

Article

Eco-Efficiency Assessment of Beijing-Tianjin-Hebei Urban Agglomeration Based on Emergy Analysis and Two-Layer System Dynamics

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Abstract: In the process of the economic development of the Beijing-Tianjin-Hebei urban agglomeration, ecological and environmental issues are still an important factor restricting high-quality development. The study of eco-efficiency is of great significance for coordinating the relationship between economy, resources and environment. This paper used a combined method of two-layer system dynamics and emergy analysis to construct an emergy–system dynamics coupling model for eco-efficiency evaluation from the subsystems of resource flow, energy flow, currency flow and population flow of urban system, which is used to simulate and analyze the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration. The results show that the overall eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration is not high, with an average value of 0.3786, and there is a trend of the value rising first and then falling from 2000 to 2035. The index values of emergy waste rate, contaminant emergy ratio, emergy output rate and environmental load rate after the decomposition of the eco-efficiency show that the high environmental pressure, the low re-use rate of pollutants and the low production efficiency of the system are important reasons for the low eco-efficiency in regional economic development. Finally, through scenario simulation, we propose that optimizing the economic structure, adjusting the population size and rationally arranging the fixed assets investment are conducive to improving the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration.

Keywords: eco-efficiency; two-layer system dynamics; emergy analysis; Beijing-Tianjin-Hebei urban agglomeration



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1. Introduction

Under the guidance of the national integration policy and the promotion of the urban upgrading, urban agglomerations are gradually becoming a new carrier of economic development. High-quality development of urban agglomerations can optimize the regional development pattern and drive the high-quality development of the whole economy [1]. The Beijing-Tianjin-Hebei urban agglomeration is an important part of China's core area, the outline of Beijing-Tianjin-Hebei Coordinated Development Planning issued in 2015 clearly stated that “by 2035, the structure and regional integration pattern of the Beijing-Tianjin-Hebei world-class urban agglomeration will be basically formed, the regional economic structure will be more reasonable, and the quality of the ecological environment will be generally well”. In 2021, The 14th Five-Year Plan for the National Economic and Social Development of the People's Republic of China and the Outline of the Vision for 2035 even put “accelerating the coordinated development of Beijing, Tianjin and Hebei” at the top of the “in-depth implementation of major regional strategies”, and listed it as the “first echelon of accelerating high-quality development” nationwide. High-quality development means that the work of ecological and environmental protection cannot be ignored in the

process of economic development. Therefore, quantifying and coordinating the relationship between economic development and resources and the environment of the Beijing-Tianjin-Hebei urban agglomeration is of great significance in order to promote the high-quality development of the Beijing-Tianjin-Hebei region.

The research on the economic development and ecological environment of the Beijing-Tianjin-Hebei region focuses on the impact of economic development on the ecological environment. For example, He and Cai measure and analysis the degree of decoupling degree between economic growth and environmental resources in the Beijing-Tianjin-Hebei region, and find that the rapid economic development in the Beijing-Tianjin-Hebei region has not fully realize the negative growth of resource consumption, as well as resource utilization rate and economical utilization rate are still at a low level [2]. Wang find that the coupling and coordinated development between economic society and ecological environment of the Beijing-Tianjin-Hebei urban agglomeration presented dynamic evolution (represented as S-shaped), showing an overall upward trend, and the growth mode gradually changed from the economic growth lag to the ecological environment lag [3]. Zhang et al. use the panel data approach (PDA) to examine the causal impact of the Beijing-Tianjin-Hebei strategy on Hebei's economy and environment under a counterfactual framework. The main finding is that the Beijing-Tianjin-Hebei strategy significantly increases the proportion of Hebei's tertiary industry in GDP and significantly reduces the geographic average PM2.5 concentration, but it has no significant impact on Hebei's GDP growth rate [4]. Xue and Zhou use the DDF-GML index to measure the green total factor productivity in the Beijing-Tianjin-Hebei region from 2005 to 2018, and found that there were "low growth" and "unbalanced" problems in the green total factor productivity during the sample period [5]. To sum up, we can see that the environmental quality of the Beijing-Tianjin-Hebei region has been improved in the process of economic development, but low energy utilization efficiency and environmental problems are still important factors restricting high-quality development.

