south of the river and the northern area to the north of the river. The EUI of blocks on both sides of the river is higher than that of "inland" areas. To the north of the river, there is an overlap between the high-electricity-EUI area and the high-heating-EUI area, which indicates that the overall building energy consumption in this area is high, and it should be a key area for energy conservation.

3.3. Urban Form Scenario

Figure 12a shows the changes in total annual building energy consumption under the urban form scenario for each block of the central area. As introduced in Section 2.2.2, the study uses 340 m as the influence radius to delimit the "block" to collect urban form data. In the simulation scenario, in order to assist in the formulation of planning strategies, the building energy consumption data are connected to the land in an urban planning context in order to calculate the change in overall building energy consumption on the block, as shown in Equation (1) in Section 2.3. Therefore, in the urban form scenario and climate scenario, the unit of simulation results is kWh/block. The area of each block is about 10^5 m^2. The highest reduction appears in the blocks for retail buildings at 44.7×10^6 kWh/block/year. The blocks for office buildings see the lowest drop, at 34.5×10^3 kWh/block/year. The simulation results indicate that the south and southwest areas of the river are more sensitive to urban form factors. This result suggests that building energy conservation through urban form measures should focus on Harbin's central and southwestern areas.

It can be seen from the comparison between Figure 12b,c that urban form factors have a more significant impact on building electricity consumption on an urban scale, with a more significant proportion of areas with high energy efficiency. These high-energy-efficiency areas are mainly concentrated in the western region south of the river, which is a new urban area mainly comprising residential and commercial land. This shows that the adjustment of urban form indicators is more effective for building energy conservation in new urban areas with high-quality residential buildings. At the same time, cross-comparison shows that the main reason that the overall energy-saving effect of these areas is not apparent is that the heating energy efficiency of these areas is not significant. The total energy consumption for heating is much higher than that for electricity consumption and it occupies a leading position in the overall energy-saving effect. Although heating is only available for six months, the annual change in heating energy consumption is similar to that in electricity consumption, with the highest drop being 20.1×10^6 kWh/block/year and the lowest drop being 19.6×10^3 kWh/block/year. This also explains that for severe cold regions, the conservation of building heating energy is of higher priority than that of electricity.

3.4. Climate Scenario

Under the RCP2.6 CO_2 emissions scenario, the average daily temperature in Harbin, China will increase by about 1.8 °C over the next 50 years [59]. The model output results show that the electricity EUI of residential buildings will increase significantly with the increase in temperature over the next 50 years (Table 5). Eventually, the increase in electricity EUI will exceed the decrease in heating EUI, resulting in a rising trend in the total annual building EUI.

Table 5. The changes in EUI under the climate scenario.

Building Type	Total EUI (kWh/m^2/Year)
Hotel	−1.461
Medical	−0.990
Residence	1.129
Office	−1.259

