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Dynamic Simulation for Carbon Emissions of the Entire Building Industry Chain Based on System Dynamics

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Abstract

The climate change issue caused by carbon emissions has attracted extensive attention. China has set the goal of reaching the carbon peak by 2030. The carbon emissions of buildings are an important part of China's total carbon emissions. Therefore, this research incorporates policy, population, and economic impacts into a system dynamics (SD) model to comprehensively simulate the carbon emission reduction effect of the entire building industry chain. The main sources of carbon emissions, key factors affecting carbon emission reduction effects, and the possibility of improvement are discussed.

The SD model predicts carbon emissions from 2023 to 2035 and establishes three scenarios: coordinated development scenario, low-carbon development scenario, and comprehensive development scenario to evaluate the emission reduction potential. These scenarios indicate that by 2035, emissions will be reduced by 6.9% to 17.2% compared to the baseline. To curb emissions, this study suggests improving low-carbon awareness, optimizing the energy structure, promoting research and development investment, and controlling building area. This provides a solid foundation for formulating low-carbon development strategies.

Keywords: Entire construction industry chain, Carbon emission, System dynamics, Scenario analysis, Carbon emission reduction path.

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1. Introduction

Climate change dominated by global warming has attracted extensive attention from the international community (Duan et al., 2022). Among anthropogenic greenhouse gas emissions, CO_2 has the greatest impact, and its cumulative emissions largely determine the magnitude of global warming (Huang et al., 2017). With the deepening understanding of climate warming, the international community signed the Paris Agreement in 2015, clearly controlling the increase in global average temperature within 2°C, and encouraging all countries to work together to achieve carbon neutrality to jointly address the challenges of climate change (Chen et al., 2022; Liu et al., 2021).

At present, China has become the world's largest emitter of $CO_{2,}$ indicating that China is facing huge pressure on energy conservation and emission reduction (López et al., 2020). To this end, the Chinese government has taken a series of emission reduction measures and promised to reach the peak of carbon emissions by 2030 (Huang and Zhou, 2020; Luo et al., 2023).

Among many industries, the construction industry is developing rapidly. It is a pillar of China's economy and also a major source of greenhouse gas emissions (Liu et al., 2022). During the period from 2010 to 2021, the comprehensive energy consumption associated with construction activities in China escalated from 1.35 billion tce to 2.35 billion tce. In the 2021, the carbon footprint of the entire building construction process in China constituted approximately 38.2% of the national carbon emissions inventory.

It is evident that the construction sector harbors substantial potential for carbon mitigation. Promoting low-carbon practices in the entire construction industry chain is an important way to achieve carbon emission reduction and address the climate crisis.

Beijing is the capital of China, and its carbon emission change trend has reference value for other regions. The "Research Report on China's Building Energy Consumption and Carbon Emissions" released in 2023 pointed out that Beijing's carbon emissions are prominent and have a significant impact on the overall national emission reduction direction. Beijing's construction industry development plan emphasizes achieving advanced development while decreasing energy and carbon intensity, demonstrating the commitment to low-carbon construction.

Based on the above analysis, this study takes the entire construction industry chain in Beijing as the perspective and combines coordination theory with the system dynamics method, which can deeply explore the intricate interactions among economic, social, energy, and environmental factors. Through the analysis of these factors, we can more accurately grasp the carbon emission situation of each link in the entire construction industry chain and predict the future carbon emissions. In addition, the research on carbon emissions of the entire construction industry chain can provide a solid foundation for Beijing to develop a more scientific and reasonable low-carbon strategy. It can also offer valuable references for other regions, promoting low-carbon development in the national construction industry and contributing to the realization of the country's carbon peak and carbon neutrality goals.

Can the construction industry in Beijing reach the carbon peak in the target year under the carbon emission reduction policy coordinated by multiple measures? The answers to these questions will be given in this study. The possible innovations and contributions of this paper are as follows: In recent years, Beijing has attached great importance to the recycling of construction waste, and its recycling level ranks among the top in the country. This paper considers the impact of recycling level on carbon emissions. Expansion of CO_2 driving factors. At the same time, the changes of major emission factors are considered, which are less mentioned in previous studies. The SD model is suitable for the actual situation of the whole process of the construction industry, and CO_2 prediction is carried out on the basis of scenario analysis. Verification of carbon emission reduction commitments. As a representative of low-carbon cities, the experience of carbon emission reduction can provide reference for other cities.

2. Literature review

In this field, research mainly focuses on determining influencing factors and then developing a prediction model to provide predictions of energy consumption and carbon emissions. The influencing factor models include the Stochastic Impacts by Regression on Population, Affluence, and Technology (STIRPAT) model, factor decomposition models, and others.

Du et al.(2022) used the STIRPAT method to consider the role of the geographical and temporal characteristics of building operation emissions on carbon emissions in the regional construction industry. In the research on embodied carbon emissions in buildings by Zhu et al.(2022), it was found that technical factors have a two-way effect. Algieri (2022)used the STIRPAT method to study the impact of tourism development on carbon emissions. Yang et al.(2023) used the STIRPAT model to divide it into six driving factors and believed that population and energy intensity increase have the highest impact on CO_2 emissions. Factor decomposition analysis models are often used to discuss the contribution of each factor to the change of the dependent variable. In their work, Qi et al.(2025) and Li et al.(2024) used the SDA decomposition method to study the carbon emissions of residents due to inter-provincial population migration and the factors of marine carbon sinks, respectively. Raza and Lin (2022)calculated the LMDI between population, activity, electricity intensity, and total electricity consumption and determined that economic activity and population are the key driving factors of carbon emissions in the power sector. In their research, Song et al. (2024) combined the Kaya equation and the LMDI method to study the relationship and trend among carbon emissions in China's construction industry, economic development, housing construction, energy structure, energy intensity, and population density.

At present, representative models for predicting energy consumption and carbon emissions in the construction industry include the LEAP model, grey model, system dynamics model, etc.

Wang et al.(2018) used an improved grey prediction model to simulate and predict primary energy consumption in China. In the research of Liu et al.(2019), a system dynamics model was used to explore the impact of socio-economic variables and scenario simulations on carbon emissions in Guangzhou. Liu(2020) used system dynamics to explore the synergy effect in the construction waste industry chain for the sustainable development of waste resources. Zhang et al. (2024)used the same method to study the impact of macro policies on carbon emissions in the construction industry chain and also emphasized the need for mutual cooperation among policies. Wang et al. (2022) used the Long-range Energy Alternatives Planning System (LEAP) model to predict urban road traffic carbon emissions from 2020 to 2025 under various scenarios. Huo et al. (2021) used the LEAP model combined with system dynamics to analyze the impact on carbon emissions of residential buildings. Cai et al. (2023) evaluated the path for Bengbu to reach peak carbon emissions and carbon neutrality by 2030. They predicted that energy structure adjustment is a key means to reduce carbon emissions. Other methods are also used for carbon emission prediction. Danish et al. (2021)studied the relationship between nuclear energy consumption and carbon emissions within the framework of IPAT and the environmental Kuznets curve.

Most methods have certain disadvantages in studying carbon emission issues. The STIRPAT model generally focuses on population, affluence, and technological level, lacking the necessary expansion to other factors (Huo et al., 2023). The LMDI model does not provide a complete explanation of carbon emissions because it overly emphasizes the relationships between factors and can only test the impact of an absolute indicator on carbon emissions to a limited extent (Huo et al., 2022). The grey model can identify the carbon emission peak but does not consider the uncertainty of future changes in variables (Wang et al., 2023), and its opacity also makes the credibility of the results affected (Zeng et al., 2018). The LEAP model relies on expert judgment and may have subjectivity issues (Li and Gao, 2018).

In contrast, system dynamics (SD) is a method of dynamic analysis and is widely used to study the changing relationships between long-term complex systems, which helps analyze the relationship between internal and external influences. Secondly, the SD model can thoroughly examine the complex interactions between variables by developing a functional model that can achieve established goals and meet predetermined requirements.

Although the literature indicates practical solutions for reducing carbon emissions in the construction industry to a certain extent, due to the multiple and complex stages, many studies do not fully cover the entire process of the construction industry. The carbon emissions of the entire construction industry chain have not been analyzed and predicted. In terms of analyzing the influencing factors of carbon emissions in construction, few studies have revealed the interaction and dynamic feedback mechanism between different factors.

Therefore, this study attempts to explore previous research more deeply and conduct a comprehensive analysis of future carbon emission trends by improving the carbon emission model of the entire construction industry chain.

3. Research methods

3.1 Research framework

To construct an SD model to simulate the carbon emission system of the entire construction industry chain in Beijing, this study adopts the method shown in Figure 1. First, in order to cooperate with the research scope, the system boundary is delineated, the key factors within the carbon emission framework of the entire construction industry chain are identified, and the interrelationships between the factors are explained. Second, feedback loops between subsystem variables are established as the basis for making causal loop diagrams and system flowcharts. The construction of the model also includes creating system equations, and then conducting strict testing and calibration. Third, four scenarios are designed: baseline scenario, coordinated development scenario, low-carbon development scenario, and comprehensive development scenario, reflecting Beijing's long-term strategic vision in the construction field. Finally, these scenarios are implemented, the simulation results are analyzed, and relevant conclusions are drawn.

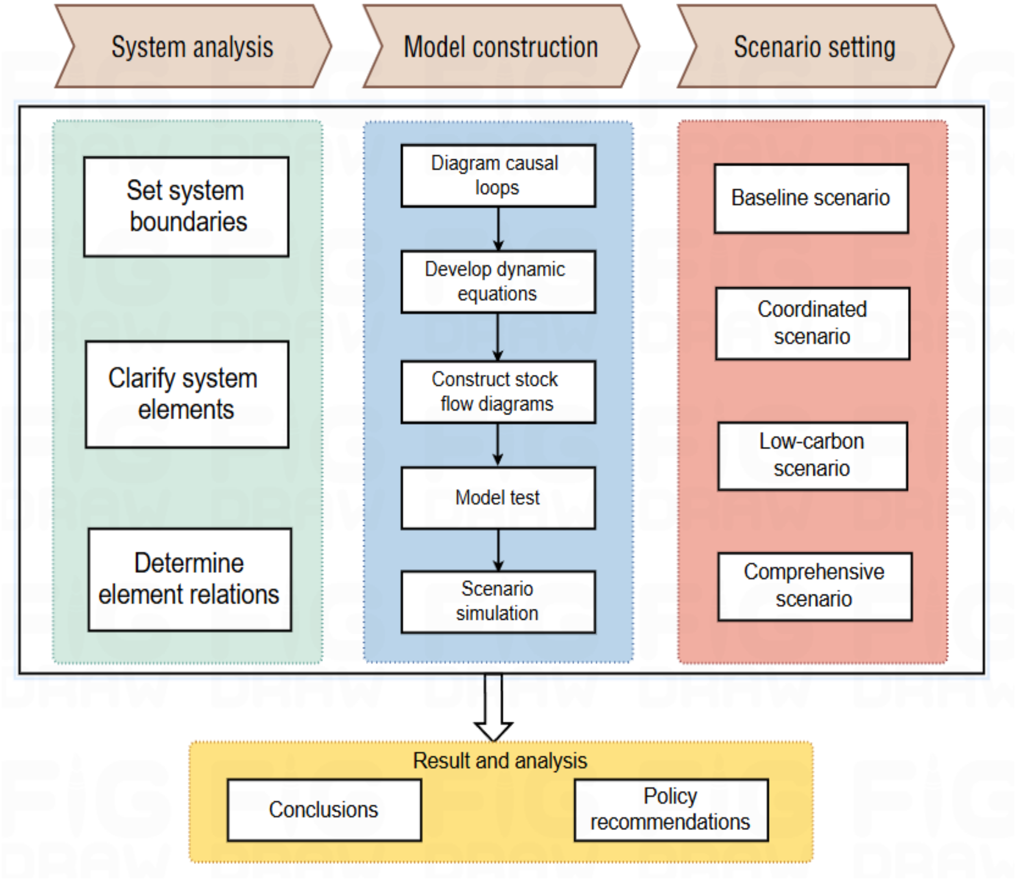

Figure 1: Research framework

3.2 Study area

As a national low-carbon pilot city in China, Beijing has achieved achievements in reducing carbon emissions. The coal substitution project has achieved remarkable results, and the energy structure has changed, thus affecting carbon emissions. In addition, Beijing's efforts in carbon emission reduction can provide valuable experience for other similar cities in China. This situation highlights the necessity of conducting a detailed investigation of the carbon emissions of the entire construction industry chain in Beijing.