Eco-efficiency as a comprehensive index reflecting the situation of economic, resource and environmental [6], the evaluation of urban eco-efficiency can objectively evaluate the efficiency relationship between the overall resource allocation, environmental quality and economic development of a city, so as to guide the coordinated and sustainable development of cities [7]. Some scholars adopted the single ratio method [8], the emergy value (or material flow) account accounting method [9], the index system method [10] and the model method (including data envelopment analysis (DEA) and stochastic frontier analysis method (SFA)) [11,12] to explore the level and spatial differences of eco-efficiency in cities and urban agglomerations. Due to the advantages of using fewer indexes and the fact that it can directly process the indexes of different dimensions, DEA is widely used in efficiency evaluation in various fields. For example, Gai and Zhan use the SBM model that considers the undesired output to measure the marine eco-efficiency of China's coastal provinces, and they describe the evolution characteristics of the spatial pattern with the help of the center of gravity model [13]. Tu et al. use super-efficiency (SBM) and Malmquist index to measure the eco-efficiency of the Pearl River Delta urban agglomeration from both static and dynamic aspects [14]. Zhang et al. use the Super-SBM model with unexpected outputs and standard deviation ellipses to study the dynamic changes and spatiotemporal differences of urban eco-efficiency in the lower Yellow River [15]. However, the calculation of eco-efficiency based on DEA model regards the region as a "black box", which cannot reflect the internal structure of the regional eco-economic system, and does not take into account the interaction between its internal subsystems.

With the development of social economy and the improvement of management practice ability, it is required to open the efficiency evaluation "black box" and deeply understand the interior of the decision-making unit. System dynamics (SD) [16] emphasizes the consideration of the problem as a whole, and understands the composition of the problem and the interaction between various parts, as well as using dynamic simulation to investigate the dynamic change behavior and development trend of the system [17]. Its essence is

to open the “black box” of the decision-making unit, decompose the complex system, and investigate the influence of each link on the overall efficiency of the system. Currently, it has been applied to study the interaction relation between environmental and economic factors [18], sustainable development strategy research of highway systems [19], and the evaluation of regional circular economy [20], and so on. However, with the strengthening of the flowing role of economic, resource and other factors in the global and regional urban networks, isolated point-like cities gradually evolve into closely interconnected planar urban agglomerations [21]. Urban agglomerations are interconnected by the elements of population, resources and economy within the urban agglomeration. Therefore, based on the existing studies [22,23], this paper introduces two-layer system dynamics (the first layer is the spatial layout of the urban agglomeration, namely the Beijing, Tianjin and Hebei province, and the second layer is the relationship of urban internal factors) to evaluate the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration.

The eco-efficiency evaluation system based on system dynamics is a complex system integrating economic, social and environmental factors. These factors interact with each other, but it is difficult to conduct a comprehensive and consistent analysis of the interaction between them due to the different equivalents. Emergy analysis (EMA) was first proposed by Odum in the 1980s [24]. It can convert all types of resources (whether energy or matter) into one form of energy, namely solar energy, that makes it possible to study various types of materials, energy and capital in one system [25]. In addition, emergy-based indicators such as emergy output rate, emergy load rate, and eco-efficiency index are directly linked to urban ecosystems in an integrated way by incorporating service value [26], that can reflect environmental pressure, eco-efficiency, changes in energy structure, and resource utilization, etc. Therefore, this method has been widely applied to the sustainability evaluation of urban circular economy [27], industrial ecosystems [9] and regional economic systems [28]. In this paper we combine it with system dynamics to make up for the deficiency of different equivalent of system dynamics.

Based on the perspective of functional flow, this paper takes the Beijing-Tianjin-Hebei urban agglomeration as the research object, constructing an emergy-SD coupling model for eco-efficiency evaluation by the method of emergy analysis and the system dynamics. Finally, the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration is evaluated, and the trend of eco-efficiency under different scenarios is discussed, which provides scientific reference for the effective implementation of urban development strategy.

Next, we introduce the research fields and data sources. Then, the framework of urban agglomeration eco-efficiency evaluation is given and the developed model and its formula, calculation method, parameters and evaluation index are explained. Finally, we will verify the model and analyze the simulation results.

2. Research Objects and Data Sources

The Beijing-Tianjin-Hebei urban agglomeration takes the capital Beijing and municipality Tianjin as the center, and other major cities include Shijiazhuang, Baoding, Langfang, Handan, etc. (as shown in Figure 1). Statistics in 2020 show that in the Beijing-Tianjin-Hebei region, Beijing hosts 20.37% of the resident population on 7.6% of the land, creating 41.78% of the regional output value; 5.5% of the land in Tianjin hosts 12.90% of the resident population and creates 16.32% of the regional output value. Of the land in in the Hebei province, 86.9% bears 66.73% of the permanent population and creates 41.89% of the regional output value.