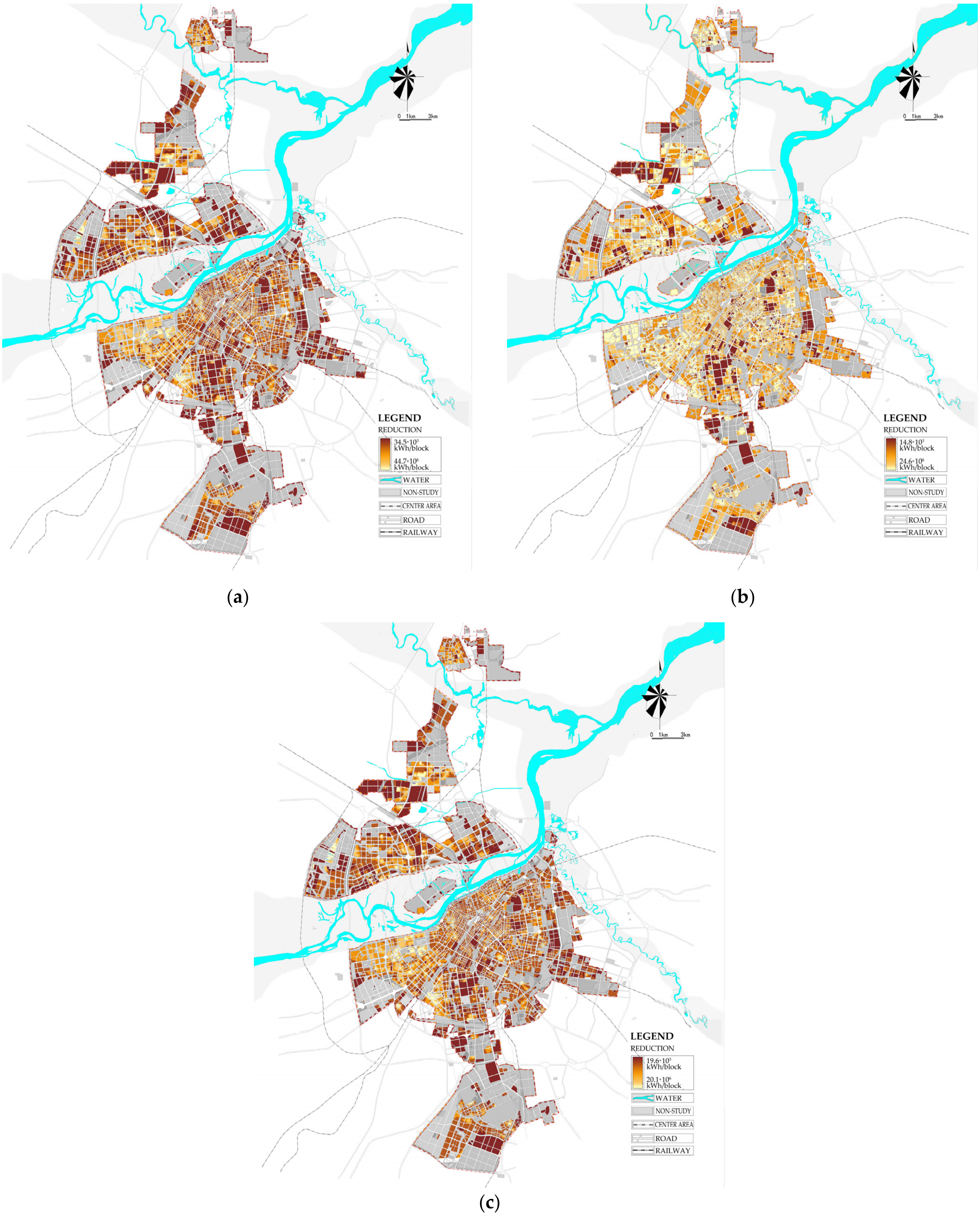


Figure 12. Annual reduction in building energy consumption of the central urban area under urban form scenario. (**a**) Total energy consumption; (**b**) electricity consumption; (**c**) heating energy consumption. Note: The term block refers to the grids mentioned in Section 2.2.2, and the area of each block is about 105 m^2.

Figure 13 shows the predicted changes in building energy consumption in the central area of Harbin under the climate scenario for the next 50 years. The energy consumption of residential buildings in the central area shows a slight increase, up to 5.3×10^5 kWh/block/year, leading to a trend of increasing building energy consumption in the central area. However, the building energy consumption of land for other functions has decreased, with a maximum decrease of 8.41×10^5 kWh/block/year. Growth in the central area is still lower than in the peripheral areas due to the influence of other environmental factors such as geographical location and building density. Growth is most evident in the southwest part of the central area. Most of the residential buildings in this area have been newly constructed in recent years, with relatively well-equipped building facilities and relatively high household living standards. Therefore, there is higher resident demand for electric cooling or heating equipment such as air conditioners and intelligent home appliances, which leads to higher energy consumption in this area.