In this study, the time boundary is from 2005 to 2035. Among them, 2005-2022 is the historical baseline period of the model, and 2023-2035 is the simulation and prediction stage. Starting from 2005, the goal of Beijing's energy structure adjustment has gradually become clear, the use of coal has been reduced, and the energy structure has changed significantly. 2030 is a key node for China to achieve the carbon peak goal. Selecting this period helps to evaluate the low-carbon transformation process of Beijing's construction industry chain and provides decision-making references for formulating relevant policies.

From 2005 to 2035, the time span is relatively long. Considering the medium-term development trend, it is conducive to comprehensively analyzing the dynamic effects of various influencing factors. The model runs with a time step of each year, providing detailed and manageable time resolution.

3.3 Carbon Emission Accounting Method

Generally speaking, carbon emissions are the total emissions of various greenhouse gases such as carbon dioxide, methane, and nitrogen oxides. They are the general term for greenhouse gas emissions and are measured in terms of carbon dioxide equivalents. Carbon dioxide emissions only refer to the emissions of carbon dioxide gas, and its scope is narrower than that of carbon emissions. The carbon emissions and carbon reduction in the construction industry mentioned in this article only refer to the emissions of carbon dioxide gas.

This article considers the materials consumed by different types of buildings, the change in the reuse ratio of construction waste, and the optimization of the energy structure. These factors all change over time.

The energy consumption and carbon emissions throughout the entire construction process include those in building material production and transportation, building construction, building operation, and building waste recycling (Zhao et al., 2024). In the stages of building material production and transportation and building construction, only housing construction is included, and infrastructure engineering is not included. The specific scopes are as follows:

1. Energy consumption and carbon emissions in building material production and transportation for housing construction projects refer to the energy consumption and carbon emissions throughout the entire production and transportation process of building materials consumed by the construction industry in that year.

This study only accounts for energy-related carbon emissions in the building material production and transportation process and does not include process carbon emissions such as those generated by cement production processes.

2. Energy consumption and carbon emissions in housing building project construction refer to the energy consumption and its carbon emissions brought about by the construction production activities of construction enterprises.
3. Building operation energy consumption and carbon emissions refer to the energy consumption of existing buildings in operation in that year, including the energy consumption for maintaining building functions such as heating, air conditioning, and lighting, as well as the energy consumption for indoor activities such as cooking, hot water, household appliances, and office equipment. In macro statistics, it is manifested as the energy consumption and carbon emissions after deducting transportation from the energy consumption of the tertiary industry and residents' lives.
4. Carbon emissions from building waste recycling refer to the carbon emissions during the transportation and treatment of building waste in that year, including building demolition, waste transportation, landfill, and reproduction. The raw materials saved due to reproduction are regarded as negative carbon emissions.

The specific calculation methods for carbon emissions in each stage of the entire construction industry chain are as follows:

Building material production and transportation. The carbon emissions (CE_{pt}) in the stage of building material production and transportation are affected by the size of the new constructed building area. This can be measured by the different building materials consumed per unit building area of different building types (wood structure, wood and brick structure, brick-concrete structure, reinforced concrete structure, steel structure, prefabricated reinforced concrete structure, prefabricated steel structure). The stage of building material production and transportation mainly includes seven kinds of building materials (steel, aluminum, wood, gravel, cement, lime, bricks), which have the characteristics of high usage and high energy consumption in the production process and high carbon emissions. According to various industry reports, calculate the carbon emissions in the production and transportation process of building materials considering the change of carbon emission coefficients.

The carbon emissions in this stage are divided into two parts: (1) carbon emissions from building material production (CE_{mp}); (2) carbon emissions from the transportation process of building materials (CE_{mt}).

The carbon emission was calculated by Formula (1), (2), (3), (4):

$$CE_m = CE_{mp} + CE_{mt} \tag{1}$$

$$CE_{mp} = \sum_{i=1}^{7} M_i \times F_{Mi} \tag{2}$$

$$M_i = \sum_{j=1}^{7} S_j \times r_{ij} \tag{3}$$

$$CE_{mt} = D_m \times T \times \sum_{i=1}^{7} M_i \tag{4}$$

Where CE_{mp} is the carbon emission during the building material production process; CE_{mt} refers to the carbon emission during the transportation process of building materials; r_{ij} is the consumption of building material i for type j building, and M_i is the consumption of building material i; F_{Mi} is the carbon emission coefficient of building material i; D_m represents the average transportation distance of building materials; T represents the carbon emission coefficient per unit weight for transportation distance.

Building construction. The carbon emissions during construction (CE_c) are affected by the new constructed area and are reflected in the direct carbon emissions from the energy consumption of mechanical equipment during construction.
The carbon emission was calculated by Formula (5):

$$CE_c = \sum_{i=1}^{n} E_{ci} \times F_{ci} \tag{5}$$

Where E_{ci} is the consumption of the type i energy in the construction stage, and F_{ci} is the carbon emission coefficient of the type i energy in the construction stage.
Building operation. Operational carbon emissions (CE_o) come from carbon emissions from residents' energy consumption and carbon emissions from other industries.
The carbon emission was calculated by Formula (6):

$$CE_o = \sum_{i=1}^{5} E_{oi} \times F_{oi} \tag{6}$$

Where E_{oi} is the consumption of the type i energy in the operation stage, and F_{oi} is the carbon emission coefficient of the type i energy in the operation stage.

Building demolition and recycling. The carbon emissions in the stage of building demolition and recycling are mainly affected by the output and recycling rate of construction waste. Different types (metal, wood, concrete) of waste are recycled and finally processed into different new materials that can be reused in construction. The carbon emissions in this stage are divided into four parts: (1) carbon emissions from building demolition (CE_{zd}); (2) carbon emissions from the transportation process of construction waste (CE_{zt}); (3) carbon emissions from the landfill process of construction waste (CE_{zl}); (4) carbon emission reduction due to recycling (CE_{zr}). The carbon emission was calculated by Formula (7), (8), (9), (10), (11), (12), (13), (14):

$$CE_z = CE_{zd} + CE_{zt} + CE_{zl} - CE_{zr} \tag{7}$$

$$CE_{zd} = S_d \times F_d \tag{8}$$

$$CE_{zt} = D_{zt} \times T \times W \tag{9}$$

$$W = S_d \times G_d \tag{10}$$

$$CE_{zl} = W_l \times F_l \tag{11}$$

$$W_l = W \times (1 - R) \tag{12}$$

$$CE_{zr} = \sum_{i=1}^{3} W_{ri} \times P_{ri} \times (F_{ri} - F_{ri1}) \tag{13}$$

$$W_{ri} = W \times R \times g_{ri} \tag{14}$$

Where S_d is the demolition area, and F_d is the carbon emission coefficient per unit demolition area. D_{zt} is the average transportation distance of construction waste; T is the carbon emission coefficient per unit weight of transportation distance; W is the weight of construction waste. G_d is the weight of construction waste generated per unit demolition area. G_c is the weight of construction waste generated per unit construction area. W_l is the weight of construction waste that needs to be landfilled, and F_l is the carbon emission coefficient per unit weight of landfill construction waste. R is the recycling rate of construction waste. P_{ri} is the reproduction rate using the type i waste; W_{ri} is the weight of the type i waste recycled; F_{ri} is the carbon emission coefficient corresponding to the building material of the type i waste; F_{ri1} is the carbon emission coefficient corresponding to the recycled building material of the type i waste. g_{ri} is the proportion of the weight of the type i waste in the construction waste.

3.4 System dynamics

For the complex system of carbon emission reduction in the entire construction industry chain, system dynamics can effectively characterize influencing factors from a macroscopic and overall perspective, fully reflecting the dynamic interactions among influencing factors. System dynamics can identify driving forces and integrate subsystems into an overall framework to analyze their interactions, and can quantify these relationships, providing strong support for formulating scientific and reasonable carbon emission reduction strategies.

System dynamics is a system analysis method that conducts computer-based simulation and can deeply study and solve the complex and dynamic feedback problems inherent in systems. It has advantages in analyzing complex social, economic, and technological aspects(Jia et al., 2019). This method achieves predetermined goals and meets predetermined needs by establishing effective models. Based on the principles of system thinking and feedback control theory, it can describe the time-varying behavior of complex systems(Gupta et al., 2019). Modeling includes defining the research object, specifying the system boundary, constructing the causal relationship among various factors in the system, and determining the quantitative relationship among various factors(Cao et al., 2019).

System dynamics has been used in many research fields such as construction waste (Hua et al., 2022), low-carbon agricultural industry chain (Song and Dou, 2024), water resource management (Hu et al., 2021), and urban heating (Wei et al., 2024). The entire construction industry chain involves multiple subsystems, and there are complex nonlinear relationships among various elements. We studied the emissions of the construction industry chain and used system dynamics to determine the relationships among influencing factors.

3.5 Model design

The carbon emission system of the entire construction industry chain is a complex system that involves multiple aspects such as economy, population, land, and energy. The influencing factors within the system are mutually restricted but also closely connected. According to the constituent elements of carbon emissions in the construction industry and combining the principles, purposes, and system boundaries of system modeling mentioned above, this paper determines the structure of the carbon emission system in the construction industry.

In the carbon emission system of the entire construction industry chain, there is a complex flow relationship between carbon emissions and economic and population benefits, and it is also dynamically affected by the policy environment. The economic-population subsystem reflects the role of economic activities and population factors in the entire system. Economic activities provide material foundation and technical support for the entire construction industry chain. At the same time, economic development and population changes will affect the demand for buildings and energy, and are closely related to carbon emissions.

The carbon emission subsystem is the core part of the carbon emission system of the entire construction industry chain.

In the entire construction industry chain, market demand drives cooperation and technological innovation throughout the chain. Developers, design institutes, building material manufacturers, construction enterprises, and waste recycling enterprises integrate resources around this common goal and promote industrial upgrading.

Developers put forward demands according to sustainable development goals. Design institutes provide innovative solutions for carbon emission reduction throughout the building's life cycle by optimizing building layouts and adopting new energy-saving materials and technical means. This close interaction not only promotes the implementation of green design concepts but also drives the widespread application of new technologies. According to the needs of construction enterprises, building material manufacturers research and develop new building materials suitable for prefabricated buildings and advanced construction technologies, reducing construction difficulty and carbon emissions. This cooperation not only improves construction efficiency but also conforms to the development trend of green buildings.