At the beginning of this century, scholar Wu Liangyong proposed the Greater Beijing Plan, which is usually regarded as the beginning of the integration of Beijing, Tianjin and Hebei. After that, the coordinated development of Beijing, Tianjin and Hebei has experienced three stages, namely, the three regions reached consensus on the cooperation of the Beijing-Tianjin-Hebei region, the initial formulation of regional development planning, and the coordinated development of the Beijing-Tianjin-Hebei region was elevated to a national strategy level and its implementation was accelerated. Recently, Beijing issued the “Implementation Plan on Establishing a More Effective New Mechanism for Coordinated

Regional Development”, which proposed that by 2035, the framework of Beijing-Tianjin-Hebei world-class urban agglomeration will be basically formed. Therefore, this paper takes 2000–2035 as the research period. The following basic data were used: the total population of Beijing, Tianjin and Hebei Province are 1382, 1001.14 and 6674 million, respectively. The energy data of Beijing-Tianjin-Hebei resource stock are calculated by emergy analysis. Updatable resources include solar energy, wind energy, rainwater chemical energy and potential energy, which provides driving forces for the ecological economic system. Unable to update resources include oil, natural gas, etc. At the same time, the area also imports goods and equipment from the outside, and exports sewage and garbage to the outside.

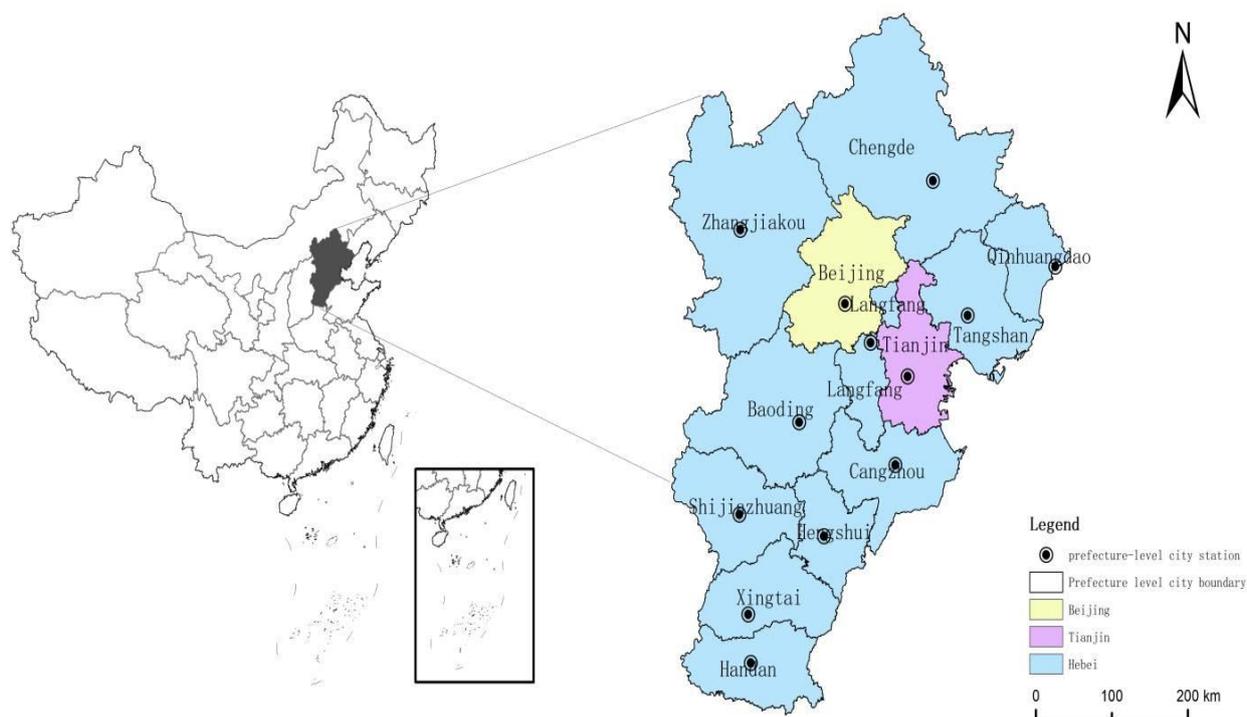


Figure 1. Beijing-Tianjin-Hebei urban agglomeration.