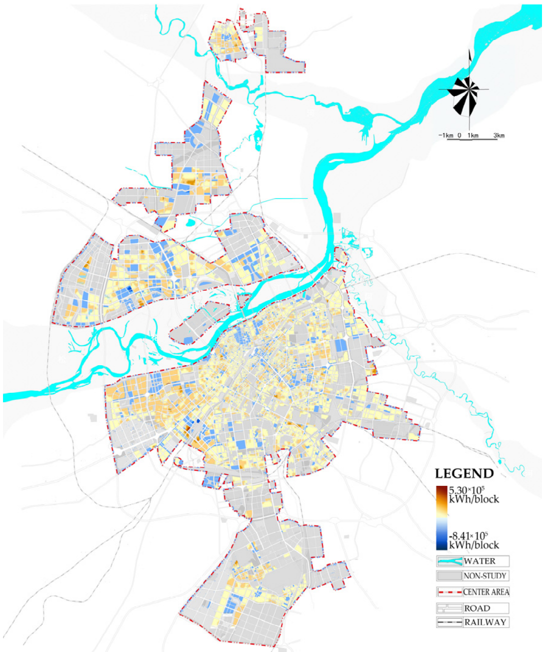


Figure 13. Changes in building energy consumption under the climate scenario over the next 50 years. Note: The term block refers to the grids mentioned in Section 2.2.2, and the area of each block is about 10^5 m^2.

4. Discussion

The simulation results confirm the following: (1) Consistent with existing studies, building energy conservation planning of cities at a macro-scale should pay attention to both urban form and climate [60–63]. (2) The energy conservation planning strategies for these two types of influencing factors should vary across the regions in the city. This section will discuss the planning strategies for building energy conservation based on the above results. Based on the simulation results, we will first discuss the targeted adjustment strategies of urban form and climate factors under the energy-saving goal. Secondly, we will discuss the strategy of incorporating building energy conservation into the current planning system based on the findings of this study.

4.1. Urban Form Planning and Control

The simulation results show that the energy-saving potential of building energy consumption through urban form planning changes with location and building type. The formulation and implementation of Harbin's planning strategy for building energy conservation needs to fully consider the correlation between urban form factors and district development level, which is reflected in the design of the agent-based model in this study. Based on the current spatial pattern and distribution characteristics of building energy consumption, urban planners can identify the sensitive areas of building energy conservation through scenario simulation and determine the leading areas for planning strategies for building energy conservation. Considering the current development stage of Harbin, the urban space form is relatively stable, and large-scale urban form adjustment based on the purpose of building energy conservation does not conform to the economy and feasibility of urban construction. Therefore, this strategy should be applied to new cities and renewal areas. In Harbin, it is in the northern part of the river and in the west region in the south of the river.

First, we will discuss spatial form coordination and optimization guidance. The implementation of the strategy should first determine the energy-saving potential area oriented by the urban form. For Harbin, the simulation results show that the southern and southwestern regions of the river are high-potential areas for urban form factors. These areas should be the focus of urban form index optimization. Then, by evaluating the suitability of building energy conservation in the planned area, optimizing the urban form and land-use function, and adjusting the intensity of land development and other factors, the urban form will be guided and controlled in a targeted way (Figure 14). According to the influence factors identified in this study, cities in severe cold regions should focus on mandatory control indicators in the detailed planning stage such as building density, floor area ratio, and building height, and guiding indicators such as aspect ratio and shape factor.

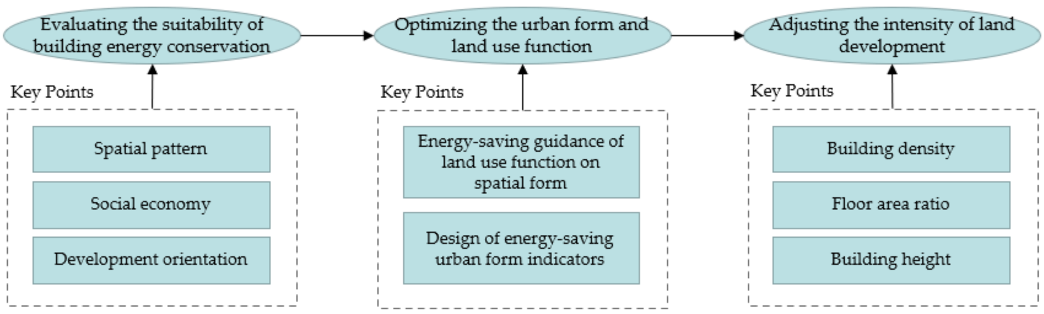


Figure 14. Guiding measures for energy-saving-oriented urban form planning.