There is also collaboration between construction enterprises and building operation and maintenance units. During construction, companies carefully consider the future operation and maintenance needs of the building, such as setting aside space for renewable energy equipment, installing energy monitoring systems and smart controls, and creating conditions for refined management during the operation and maintenance phase. This connected cooperation model improves the energy utilization efficiency of buildings and provides more possibilities for future energy-saving renovations. In addition, construction enterprises also cooperate with waste recycling enterprises. By classifying and labeling construction waste, the recycling efficiency of recyclable materials is improved, further reducing the consumption of natural resources and carbon emissions. This closed-loop economic model reflects the high degree of collaboration in resource recycling throughout the entire industry chain.

Technological innovation runs through all links of the entire construction industry chain. According to building functional requirements and carbon emission targets, design institutes put forward material performance requirements to building material manufacturers, making material characteristics more in line with building needs and achieving carbon reduction effects. The technological breakthroughs of building material manufacturers not only meet the needs of construction enterprises but also provide high-quality environmentally friendly building materials for other links. In the operation and maintenance stage, intelligent systems are used to monitor building energy consumption in real time, implement refined management, and continuously optimize technology applications based on feedback. The entire process forms a conduction effect of technological innovation in the entire industry chain to ensure the environmental protection performance and sustainability of the entire building life cycle.

Various activities in the entire construction industry chain consume materials and energy, and will inevitably generate carbon emissions. Changes in carbon emissions will also provide feedback to the factors of the other two subsystems.

Policies can guide and regulate the behavior of the entire construction industry chain and regulate carbon emissions. Changes in the policy environment will affect the development direction and carbon emission level of the entire construction industry chain. Therefore, the carbon emission system of the entire construction industry chain is composed of the economic-population subsystem, the carbon emission subsystem, and the policy subsystem.

1. Economic-population subsystem

The economic-population subsystem is the basic system that carries the construction system. It does not generate carbon emissions itself but affects the entire construction industry chain carbon emission subsystem through economic indicators and population indicators.

GDP and population size are factors that cannot be ignored in affecting building area. The expansion of the building area is related to the increase in energy consumption in the operation stage, and the increase in the energy consumption in the operation stage, in turn, affects carbon emissions and environmental quality. This feedback loop continues as carbon emission reduction costs affect GDP.

GDP promotes R&D investment. The increase in investment in technological innovation will strengthen the maturity and application of green and energy-saving technologies, reduce carbon emission factors, and also reduce the energy cost of production and living, thereby increasing a part of energy consumption. This is also fed back to GDP through its impact on carbon emissions and environmental quality. The main causal relationship observed is that economic growth not only stimulates social development and the expansion of building area, leading to an increase in carbon emissions, but also promotes R&D investment. These investments in turn help to formulate strategies to reduce pollution.

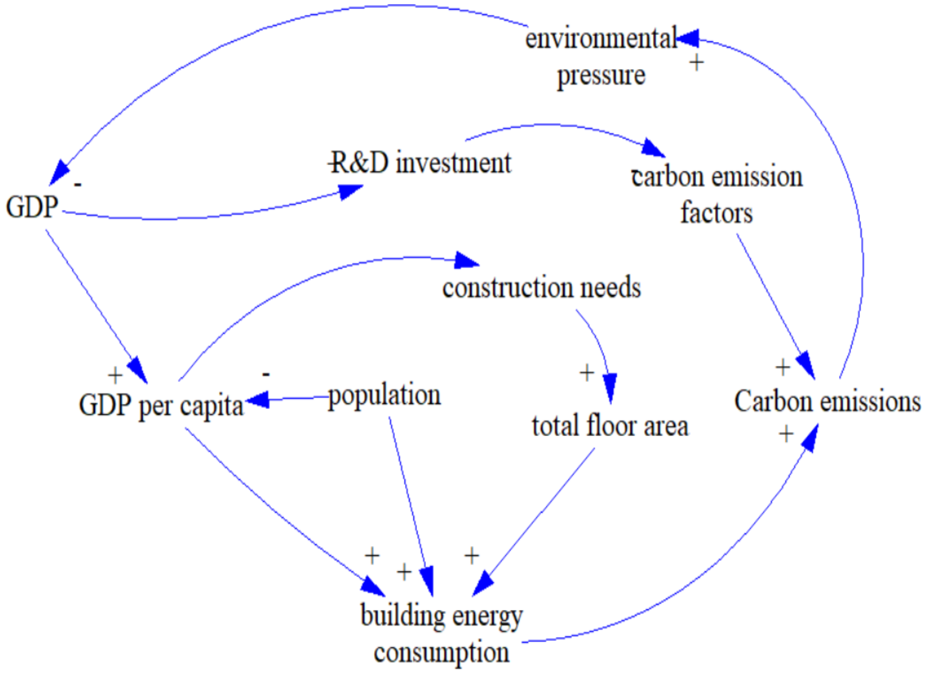

Figure 2: Causal loop diagram of economic-population subsystem

2. The entire construction industry chain carbon emission subsystem.

The carbon emission subsystem mainly focuses on the consumption of materials and energy in the entire construction industry chain, as well as the carbon flow at various stages. It includes carbon emissions in the stages of building material production and transportation, building construction, building operation, and building demolition and disposal.

The total population affects the increase in building area demand, which will increase construction energy consumption and the use of building materials. The expansion of building area will increase the energy consumed in the operation and demolition stages, and also indirectly affect the generation of construction waste. The carbon emissions corresponding to these factors are fed back to the control of new construction area.

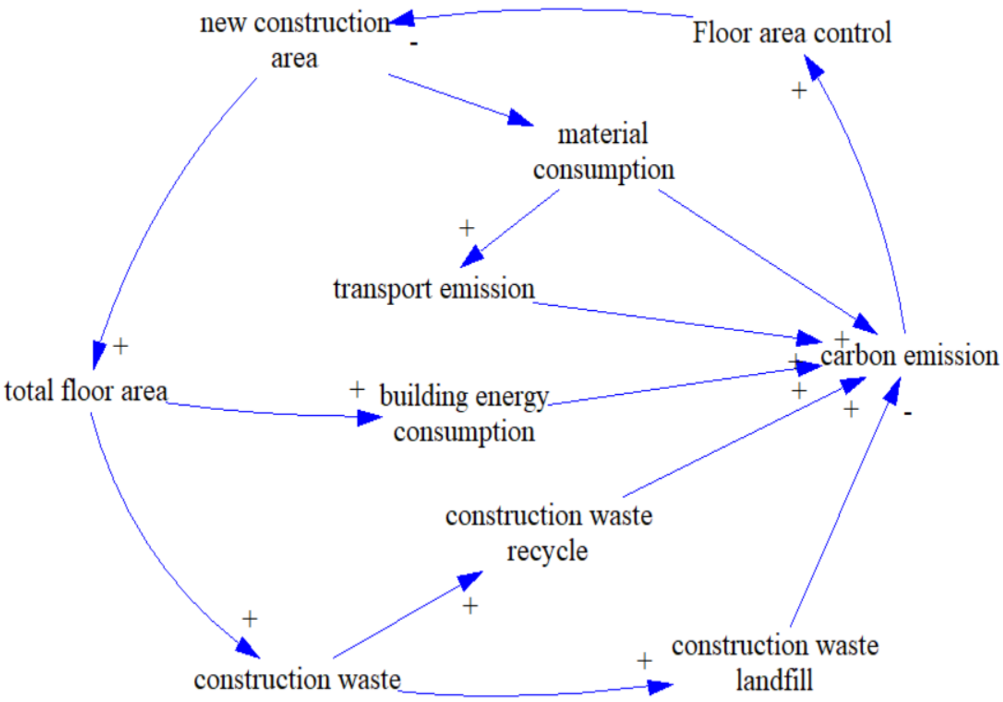

Figure 3: Causal loop diagram of the entire construction industry chain carbon emission subsystem

3. Policy subsystem

The Policy subsystem includes the policy regulation and affects the changes of the entire system through the implementation of policies. In order to achieve the expected purpose of institutional operation, it is necessary to adjust the implementation intensity of policies. Therefore, this study aims to provide the government decision-making subsystem with a decision-making basis and measurement method. The policy subsystem includes education promotion, policy subsidy intensity, energy structure adjustment, population control intensity, etc.

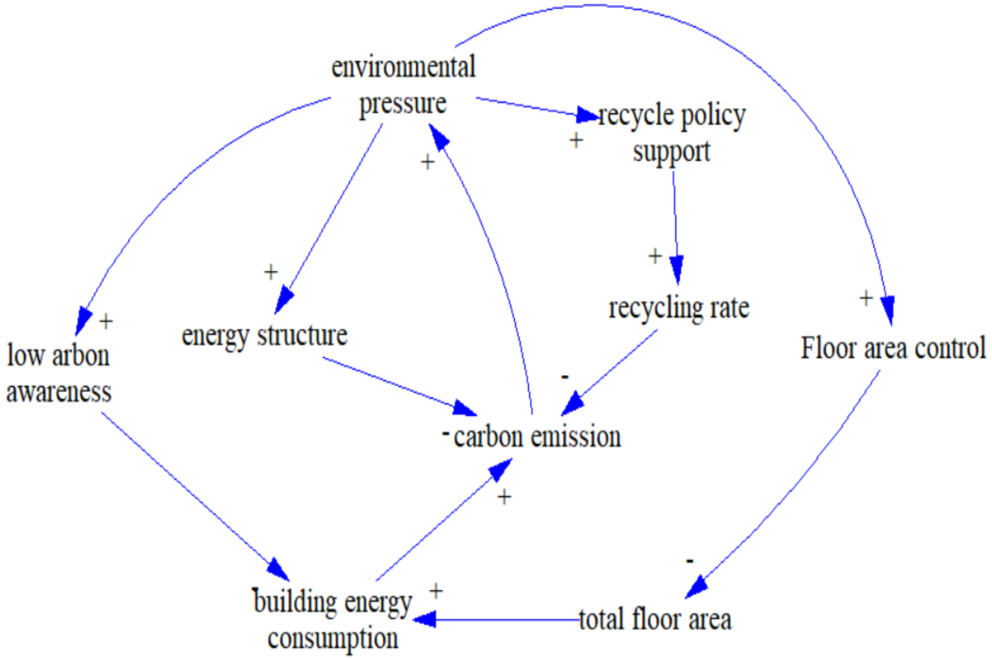

Figure 4: Causal loop diagram of policy subsystem

Through the combination of the above three subsystems, the relationships and interactions among various factors can be examined. The mutual influence of the three subsystems not only includes the complex flow of internal carbon emissions and economic and population benefits in the entire industry chain, but also considers the dynamic changes of the external policy environment.

Based on the causal loop diagrams, the material flow and feedback effect of carbon emissions in the entire construction industry chain are analyzed. Further collect data to clarify the relationship between various elements and establish a stock-flow diagram.