The original data used in this study came from China Statistical Yearbook, China Energy Statistical Yearbook, Beijing Statistical Yearbook, Tianjin Statistical Yearbook, Hebei Statistical Yearbook, Regional Statistical Yearbook, National Economic and Social Development Statistical Bulletin, China’s economic and social big data research platform, etc. The energy statistical yearbook reflects China’s energy construction, production, consumption, and the balance between supply and demand. The statistical yearbooks of various provinces and cities reflect the annual data of local economic and social development. These data are mainly derived from the census, and are verified and corrected in comparison with historical data, and they have a certain reliability.

3. System Dynamics Method

3.1. Framework of the Model

The urban eco-efficiency evaluation system may contain several subsystems, which may be included in a larger system (urban agglomeration or country). Therefore, we established a two-layer system dynamics model to study the eco-efficiency of urban agglomerations. In this model, the first layer is the spatial layout of the urban agglomeration. Each urban system within the urban agglomeration is regarded as an element in the system, so as to realize the overall analysis. The second layer is the smaller scale—urban scale. In addition to the influence of factors within the subsystem, there is population flow among subsystems, as shown in Figure 2.

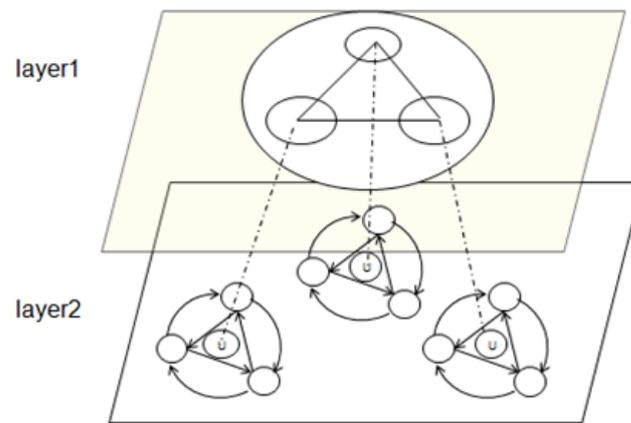


Figure 2. Framework description of the two-layer model of system dynamics.

Some scholars have studied the influencing factors of eco-efficiency. Ou uses the spatial error model (SEM) to study the influencing factors of eco-efficiency, and found that factors such as environmental regulation, economic development level, structural changes, opening to the outside world and urbanization all have a significant impact on eco-efficiency [29]. Qu uses the spatial lag model (SLM) to analyze the influencing factors of regional eco-efficiency. The results show that the regional economic development level, state-owned proportion, foreign investment and R&D intensity have a positive effect on the improvement of eco-efficiency level, while the increase in capital–labor ratio and the proportion of export trade are not conducive to the improvement of eco-efficiency level [30]. Chen et al. use the spatial panel econometric model to explore the impact of tourism economic development on regional eco-efficiency and its spatial effect. It is found that in the long-term development, tourism economic development and regional eco-efficiency shows a relatively obvious “Kuznets Curve” effect [31]. Tang et al. construct a macroeconomic model with output loss and innovation compensation factors to prove that land urbanization has a negative impact on urban eco-efficiency, and the improvement of industrial structure plays a positive mediating role between the two [32]. To sum up, existing studies have found that economic development level, industrial structure, urban population size and density, energy structure, government environmental regulation and foreign direct investment have an impact on eco-efficiency.

This paper analyzes the influencing factors of eco-efficiency system with reference to the conceptual framework “Driving-Force-Pressure-State-Impact-Response” (DPSIR) recommended by the United Nations Environment Programme (UNEP). The main “driving factors” affecting the eco-efficiency system of urban agglomerations are total change in economy and population. The evaluation of eco-efficiency is mainly through the measurement of “status and impact” indicators such as economic quality, resource supply, and environmental impact. The “response” in the DPSIR framework mainly refers to the fact that decision-makers adjust policies and management methods and optimize the interaction of economy, society and environment by changing driving forces and pressure factors, which corresponds to the scenario analysis and policy simulation of eco-efficiency implementation.

Based on this analysis framework, the dynamic simulation model of an eco-efficiency evaluation system is divided into currency flow subsystem, energy logistics subsystem and population flow subsystem, and the energy evaluation index is integrated into the energy logistics subsystem. The currency flow subsystem mainly focuses on the economic operation of the Beijing-Tianjin-Hebei region, studies the input and output of the industry, and the economic growth should be in response to the society and the environment. This model of this paper will focus on the impact of labor and fixed assets on the economy. The subsystem of population flow provides labor supply for economic development, and the increase in human capital has a positive effect on the economy. However, the increase in

population will mean that more living resources are consumed and more domestic garbage is discharged, which will have a negative impact on environment quality. The energy logistics subsystem is composed of material flow (resource flow) and energy flow. Material flow records the movement state and mutual transformation process of different kinds of substances in the system, and the energy flow represents the process of energy transfer and consumption in the system. The energy logistics system provides resources and power for the development of the eco-efficiency system. The evaluation index system of eco-efficiency was based on the calculation of energy flows among several subsystems.