Second, we will focus on the differential control of land-use indicators. The content of the indicator control varies according to the block's land-use type. Based on the simulation results, the decreased floor area ratio of residential land and the building density of medical land in Harbin can reduce the total building energy consumption. The building height of office land and education land can be appropriately raised. The effect on building heating energy consumption should be considered first, followed by electricity consumption. However, it is undeniable that not all actual planning can reduce the floor area ratio due to the limitation of land cost. Therefore, we suggest that the floor area ratio and building energy conservation be exchanged through specific policies and financial means. At the stage of urban design, this study suggests that the shape factor of residential and retail buildings should be appropriately reduced. The aspect ratio of the commercial area should be appropriately reduced to avoid the formation of vertical "deep grooves" in the street space, without damaging the building functions.

4.2. Climate Optimization and Regulation

Since it is difficult to change the climate at the macro-level of the city, the energy efficiency planning strategy should aim to optimize the local climate environment through specific planning tools under the background of adapting to future climate change.

First, one should strengthen climate protection and reduce heating energy consumption. From the results of the urban form scenario, it can be seen that heating energy consumption should be the priority of energy saving as its annual change is similar to that of electricity consumption, although it takes half as long as electricity consumption. This study suggests that at this stage, energy efficiency planning and adjustment should be carried out for heating energy consumption in winter. By strengthening the planning of the urban landscape system, the ability of urban ecological barriers to resist and adjust the high-speed cold air generated by river space can be improved to achieve climate protection. The opening of an enclosed building complex as a public space can be carried out in the east or south to achieve ventilation and cooling in summer and cold prevention in winter.

Second, we must consider local climate adjustment in climate-sensitive areas by ecological means. The climate scenario simulation results show that the area southwest of Harbin's central area will show evident energy consumption growth in the future climate. This area is a new urban area under construction, with great potential for energy conservation planning and climate-suitable environmental design. Therefore, this study suggests that at the level of detailed planning, the control of greening rate indicators can be appropriately improved to create a more energy-saving climate for the region to face future climate change [64]. Urban street green space should be appropriately supplemented to enhance the connectivity between green spaces within blocks. The composite green space structure of trees, irrigation, and grassland can be used to improve green coverage, and the hard substrate materials can be updated to create an environment with suitable temperature and humidity to help with building energy conservation and emission reduction.

4.3. Building Energy Conservation Planning System

This strategy is an expanded discussion of the overall research. Urban-scale building energy conservation planning is a systematic, preventive, and guided approach to carbon control and emission reduction. Therefore, synergy with the existing planning system is necessary to ensure the implementation of urban-scale building energy conservation planning [65]. This study provides detailed coordination of building energy conservation planning mechanisms and measures in terms of planning content, planning indicators, planning implementation, and management evaluation for municipal-level territorial spatial planning, forming a layer-by-layer transmission in the content of the planning system.

First, content relevant to building energy conservation planning should be included in the preparation of the spatial master plan of the municipal territory. This study supplements the contents of the master plan of Harbin from the aspects of space development goals, space structure, development intensity, functional pattern, and public space configuration to accelerate the improvement of urban building energy conservation (Table 6).

Table 6. Energy conservation planning points in the Harbin Municipal Territorial Spatial Master Plan.

Planning Highlights	Highlights
Space development goals	Determine the development goal of total building energy conservation at an urban scale.
Spatial structure	Determine the total amount and structure of types of construction land.
Development intensity	Delineate the key control areas of spatial form under the guidance of building energy conservation, propose development intensity zoning, and guide the formulation of mandatory indicators such as building density, floor area ratio, and building height.
Functional layout	Focus on areas with highly mixed urban land functions and comprehensively optimize the land-use structure.
Public space configuration	Improve blue–green space system planning, and put forward the layout and control requirements for ventilation corridors and greening systems in the areas with energy-sensitive climate.