Stock and flow diagram show the characteristics of a dynamic system and can more clearly analyze the logical relationship between variables. According to the qualitative relationship determined in the causal loop diagrams, the variable equation is substituted into the stock and flow diagram constructed by Vensim, as shown in Figure 5. Variables are divided into level variables, rate variables, constant variables and auxiliary variables. Level variables represent the quantity that exists at a given point in time and accumulates in the past, and rate variables are measured over a time interval. Use auxiliary variables as intermediate variables to describe the information transmission and conversion process between constant variables, level variables, and rate variables. The initial values in the model and the parameter values of some variables are based on development strategic goals, statistical yearbooks, and relevant literature. The research uses table function entries to systematically collect variable data that changes over time, introducing a time element for analysis. This method helps to capture the dynamic evolution of variables. For regression fitting the relationship between various factors, analysis is needed. SPSS 25.0 software is used for regression analysis. The mathematical relationship between variables in the inventory flow chart is shown in Appendix.

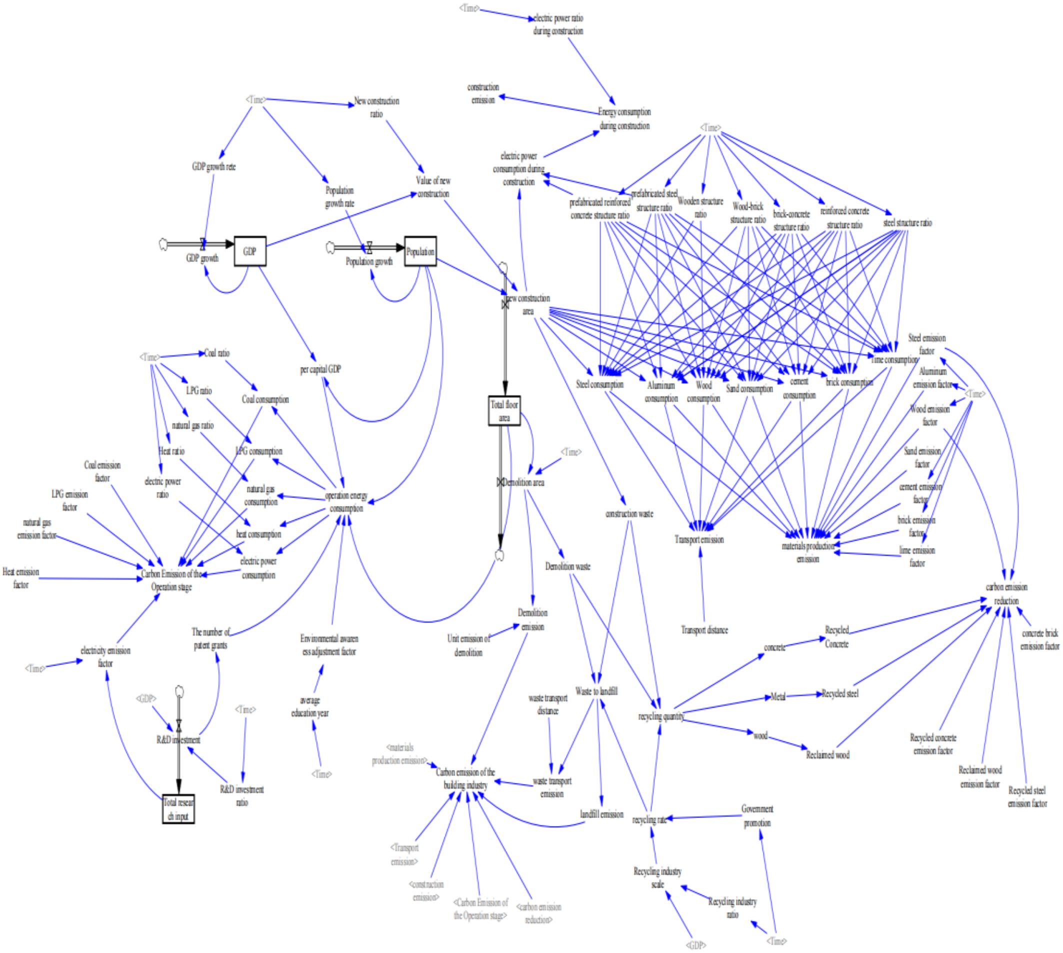

Figure 5: Stock-flow diagram

3.6 Data sources

The data on gross domestic product, population, and industry energy consumption in this study are derived from the "Beijing Statistical Yearbook" over the years. The consumption of building materials and the carbon emission coefficient of building materials refer to previous research (Dai and Yue, 2023), and the building area is derived from the "China Urban and Rural Building Statistical Yearbook". The output of construction waste refers to SJG21-2011. The conversion coefficient of standard coal is derived from GB/T2589-2008, and the carbon emission coefficient is derived from the 2006 IPCC "Guidelines for National Greenhouse Gas Inventories" and "Research on Carbon Dioxide Emission Factors of China's Regional Power Grids (2023)".

3.7 Testing the model

To ensure the validity and reliability of the SD model, the effectiveness of the model is judged by comparing the simulation results with the actual data values and analyzing the error size. These methods are essential for the comprehensive re-evaluation and integration of the model's boundaries and subsystem feedback loops. They help ensure that the model's equations are correct in showing how different variables are related to each other, that parameter value estimates are based on good evidence, and that the quantitative framework is consistent.

3.7.1 Intuitive inspection

Intuitive inspection is to analyze the actual data and materials to check whether the variable definitions, causal relationships, mathematical relationships between variables, and variable units in the model are correct. Through a comprehensive analysis of each subsystem, clarify the causal relationship between each variable, and use Vensim software to test the rationality of the equation and the feasibility of dimensions. The results show that the inspection is correct, indicating that the causal relationship between each variable in the model is reasonable and the dimensions are consistent, and it can accurately and effectively reflect the operation process of the system.

3.7.2 Historical inspection

Historical inspection is to determine whether the error between the simulation results of the model and the actual situation is within a reasonable range, and to determine whether the change trends of variables in the model are consistent. This paper selects the total building area, operating energy consumption, and carbon emissions of the entire construction industry chain for analysis, and compares and analyzes the simulation results of the model with the actual data to obtain the error fitting situation between the simulated value and the actual value. We compared the simulation results of the SD model with the actual values. The error of the simulation result of each year is less than 6%, indicating that the model has high precision. As shown in the table, it indicates that the error between the simulation value and the actual value of the system model is small.

Table 1: Comparison of actual and simulated values of total building area

Unit: 10000 square meters	Actual Value	Simulated Value	Error
2005	78421.0	78421	0.0%
2006	83130.4	82597.6	0.6%
2007	87839.8	86828.5	1.2%
2008	92549.2	91985.3	0.6%
2009	95707.3	95668.9	0.0%
2010	98879.8	99247.9	0.4%
2011	101512.8	101872	0.4%
2012	105633.0	105962	0.3%
2013	109700.2	110929	1.1%
2014	116478.2	116143	0.3%
2015	122272.2	122495	0.2%
2016	128503.2	128529	0.0%
2017	135364.2	134683	0.5%
2018	141160.2	140126	0.7%
2019	146710.2	145895	0.6%
2020	153254.2	152858	0.3%
2021	158257.2	158279	0.0%
2022	166777.2	166051	0.4%

Table 2: Comparison of actual and simulated values of operational energy consumption

Unit: 10000 tons of standard coal equivalent	Actual Value	Simulated Value	Error
2005	2170.8	2254.0	3.8%
2006	2356.7	2412.9	2.4%
2007	2615.8	2629.7	0.5%
2008	2763.2	2821.3	2.1%
2009	3014.5	2973.8	1.4%
2010	3191.0	3191.5	0.0%
2011	3402.3	3374.0	0.8%
2012	3652.7	3531.9	3.3%
2013	3598.2	3701.0	2.9%
2014	3760.1	3848.3	2.3%
2015	3882.3	3982.9	2.6%
2016	4036.4	4123.5	2.2%
2017	4179.7	4284.5	2.5%
2018	4422.0	4472.2	1.1%
2019	4473.2	4628.0	3.5%
2020	4551.1	4686.7	3.0%
2021	4867.0	4959.9	1.9%
2022	5126.7	5018.9	2.1%

Table 3: Comparison of actual and simulated values of carbon emissions

Unit: 10000 tons of CO2	Actual Value	Simulated Value	Error
2005	7866.63	7833.16	0.4%
2006	8050.47	8029.27	0.3%
2007	8488.81	8659.52	2.0%
2008	8564.32	9004.13	5.1%
2009	8954.06	8988.27	0.4%
2010	9190.17	9192.26	0.0%
2011	9670.82	9769.64	1.0%
2012	10502.65	9966.68	5.1%
2013	10402.79	10288.7	1.1%
2014	10716.46	10882.5	1.5%
2015	10879.18	10933	0.5%
2016	11164.91	11085.5	0.7%
2017	10749.32	10408.7	3.2%
2018	10507.22	10581.6	0.7%
2019	10801.17	11098	2.7%
2020	10410.85	10643.4	2.2%
2021	11767.27	11541.4	1.9%
2022	12027.09	11915.2	0.9%

3.7.3 Operational inspection

Operational inspection is mainly to test the stability of the model. In this paper, step sizes of 0.25, 0.5, and 1 year are set respectively for model inspection. The results of the operational inspection are shown as follows. As can be seen from Figure 6, the simulation results of carbon emissions of the entire construction industry chain under different step sizes are almost the same, indicating that the model is not sensitive to step size changes and the model is relatively stable.

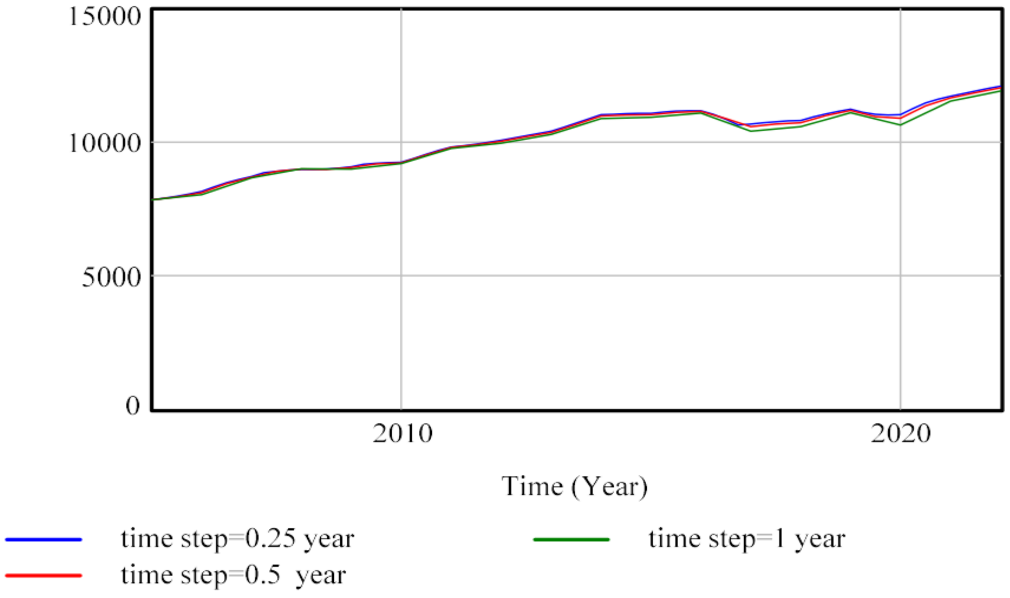

Figure 6: Test of step change in carbon emissions of the entire construction industry chain

3.8 Analysis of simulation results

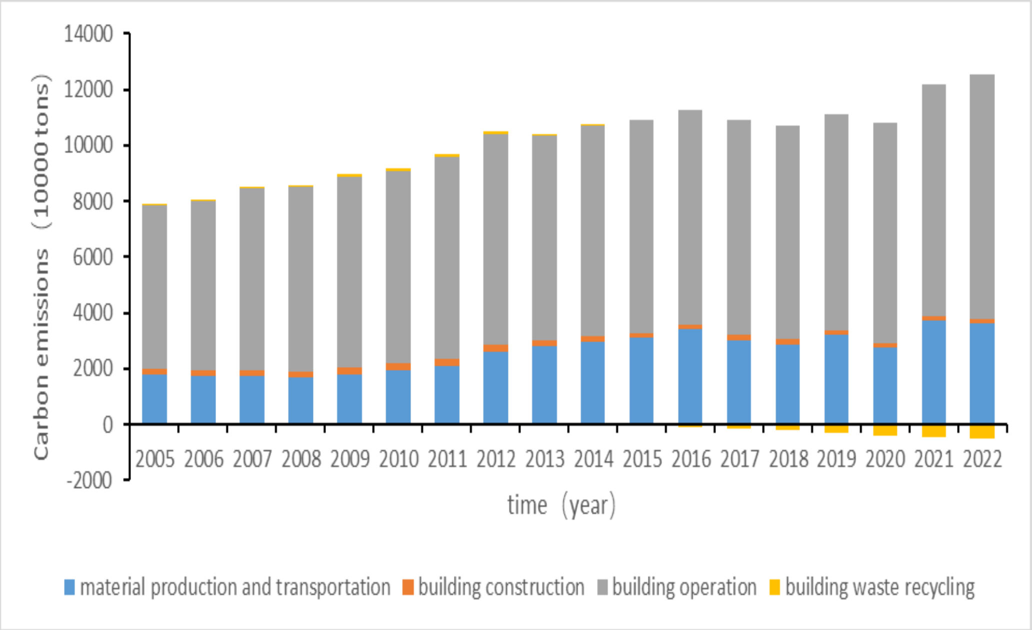

Figure 7: Carbon emissions of the entire construction industry chain in Beijing

From 2005 to 2022, the carbon emissions of the entire construction industry chain in Beijing generally showed an increasing trend, and the growth rate gradually slowed down. This is mainly due to the rapid economic development. Urbanization and industrialization have led to a surge in building demand, and carbon emissions in the building material production stage have increased rapidly. In contrast, the carbon emissions in the building operation stage are stable. At the same time, starting from 2011, Beijing gradually increased the intensity of building waste recycling and reduced the proportion of landfill disposal. This not only saves land but also can reduce the consumption of raw materials and carbon emissions in the industrial chain through reproduction.

4. Results

4.1 Designing the Baseline scenario

We predicted the carbon emissions of the entire construction industry chain in Beijing from 2023 to 2035 through simulation.

In the baseline scenario, each variable in the SD model is predicted using the ARIMA model. Based on the data from 2005 to 2022, the unit root test (ADF) is used to determine the value of i in the ARIMA model, and the autocorrelation function (ACF) analysis and partial autocorrelation function (PACF) analysis are used to determine the possible values of p and q. The optimal model is determined according to the Akaike info criterion (AIC) and Schwarz criterion (SC). The prediction models of each variable are shown in Table 4.

Table 4: ARIMA model

Variable	Model
Gross domestic product	ARIMA (3,2,0)
Population	ARIMA (0,2,0)
Value of new construction	ARIMA (0,1,0)
R&D investment	ARIMA (2,2,0)
Average education year	ARIMA (0,2,0)
Proportion of energy consumption	ARIMA (0,1,0)

Most economic data are given in the form of time series, while in real life, the most common are non-stationary time series, and stationary series are not common. The Autoregressive lntegrated Moving Average model (ARIMA) is a common model for solving non-stationary time series and has achieved remarkable results in prediction and other aspects. The ARIMA model extracts time series patterns through data autocorrelation and differencing methods to predict future data. The AR part handles autoregression and considers the influence of observed values of several past periods on the current value; the I part eliminates trends and seasonal factors through differencing; the MA part handles moving averages and considers the influence of past prediction errors on the current value. Combining these three parts, the ARIMA model can not only capture changes in data trends but also handle temporary, sudden changes or data with large noise, so it has a very good performance in many time series prediction problems.

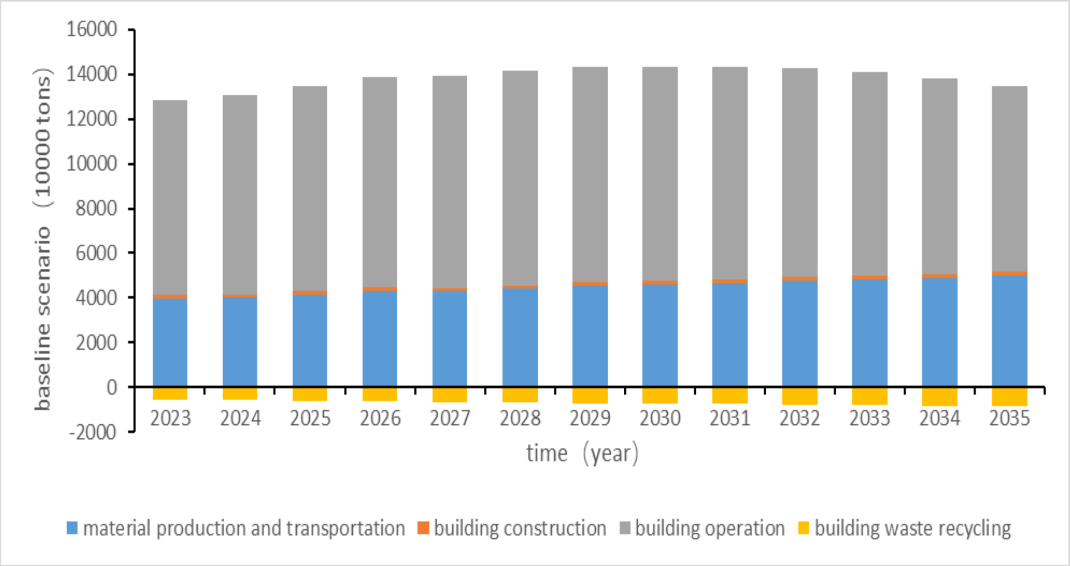

Figure 8: Carbon emissions in each stage of the baseline scenario

Under the baseline scenario, the carbon emissions of the entire construction industry chain in Beijing will reach a peak in 2029 from 2023 to 2029. The main reason is that Beijing's population will reach a peak around 2020 and the economy will enter a stage of stable development. R&D investment provides conditions for the reduction of emission factors. In the waste recycling stage, the recycling ratio approaches the maximum value, and the carbon emission reduction from reproduction steadily increases.

4.2 Simulation of the impact of a single factor on carbon emissions

Using the scenario analysis, we examine how different factors affect various potential trajectories to gain in-depth understanding of the specific strategies implemented. In this simulation, each factor is increased by 1% on the basis of the original predicted value.

Table 5: Increase emission factors

Unit: ten thousand tons of CO2	Baseline scenario	Accelerating economic development	Increase the population growth rate	Increase the value of new construction
2023	12253.7	12260.2	12260.2	12282.9
2024	12511.6	12601.4	12533	12541.7
2025	12892.2	13065.7	12916.8	12923.8
2026	13265.8	13516.1	13274.2	13299.2
2027	13252.2	13584	13253.7	13285.8
2028	13489.5	13900.9	13463.6	13524.4
2029	13638.8	14114.5	13568.9	13674.9
2030	13630.2	14154.6	13509	13667.1
2031	13557.8	14126.1	13385.5	13595.1
2032	13508	14060.4	13230.5	13546.1
2033	13274.4	13764	12875.8	13312.8
2034	12981.2	13363.9	12440.8	13019.7
2035	12644.1	12867.4	11936.7	12682.8

Table 5 presents the analysis results of increased carbon emissions under the basic scenario. Factors affecting the increase in emissions include: accelerated economic development, population size, and the value of new buildings. It is worth noting that if the gross domestic product accelerates by an additional 1% on the basis of the initial growth rate, it will lead to an increase of approximately 65 thousand tons of carbon emissions in 2023, reaching an increase of 5.683 million tons by 2031 and an increase of 2.233 million tons by 2035. This indicates that there is a relationship of first rising and then falling between GDP growth rate and carbon emissions growth over time. This is because the growth of GDP will also accelerate scientific research investment to a certain extent, thereby reducing the carbon emission factor. If the population increases by an additional 1% on the basis of the initial growth rate, it will lead to a maximum increase of approximately 246 thousand tons of carbon emissions in 2025. However, starting from 2028, the carbon emissions in the case of population increase will be lower than the basic scenario. This shows that not the fewer the population, the lower the carbon emissions of the entire industrial chain. Maintaining an appropriate population growth trend is also a part of carbon emission reduction. If the output value of new buildings increases by an additional 1% on the basis of the original predicted value, it will lead to an increase of approximately 292 thousand tons of carbon emissions in 2023 and an increase of 387 thousand tons by 2035, continuously increasing over time.

These findings indicate that the main sources of increased carbon emissions in the entire construction industry chain are economic growth and population changes. These factors will affect residents' consumption levels and the demand for new buildings, thereby leading to corresponding increases in carbon emissions in the operation stage, building material production stage, and construction stage. Due to the transformation of new building types and the reduction of material carbon emission factors, the value of new buildings is factor with less influence.

Table 6: Reduce emission Factors

Unit: ten thousand tons of CO2	Baseline scenario	Increase R&D investment	Increase average education year	Optimizing the energy structure
2023	12253.7	12257.4	12231.7	12253.6
2024	12511.6	12515.1	12488.9	12511.4
2025	12892.2	12894.9	12868.8	12895.4
2026	13265.8	13266.9	13241.7	13262.6
2027	13252.2	13250.5	13228	13249.2
2028	13489.5	13484.2	13464.9	13477.8
2029	13638.8	13628.6	13614	13620
2030	13630.2	13613.9	13605.6	13601.7
2031	13557.8	13534.1	13533.5	13517.5
2032	13508	13475.5	13484	13449.7
2033	13274.4	13231.8	13251.2	13196.6
2034	12981.2	12927.2	12958.8	12879.7
2035	12644.1	12577.5	12622.9	12513.5

Table 6 illustrates the relative impacts of various strategies on reducing carbon emissions. These strategies are classified according to their effectiveness: increased average education year, optimizing energy structure, and increasing investment in scientific research.

Increasing investment in scientific research will initially increase carbon emissions. This is because scientific research investment will also improve the overall technological level, making it more convenient for people to use energy in daily life, thus temporarily increasing carbon emissions in the maintenance stage. At the same time, scientific research investment will reduce the energy consumed per unit of electricity, thereby reducing the electricity emission factor and reducing carbon emissions in the long term, with a reduction of 666 thousand tons in 2035.

Raising low-carbon awareness will encourage residents to adopt more sustainable consumption habits and lifestyles, which is the key to reducing carbon emissions in the building operation stage. If the years of education increase by an additional 1% on the basis of the original predicted value, it will lead to an average annual reduction of 220 thousand tons of carbon emissions.