Secondly, at the level of detailed planning, planning indicators are used as carriers to control specific planning blocks. The mandatory control indicators of energy conservation planning should be building density and floor area ratio, and the guiding control indicators should be building height, aspect ratio, and shape factor. In addition, the impact of planning indicators on local climate and environment, such as temperature, wind speed, relative humidity, and sunshine, should be comprehensively considered. Especially for cities in severe cold regions, it is necessary to create a positive climate protection space while building an energy-saving and emission-reduction urban space environment, to achieve the dual purpose of improving building energy conservation and urban livability.

Third, in the construction and implementation of urban-scale building energy conservation planning, not all urban areas should be treated in the same way. The differences between regions in the city should be respected, and planning measures should be formulated according to the energy-saving potential and current development conditions, development goals, and characteristics of each region. The demonstration role of energy conservation in new urban areas and urban renewal areas should be strengthened. Energy-saving-oriented indicator control, green space creation, and other methods can be tried in the new urban area first, and then, further promoted to other areas of the city. One must establish an impact chain between the demonstration area and the surrounding areas and gradually expand the impact of energy conservation to the surrounding areas, or even wider areas, through the extension and radiation of the environment.

Fourth, "urban physical examination" is an innovative urban governance tool and an effective way to support high-quality urban development in the future. The "urban physical examination" should be used as a powerful tool to regularly review, manage, monitor, and correct the effects of energy efficiency planning and policy measures [66]. This study suggests that the urban form and climate indicators identified in the previous analysis should be supplemented to conduct a comprehensive review of energy efficiency planning. These indicators will help monitor the effectiveness of building energy conservation planning objectives in a specific planning cycle. Based on the eight aspects of the urban physical examination of China in 2020, this study proposes an urban physical examination indicator system related to building energy conservation planning (Table 7).

Table 7. Suggested urban physical examination indicators related to building energy conservation.

Objectives	Current Indicators	Supplementary Indicators
Ecological Livability	Urban population density (10,000 people/km^2)	Floor area ratio of building energy conservation planning area
	Urban development intensity (sqm/km^2)	The average height in the building energy conservation planning area (m)
	Urban greenway density (km/km^2)	Heating days (days)
	Percentage of green buildings in new construction (%)	/
Health and comfort	Percentage of high-rise, high-density residential land use (%)	Proportion of land area in building energy conservation reconstruction area (%)
Convenient transportation	Road network density (km/km^2)	Road width in building energy conservation reconstruction area (m)
Innovation	/	Number of participants in the publicity and education activities of building energy conservation
	/	Number of high-tech enterprises for energy efficiency per 10,000 people
	/	Building energy consumption monitoring-platform completion (%)

4.4. Study Limitation and Future Research Avenues

In this study, we use an agent-based technique to build a model and simulate the overall building energy consumption at an urban scale under different scenarios. There are two innovations in this research: At the technical level, this research uses the agent-based modeling technique to realize the systematic coupling calculation of multiple urban planning elements and building carbon emissions. At the level of findings, based on the simulation results, this research puts forward urban-scale planning strategies for building energy conservation for severe cold regions. In general, the agent-based model built in this study is a combination of top-down and bottom-up models. Compared with other types of models, it contains both macro- and micro-level information. This feature allows it to adapt to other research purposes by adjusting information at different levels. The structure, composition, and code of the model constructed in this research work for cities in severe cold regions where urban central heating is the primary heating mode in winter. Specifically, the city or heating company provides heating according to the urban temperature, rather than the residents independently adjusting the heating demand. In this study, the model's parameter values were calculated based on the conditions of Harbin, that is, the specific impact level of urban form and climate on building energy consumption. Although they were obtained from statistics based on large sample sizes, we believe that the current parameter values only work for Harbin and other cities similar to Harbin. For cities in other severe cold regions, the following parameters should be replaced for the application of this model according to the local conditions: (1) the influence level of urban form on building energy consumption in the calculation command codes on the main panel of the model, and (2) the table function of the historical data of the urban macro-climate on the main panel of the model.