The transformation of the energy structure to electricity is a powerful measure for carbon emission reduction. Within the research time range, accelerating the increase in the proportion of electricity will make the annual carbon emission reduction effect more and more obvious, reducing 1.306 million tons of carbon emissions in 2035.

The above results indicate that increasing R&D investment, increasing average education year, and optimizing the energy structure have considerable potential to reduce carbon emissions.

However, it must be pointed out that considering the complexity and interactivity of the carbon emission system of the construction industry chain, it is not enough to examine the contribution of a single factor in isolation.

4.3 Simulation of the impact of multi-factor on carbon emissions

To fully understand and determine effective ways to reduce carbon emissions, the synergy of multiple factors is needed to support the low-carbon transformation of the entire construction industry chain.

After research on these key factors, three other scenarios were developed to accurately describe the general situation in Beijing.

The coordinated development scenario includes moderately increasing the GDP growth rate and reducing the proportion of the value of new buildings, while increasing investment in education and scientific research. The focus is on promoting low-carbon awareness and technological progress, managing residential electricity consumption, and increasing the proportion of renewable energy. This scenario regulates carbon emissions through the implementation of coordinated policies including policies, technological progress, and structural adjustments.

The low-carbon development scenario is an extension of the coordinated development scenario and adopts a more stringent approach to reducing emissions. This requires stricter control of building area and further optimization of the energy consumption structure. It further slows down the speed of new building construction and gives priority to the fair progress of economic expansion and carbon emission reduction. The GDP growth rate is slightly lower than that in the coordinated development scenario, and the emission factor decreases more rapidly.

Under the comprehensive development scenario, it is assumed that there is a relatively high growth in GDP and scientific research investment, and a slight increase in population. Secondly, control building carbon emissions on the basis of maintaining the GDP growth of the construction industry.

According to the industrial development and overall urban planning of Beijing, considering economic development, population growth, construction land, and energy structure adjustment, three development speeds of coordinated development, low-carbon development, and comprehensive development scenarios are set up. Detailed parameter settings for population size, GDP, energy structure, and proportion of scientific and technological investment are planned.

1. Population size

In recent years, Beijing has continuously relieved non-capital functions and achieved results in controlling the population size. The natural population growth rate has been continuously declining. As of 2020, the permanent resident population of Beijing has decreased by 0.27%. The Beijing Urban Master Plan (2016 - 2035) proposes that from 2020 to 2035, the scale of the permanent resident population of Beijing will be in a long-term stable state. Based on this, in this paper, the coordinated development, low-carbon development and comprehensive development scenarios are set to fluctuate by about 1% to 1.6% on the basis of the baseline scenario respectively.

2. GDP

The 14th Five-Year Plan of Beijing points out that by 2035, the regional GDP will double compared with 2020, and the average annual growth rate of regional GDP will be about 5%. Based on this, in this paper, the coordinated development, low-carbon development and comprehensive development scenarios are set to fluctuate by about 0.3% to 1.6% on the basis of the baseline scenario respectively.

3. Science and technology investment

The long-term goals point out that strengthening the core support of national strategic scientific and technological strength. During the 14th Five-Year period, the investment in research and development of the whole society will increase by more than 7% annually on average. In this paper, the coordinated development, low-carbon development and comprehensive development scenarios are set to fluctuate by about 0.5% on the basis of the baseline scenario.

4. Energy structure

The Beijing Urban Master Plan (2016 - 2035) points out that by 2020, the proportion of high-quality energy will increase from the current 86.3% to 95%, and reach 99% by 2035. By 2020, the proportion of new energy and renewable energy in total energy consumption will increase from the current 6.6% to more than 8%, and reach 20% by 2035. Based on this, in this paper, under the baseline scenario, the proportion of electricity consumption in the coordinated development and low-carbon development scenarios is set to fluctuate upward by about 1.2% to 2.6% on the basis of the baseline scenario respectively.

5. Construction output value and demolition area

The Beijing Urban Master Plan (2016 - 2035) proposes that the proportion of urban and rural industrial land in urban and rural construction land will decrease to less than 20% by 2035. The outline of Beijing's long-term goals points out that the urban renewal plan should be implemented. Based on this, in this paper, in the coordinated development, low-carbon development and comprehensive development scenarios, the output value of new buildings is set to fluctuate by about 0.1% to 0.7% respectively. The demolition ratio fluctuates by about 1%.

6. Years of education

The Beijing Urban Master Plan (2016 -2035) puts forward educational requirements in terms of enhancing people's well-being. By 2035, the average years of education will reach 13.5 years. Based on this, in this paper, in the coordinated development, low-carbon development and comprehensive development scenarios, the years of education fluctuate by about 0.4 years.

Each scenario is specifically created to test a plan that combines economic growth with carbon emission reduction in a sustainable way. This provides valuable information for Beijing to achieve a feasible path for low-carbon development.

Table 7 lists in detail the adjustments made in these simulations to gain understanding of the specific strategies implemented.

Table 7: Multi-factor carbon emission scenario modeling options for Beijing

Norm	Baseline	Coordinated development	Low-carbon development	Comprehensive development
GDP growth rate	original data	0.6 % increase per year	0.3 % increase per year	1.6 % increase per year
Population growth rate	original data	1 % increase per year	1 % increase per year	1.6 % increase per year
New construction ratio	original data	0.6 % reduction per year	0.7% reduction per year	0.1% reduction per year
average education year	original data	Increase by 0.04 years per year	Increase by 0.04 years per year	Increase by 0.04 years per year
Demolition area ratio	original data	1 % increase per year	1 % increase per year	1 % increase per year
R&D investment ratio	original data	0.5 % increase per year	0.5 % increase per year	0.5 % increase per year
Energy consumption structure	original data	0.7% decrease for natural gas, 0.5% decrease for heat power, 1.2% increase for electricity	1.5% decrease for natural gas,1.1% decrease for heat power,2.6% increase for electricity	original data

Based on the prediction results of the above scenarios, a comparative analysis was conducted on the changing trend, peak value, and peak time of the total carbon emissions.

The optimization of the energy structure, especially the transformation towards electricity, has become an important matter. Increasing financial resources for R&D investment can promote the development and application of low-carbon technologies. These technologies, combined with effective management and the improvement of public awareness, jointly contribute to the increase in carbon emissions of the entire construction industry chain. Increasing the proportion of prefabricated building can reduce the use of raw materials, thereby reducing carbon emissions in the production stage.

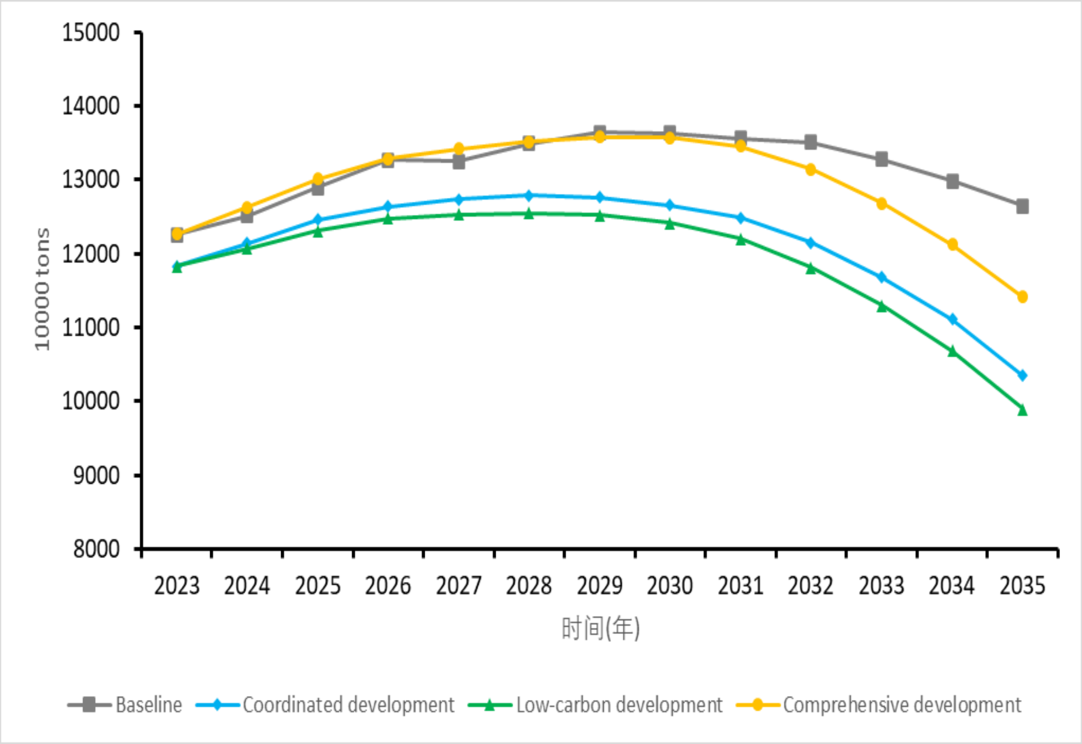

Figure 9: Trend of carbon emission in different scenarios for Beijing

Figure 9 shows the situation of reaching the carbon peak under all scenarios. Under the coordinated development scenario, under the combined action of multiple factors, the carbon emissions of the entire construction industry chain will reach a peak of 127.9 million tons in 2028.

The economic growth rate in the low-carbon development scenario is slower than that in the comprehensive development scenario, and the trend of carbon emission changes is also relatively slow. Under the low-carbon development scenario, the peak emission is 125.5 million tons. Compared with the baseline scenario, the cumulative emissions will be reduced by 16.3 million tons.

In terms of economic development, the comprehensive development scenario is the most ideal scenario. The change rate of each variable is higher than that in the coordinated development scenario. Under the comprehensive development scenario, the carbon emissions of the entire industry chain reach the carbon peak in 2029, which is 7.8 million tons higher than that in the coordinated development scenario. Through the analysis of different stages, it is found that the production and transportation of building materials are always the main contributors to carbon emissions. Although the increase in carbon emissions after the adjustment of new building types has slowed down, the peak value cannot be reached by 2035. In the construction stage, through the adjustment of the energy structure, except for the comprehensive development scenario, the carbon peak has been reached. In the operation stage of buildings, with the optimization of the energy structure and the reduction of emission factors, the carbon peak can also be reached. In the waste recycling stage, the amount of carbon emission reduction brought by reproduction continues to grow.

For the entire construction industry chain, under the baseline scenario without policy regulation and the comprehensive development scenario, the peak carbon emissions in the construction industry will appear in 2029; under the coordinated development scenario where policy targets are tightened according to the current trend, the carbon emission peak will appear in 2028; and in the low-carbon development scenario with stricter policy targets, the carbon emission peak will also appear in 2028. Although the carbon peak in the comprehensive development scenario is the highest among the four scenarios, the downward trend of carbon emissions is the fastest.

For the material production stage, the emissions at this stage are mainly based on the changes in building area demand caused by changes in the socio-economic population subsystem. Although the carbon emissions generated in the construction stage are relatively small compared to the entire construction industry, the energy structure also needs to be adjusted. In the building operation stage. After a building is put into use, there will be long-term energy consumption. This is not only true for new buildings, but the adjustment of the energy structure of existing buildings also has an important impact on carbon emission reduction. Increasing the proportion of power energy consumption can avoid carbon emissions caused by large-scale use of fossil energy.

The effect of multi-factor coordinated regulation and single-factor regulation: Research shows that compared with single-factor regulation, the multi-factor coordinated regulation strategy is more effective in emission reduction. From different scenarios, it can be seen that the impact of carbon emission reduction brought by the implementation of measures in multiple aspects will reach a sum higher than the effect of a single measure. Therefore, it is crucial to expand the scope of policy formulation.

5. Conclusion

The main research conclusions of this paper mainly include the following aspects:

(1) Through the research on the entire construction industry chain and carbon emissions, the research object and scope of this paper are clarified. The carbon emission factor measurement method is used to calculate carbon emissions. The calculation results show that the carbon emissions of the entire construction industry chain in Beijing have increased by nearly 2.4% annually from 2005 to 2022, with an overall increase of 49.4%. Although carbon emissions in some years have slightly decreased, there is an overall significant growth trend. The main reasons for this trend are the expansion of building area and energy consumption due to the improvement of residents' living standards. At the same time, it can be noted that due to changes in the energy use structure, the carbon emission growth trend is gradually slowing down.

(2) Based on the analysis of the carbon emission accounting method and the operation mechanism of the entire construction industry chain, combined with the selection principles of influencing factors, the main factors affecting carbon emissions are selected, including GDP, total population, building area, low-carbon awareness, proportion of scientific research investment, energy structure, and low-carbon awareness. On this basis, a system dynamics model is established to analyze the dynamic relationship between carbon emission influencing factors.

(3) Through scenario analysis to study the carbon emission reduction path of the entire construction industry chain in Beijing. The most significant factors that increase carbon emissions include economic growth, population growth, and the value of new buildings. Conversely, the key factors that promote emission reduction, ranked in order of effect, are: adjusting the energy structure, increasing investment in scientific research, and enhancing low-carbon awareness.

Research predictions show that all scenarios will reach a peak between 2028 and 2029, and then carbon emissions will continue to decline. Under the baseline scenario, carbon emissions will reach a peak of 136.4 million tons in 2029. Under the coordinated development scenario, carbon emissions of the entire construction industry chain will reach a peak of 127.9 million tons in 2028. Under the low-carbon development scenario, it will reach 125.5 million tons in 2028. Under the comprehensive development scenario, carbon emissions will reach the carbon peak target in 2029, reaching a peak of 135.6 million tons of carbon dioxide. The coordinated development scenario and the low-carbon development scenario show higher emission reduction potential than the comprehensive development scenario. Especially in the low-carbon development scenario, emissions can be reduced by up to 21.8%.

The multi-factor coordinated regulation strategy is more effective in emission reduction than single-factor regulation. Through the analysis of different scenarios, it can be found that the carbon emission reduction impact brought by the joint implementation of measures in multiple aspects will be higher than the simple sum of the effects of individual measures. The formulation of decarbonization and emission reduction policies in the construction industry cannot be simply limited to a certain stage or a certain factor, but must take into account the entire industrial chain of the construction industry. The synergy effect of policy effects becomes a key consideration factor when formulating policy measures.

6. Recommendation

The development of cities requires a balance between economic growth and environmental protection. This requires formulating a systematic low-carbon development route for the entire construction industry chain and implementing these plans at different administrative levels.

Based on the above conclusions, the following suggestions are put forward for emission reduction in the entire construction industry chain:

Reasonably control building energy consumption and annual new building area. Through the analysis of the influencing factors of building carbon emissions, it can be seen that in addition to economic factors, the factors that have the greatest impact on carbon emissions are the output value of new buildings and population. To control building carbon emissions while ensuring economic growth, macro-control is necessary, including reasonably controlling building area and maintaining a healthy population growth. For example, subsidy policies can be used to encourage real estate developers to develop small-sized residences. While meeting the needs of residents, by reducing the new building area, building energy consumption and carbon emissions can be reduced from the source.

Promote the low-carbon transformation of the building materials industry. Building materials production is one of the important components of carbon emissions in the entire industrial chain. Therefore, reducing carbon emissions through production energy conservation is a very effective way. Construction enterprises should increase the use of green building materials and reduce power and heat consumption in the building operation stage. Moreover, the low-carbon transformation of the building materials industry is a path to achieving sustainable development, green production, and efficient utilization of enterprises related to building materials production. Firstly, the low-carbon transformation of the building materials industry has driven technical upgrades and green development in upstream and downstream enterprises such as building material producers, equipment manufacturers, and raw material suppliers. Secondly, the low-carbon shift in the building materials sector has significantly boosted the integration of fields like law, finance, and capital with the building materials industry, fostering innovative development in producer services for energy conservation and emission reduction.

Adopt active energy policies to improve energy efficiency and optimize the energy structure. Beijing's renewable energy substitution action plan points out that accelerating the development of renewable energy in Beijing in the future is a measure to promote the energy revolution and build a clean, low-carbon, safe and efficient energy system. There are clear plans for the installed capacities of photovoltaic, biomass energy, wind power, and hydropower, and the proportion of renewable energy continues to rise. In addition, government incentive measures such as financial subsidies or tax exemptions can encourage enterprises to invest in low-carbon technology research and development. This can not only improve the energy efficiency of electrical appliances in the building operation stage, but also accelerate the low-carbon development in the building waste recycling stage. The government should also take the lead in strengthening incentive and restraint mechanisms and promoting cooperation among enterprises, the public, and other social actors to promote energy conservation and emission reduction in the construction field.

The government should strengthen education and energy conservation publicity to raise residents' awareness of energy conservation and emission reduction. Carbon emissions in the building operation stage are the main component of building carbon emissions. Residents are the main consumers of energy in the building operation process. Through strengthening education and energy conservation publicity, the government can encourage residents to develop a low-carbon lifestyle and reduce the consumption of electrical energy and heat energy in daily life.

Conduct low-carbon renovation of existing buildings. Some existing old buildings do not use energy-saving materials and energy-saving equipment. It is necessary to apply new energy conservation and emission reduction technologies to the renovation of old buildings. For example, adding insulation layers to the exterior walls of old residences to reduce heat consumption in winter, and renovating the water supply and power supply, etc. to improve residents' living standards and energy efficiency. In addition, low-carbon renovation can extend the service life of buildings, thereby reducing carbon emissions generated by building demolition and new construction.

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Appendix.

The Main Equations of the SD Systems

(1) Population growth rate = WITH LOOKUP (Time, ([(2005, -0.1)-(2035, 0.2)], (2005, 0.041), (2006, 0.0468), (2007, 0.0567), (2008, 0.0503), (2009, 0.0548), (2010, 0.0316), (2011, 0.0265), (2012, 0.0231), (2013, 0.0215), (2014, 0.0079), (2015, 0.0032), (2016, -0.0005), (2017, -0.0012), (2018, -0.0007), (2019, -0.0005), (2020, -0.0002), (2021, -0.02), (2022, 0.0008), (2023, 0.0007), (2024, -0.001), (2025, -0.0026), (2026, -0.0043), (2027, -0.006), (2028, -0.0077), (2029, -0.0095), (2030, -0.011), (2031, -0.0131), (2032, -0.015), (2033, -0.017), (2034, -0.0191), (2035, -0.021))

(2) GDP growth rate = WITH LOOKUP(Time, ([(2005, 0)-(2022, 0.3)], (2005, 0.173), (2006, 0.243), (2007, 0.133), (2008, 0.092), (2009, 0.16), (2010, 0.149), (2011, 0.107), (2012, 0.111), (2013, 0.085), (2014, 0.081), (2015, 0.091), (2016, 0.105), (2017, 0.108), (2018, 0.071), (2019, 0.014), (2020, 0.142), (2021, 0.014), (2022, 0.007), (2023, 0.0516), (2024, 0.066), (2025, 0.0582), (2026, 0.0297), (2027, 0.0596), (2028, 0.0493), (2029, 0.0393), (2030, 0.0432), (2031, 0.0484), (2032, 0.0383), (2033, 0.0395), (2034, 0.042), (2035, 0.0386))

(3) New construction ratio = WITH LOOKUP (Time, ([(2005, 0.01)-(2035, 0.5)], (2005, 0.1137), (2006, 0.0937), (2007, 0.0863), (2008, 0.0757), (2009, 0.0664), (2010, 0.0551), (2011, 0.0615), (2012, 0.0631), (2013, 0.0582), (2014, 0.0624), (2015, 0.0554), (2016, 0.0513), (2017, 0.0415), (2018, 0.0384), (2019, 0.0417), (2020, 0.0341), (2021, 0.0388), (2022, 0.0454), (2023, 0.0472), (2024, 0.0458), (2025, 0.0447), (2026, 0.0447), (2027, 0.0435), (2028, 0.0427), (2029, 0.0423), (2030, 0.0417), (2031, 0.0408), (2032, 0.0404), (2033, 0.0398), (2034, 0.0392), (2035, 0.0387))

(4) R&D investment ratio = WITH LOOKUP (Time, ([(2005, -0.1), - (2022, 0.2)], (2005, 0.0531), (2006, 0.0521), (2007, 0.0523), (2008, 0.0544), (2009, 0.0538), (2010, 0.0569), (2011, 0.0563), (2012, 0.0559), (2013, 0.0561), (2014, 0.0553), (2015, 0.0559), (2016, 0.0549), (2017, 0.0529), (2018, 0.0565), (2019, 0.063), (2020, 0.0647), (2021, 0.0641),
(2022, 0.0683), (2023, 0.0684), (2024, 0.0674), (2025, 0.0668), (2026, 0.0678), (2027, 0.0668), (2028, 0.0663), (2029, 0.0664), (2030, 0.0661), (2031, 0.0654), (2032, 0.0652), (2033, 0.0649), (2034, 0.0644), (2035, 0.064))

(5) Average education year = WITH LOOKUP(Time, ([(2005, 8)-(2022, 17)], (2005, 10.7), (2006, 10.9), (2007, 11.1), (2008, 11.3), (2009, 11.5), (2010, 11.7), (2011, 11.79), (2012, 11.88), (2013, 11.97), (2014, 12.06), (2015, 12.15), (2016, 12.24), (2017, 12.33), (2018, 12.42), (2019, 12.51), (2020, 12.6), (2021, 12.69), (2022, 12.78), (2023, 12.863), (2024, 12.939), (2025, 13.009), (2026, 13.071), (2027, 13.127), (2028, 13.176), (2029, 13.217), (2030, 13.252), (2031, 13.281), (2032, 13.302), (2033, 13.316), (2034, 13.324), (2035, 13.324))

(6) Electric power ratio during construction = WITH LOOKUP (Time, ([(2005, 0.1) - (2022, 0.8)], (2005, 0.241), (2006, 0.24), (2007, 0.237), (2008, 0.234), (2009, 0.214), (2010, 0.232), (2011, 0.27), (2012, 0.302), (2013, 0.328), (2014, 0.313), (2015, 0.298), (2016, 0.301), (2017, 0.301), (2018, 0.344), (2019, 0.367), (2020, 0.417), (2021, 0.446), (2022, 0.46), (2023, 0.472), (2024, 0.485), (2025, 0.497), (2026, 0.51), (2027, 0.522), (2028, 0.534), (2029, 0.546), (2030, 0.558), (2031, 0.571), (2032, 0.583), (2033, 0.595), (2034, 0.607), (2035, 0.62))