This research has the following three limitations: (1) Potential inaccuracies may result from the limits of the data and the correlations between the variables. Since the building energy consumption data are not open data in China, we have limited access to actual data, which may lead to errors in determining the impact relationship. To minimize this problem, we tried our best to set strict selection conditions to ensure that the sample buildings could represent the general situation of each type of building in the central urban area of Harbin. (2) The construction of individual buildings, such as the air tightness of buildings and the quality of the insulation installations, as well as the energy-use behavior of occupants, are not fully involved in this model. Although we try to avoid the impact of these factors on different scenarios through sample selection conditions and building type division, these factors may still lead to controversial results. (3) Although using urban macro-climate data can meet the research needs of all building groups, it is not enough to support the improvement of energy efficiency planning strategies in key areas. At present, obtaining local climate data from authoritative departments is difficult, which is also one of the challenges in improving the accuracy of the model. Determining how to change the limitation whereby the climate module in the current model depends on pre-processed climate data is the first challenge to be solved when updating the model.

We will improve future research based on the above three limitations. (1) The research will explore other ways to supplement the actual building energy consumption data, such as cooperation with government departments or demonstration projects. (2) The research will expand the building types and continue to subdivide them according to the energy-use characteristics of individual buildings under each category. Refining the building type will improve the accuracy of the quantitative results, whether they are the influencing relationships or the simulation results. (3) At the same time, with the increase in basic data and types of impact factors, the study will also consider using global sensitivity analysis instead of stepwise regression to improve the accuracy of the impact value of factors. (4) According to the zoning based on energy conservation potential obtained from the above climate scenario simulation, the selected key areas of climate-oriented energy conservation will be added with climate field measurement points to explore more detailed and targeted energy efficiency planning strategies for the climate. In addition, new ports will also be developed under the climate module to link with existing climate models, to achieve independent energy consumption prediction under future climate conditions. (5) We will collect more typical urban data in severe cold regions to build a more general model, and we will try to build an adjustment system within the model to respond to the particularities of different cities automatically.

5. Conclusions

Reducing the total building energy consumption through urban planning is crucial to achieve the strategic goal of a sustainable and low-carbon city. Due to the constraints of climate and development, urban-scale building energy conservation in severe cold regions is facing many difficulties. It is urgent to explore effective methods and strategies for building energy conservation through scientific and reasonable urban and rural planning methods. In this study, taking Harbin as an example, the agent-based modeling method is used to establish an urban-scale building energy consumption simulation model. The building energy conservation planning strategies for planning systems, urban form planning, and climate optimization are analyzed and discussed based on scenario simulation.

The simulation results show that under the baseline scenario, the building energy consumption of adjacent blocks on both river banks is generally higher than that of non-river-adjacent areas. The building energy consumption of central urban areas with a higher density is relatively low. The urban form scenario simulation results confirm that the selected factors significantly impact building energy conservation, and their impact varies with location. The elements with a highly significant impact change by 1 unit; the retail building block has the most obvious change in energy consumption, up to 44.7×10^6 kWh/10^5 m^2/year, while the office building block has the lowest change, with 34.5×10^3 kWh/10^5 m^2/year. Although this effect has a more noticeable impact on electricity consumption, the total consumption of heating energy is much higher than that of electricity, occupying the leading position in the overall energy-saving effect. Under the climate scenario in the next 50 years, this study predicts that the energy consumption of residential land in urban centers will constantly increase up to 5.3×10^5 kWh/10^5 m^2/year. Based on the above results, the following three points are proposed for the energy efficiency planning of buildings in severe cold regions. First, this study believes that a complete framework for a building energy conservation planning system is essential because building energy consumption and energy conservation potential in different regions are not homogeneous. Second, the adjustment and control of urban form are necessary for building energy conservation planning. Guiding measures for energy-saving-oriented urban form planning and different control of land-use indicators are proposed. Third, considering the impact of climate and the unique conditions in severe cold areas, this study proposes suggestions for strengthening climate protection and saving energy via greening and ecological means.

The results of this scenario simulation provide quantitative support for energy-conservation-oriented climate protection, planning index adjustment, and optimization strategies to adapt to future climate conditions in Harbin. The proposal of the planning strategy further provides guidance for macro-building energy conservation from the perspective of urban planning. The model provides technical and methodological support for urban building energy conservation planning. Meanwhile, as mentioned in 4.4, the specific parameters in this paper still need to be tested and optimized for long-term application. The planning strategy will be further refined with the development of the territorial spatial planning system in future research.

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