(7) Prefabricated reinforced concrete structure ratio = WITH LOOKUP (Time, ([(2005, 0.8) - (2022, 0)], (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0.0155), (2011, 0.0219), (2012, 0.0651), (2013, 0.0882), (2014, 0.0978), (2015, 0.1104), (2016, 0.1223), (2017, 0.1323), (2018, 0.2638), (2019, 0.2103), (2020, 0.2982), (2021, 0.3111), (2022, 0.3803), (2023, 0.3903), (2024, 0.4153), (2025, 0.4249), (2026, 0.4481), (2027, 0.473), (2028, 0.498), (2029, 0.518), (2030, 0.5353), (2031, 0.5484), (2032, 0.566), (2033, 0.5841), (2034, 0.599), (2035, 0.6125))

(8) Prefabricated steel structure ratio = WITH LOOKUP (Time, ([(2005, 0.3)-(2022, 0.1)], (2005, 0), (2006, 0), (2007, 0), (2008, 0), (2009, 0), (2010, 0.0013), (2011, 0.0017), (2012, 0.0047), (2013, 0.0113), (2014, 0.0122), (2015, 0.0116), (2016, 0.0128), (2017, 0.0168), (2018, 0.025), (2019, 0.0499), (2020, 0.0815), (2021, 0.0725), (2022, 0.0487), (2023, 0.0445), (2024, 0.0605), (2025, 0.0796), (2026, 0.0831), (2027, 0.077), (2028, 0.0724), (2029, 0.0782), (2030, 0.0884), (2031, 0.0948), (2032, 0.0942), (2033, 0.0928), (2034, 0.0947), (2035, 0.0992))

(9) Wooden structure ratio = WITH LOOKUP(Time, ([(2005, 0.1) - (2022, 0)], (2005, 0.0016), (2006, 0.0008), (2007, 0), (2008, 0), (2009, 0), (2010, 0), (2011, 0), (2012, 0), (2013, 0), (2014, 0), (2015, 0), (2016, 0), (2017, 0), (2018, 0), (2019, 0), (2020, 0), (2021, 0), (2022, 0), (2023, 0), (2024, 0), (2025, 0), (2026, 0), (2027, 0), (2028, 0), (2029, 0), (2030, 0), (2031, 0), (2032, 0), (2033, 0), (2034, 0), (2035, 0))

(10) Wood-brick structure ratio = WITH LOOKUP (Time, ([(2005, 0.1) - (2022, 0)], (2005, 0.0318), (2006, 0.0247), (2007, 0.0217), (2008, 0.0104), (2009, 0.0074), (2010, 0.0092), (2011, 0.0066), (2012, 0.0074), (2013, 0.0117), (2014, 0.0111), (2015, 0.007), (2016, 0.0035), (2017, 0.0081), (2018, 0.0026), (2019, 0.0205), (2020, 0.0218), (2021, 0.0154), (2022, 0.0033), (2023, 0), (2024, 0), (2025, 0), (2026, 0), (2027, 0), (2028, 0), (2029, 0), (2030, 0), (2031, 0), (2032, 0), (2033, 0), (2034, 0), (2035, 0))

(11) Brick-concrete structure ratio = WITH LOOKUP (Time, ([(2005, 0.3)-(2022, 0)], (2005, 0.2114), (2006, 0.2089), (2007, 0.1923), (2008, 0.161), (2009, 0.1899), (2010, 0.1866), (2011, 0.1906), (2012, 0.226), (2013, 0.1531), (2014, 0.1558), (2015, 0.1587), (2016, 0.0912), (2017, 0.0995), (2018, 0.0986), (2019, 0.0971), (2020, 0.0973), (2021, 0.0758), (2022, 0.0678), (2023, 0.0631), (2024, 0.0504), (2025, 0.0428), (2026, 0.0336), (2027, 0.025), (2028, 0.0171), (2029, 0.008), (2030, 0), (2031, 0), (2032, 0), (2033, 0), (2034, 0), (2035, 0))

(12) Reinforced concrete structure ratio = WITH LOOKUP(Time, ([(2005, 0.8)-(2022, 0.1)], (2005, 0.7306), (2006, 0.7335), (2007, 0.749), (2008, 0.786), (2009, 0.7627), (2010, 0.7491), (2011, 0.7389), (2012, 0.6662), (2013, 0.6878), (2014, 0.6776), (2015, 0.6647), (2016, 0.7084), (2017, 0.6887), (2018, 0.5634), (2019, 0.5757), (2020, 0.4606), (2021, 0.4783), (2022, 0.4523), (2023, 0.4513), (2024, 0.4234), (2025, 0.4001), (2026, 0.3828), (2027, 0.371), (2028, 0.3561), (2029, 0.3387), (2030, 0.3188), (2031, 0.2981), (2032, 0.2806), (2033, 0.2631), (2034, 0.245), (2035, 0.2268))

(13) Steel structure ratio = WITH LOOKUP (Time, ([(2005, 0.3) - (2022, 0)], (2005, 0.0246), (2006, 0.032), (2007, 0.0369), (2008, 0.042), (2009, 0.04), (2010, 0.0383), (2011, 0.0404), (2012, 0.0306), (2013, 0.048), (2014, 0.0454), (2015, 0.0476), (2016, 0.0618), (2017, 0.0547), (2018, 0.0466), (2019, 0.0463), (2020, 0.0406), (2021, 0.0469), (2022, 0.0475), (2023, 0.0507), (2024, 0.0504), (2025, 0.0517), (2026, 0.0524), (2027, 0.054), (2028, 0.0563), (2029, 0.0571), (2030, 0.0576), (2031, 0.0587), (2032, 0.0592), (2033, 0.06), (2034, 0.0612), (2035, 0.0614))

(14) GDP = INTEG (GDP growth, 7149.8); Units: 100 million CNY

(15) Population = INTEG (population growth, 1538), Units: 10,000 people

(16) Total floor area = INTEG (new construction area - demolition area, 78421), Units: 10000 m^2

(17) Total research input= INTEG (R&D investment,0), Units: one hundred million CNY

(18) Demolition area =if then else (Time>2007, if then else (Time>2009, Total floor area *0.03, Total floor area *0.02), Total floor area *0.002) , Units: 10000 m2

(19) GDP growth = GDP × GDP growth rate, Units: 100 million CNY/year

(20) Population growth = Population growth rate × Total population, Units: 10,000 people/year

(21) Per capita GDP = GDP × 10,000/total population, Units: CNY

(22) Value of new construction= GDP* New construction ratio, Units: 100 million CNY

(23) Energy consumption during construction= electric power consumption during construction /electric power ratio during construction, Unit: 10000 tons of standard coal

(24) Electric power consumption during construction= 0.000874* new construction area +3.558*(prefabricated reinforced concrete structure ratio+ prefabricated steel structure ratio)+14.11, Unit: 10000 tons of standard coal

(25) New construction area= Value of new construction *5.472+ Population *1.327+ per capital GDP *0.0216-3160

(26) Operation energy consumption= (0.0067* Total floor area +1.52* Population +0.012* per capital GDP +0.0011* Number of patents granted)* Environmental awareness adjustment factor -645.7

(27) Environmental awareness adjustment factor=1- average education year/70.1

(28) Construction emission= Energy consumption during construction *2.49

(29) Steel consumption=new construction area*(Wooden structure ratio*0.9+Wood-brick structure ratio*100+brick-concrete structure ratio*210+reinforced concrete structure ratio*733+steel structure ratio*1431+prefabricated reinforced concrete structure ratio*537.4+prefabricated steel structure ratio*966.3)

(30) Aluminum consumption = new construction area * (brick-concrete structure ratio * 5.6 + reinforced concrete structure ratio * 18.7 + steel structure ratio * 92.8 + prefabricated reinforced concrete structure ratio * 33.2 + prefabricated steel structure ratio * 88.9)

(31) Wood consumption = new construction area * (Wooden structure ratio * 860 + Wood-brick structure ratio * 1,070 + brick-concrete structure ratio * 240 + reinforced concrete structure ratio * 286.9 + steel structure ratio * 321.9 + prefabricated reinforced concrete structure ratio * 71.3 + prefabricated steel structure ratio * 57.9)

(32) Sand consumption = new construction area * (Wood-brick structure ratio * 9770 + brick-concrete structure ratio * 13450 + reinforced concrete structure ratio * 12621.4 + steel structure ratio * 6137.1 + prefabricated reinforced concrete structure ratio * 7284.1 + prefabricated steel structure ratio * 5143.3)

(33) Cement consumption = new construction area * (Wood-brick structure ratio * 1120 + brick-concrete structure ratio * 1720 + reinforced concrete structure ratio * 2524.3 + steel structure ratio * 1358.7 + prefabricated reinforced concrete structure ratio * 1829.1 + prefabricated steel structure ratio * 1391.3)

(34) Brick consumption = new construction area * (Wood-brick structure ratio * 8550 + brick-concrete structure ratio * 7050 + reinforced concrete structure ratio * 632.9 + steel structure ratio * 1532 + prefabricated reinforced concrete structure ratio * 438.9 + prefabricated steel structure ratio * 120.5)

(35) Lime consumption = new construction area * (Wood-brick structure ratio * 180 + brick-concrete structure ratio * 320 + reinforced concrete structure ratio * 446.6 + steel structure ratio * 274 + prefabricated reinforced concrete structure ratio * 315.4 + prefabricated steel structure ratio * 274)

(36) Transport emissions = (Steel consumption + Cement consumption + Sand consumption + Wood consumption + Aluminum consumption + Brick consumption + Lime consumption) / 10000 * 0.0001 * Transport distance

(37) Materials production emissions = (Wood consumption * Wood emission factor + Cement consumption * Cement emission factor + Sand consumption * Sand emission factor + Brick consumption * Brick emission factor + Steel consumption * Steel emission factor + Aluminum consumption * Aluminum emission factor + Lime consumption * Lime emission factor) / 10000

(38) Electricity emission factor = if then else(Time < 2018, (-Total research input * 0.000206 + Total research input^2 * 2.8049 * 10^-8 - Total research input^3 * 1.3038 * 10^-12 + 1.234) * 10, (2.692 * Total research input * 10^-6 - Total research input^2 * 8.52 * 10^-11 - Total research input^3 * 1.202 * 10^-16 + 0.594) * 10)

(39) The carbon emissions during the operation stage are calculated using the formula: (natural gas emission factor * natural gas consumption / 13.3) + (LPG emission factor * LPG consumption / 1.7143) + (heat emission factor * heat consumption / 0.0341) + (coal emission factor * coal consumption / 0.7143) + (electricity emission factor * electric power consumption / 4.04).

(40) The number of patent grants= 82.332* R&D investment -30384

(41) Construction waste= new construction area *0.037

(42) Demolition waste= Demolition area*1.3

(43) Waste to landfill= (construction waste+ Demolition waste) *(1- recycling rate)

(44) Landfill emission= Waste to landfill*0.01376

(45) Waste transport emission= Waste to landfill*0.0001 *waste transport distance

(46) Recycling quantity= (construction waste+ Demolition waste)*recycling rate

(47) Concrete= recycling quantity *0.8879

(48) Metal= recycling quantity *0.051

(49) Wood= recycling quantity *0.0045

(50) Recycled Concrete= concrete *0.7

(51) Recycled steel= Metal *0.9

(52) Reclaimed wood= Wood *0.67

(53) Carbon emission reduction = Reclaimed wood * (Wood emission factor - Reclaimed wood emission factor) + Recycled concrete * (Concrete brick emission factor - Recycled concrete emission factor) + Recycled steel * (Steel emission factor - Recycled steel emission factor)