In this paper, the SD model of eco-efficiency evaluation subsystem (city scale) was established on the second level by sorting out the causal relationship of influencing factors of the sub-system, in order to overcome the limitations of the “black box” of the urban eco-efficiency system, as shown in Figure 3.

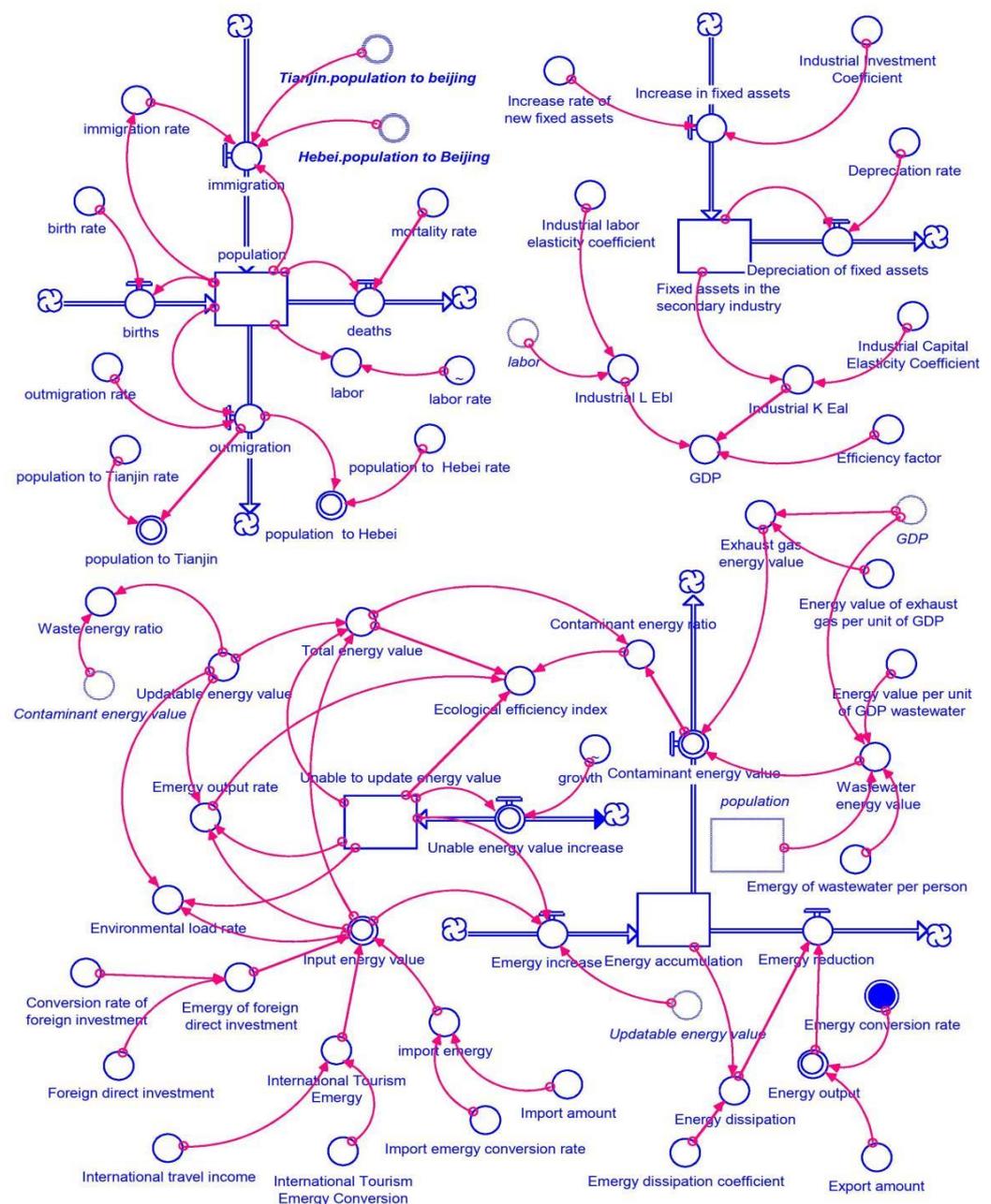


Figure 3. The second-level SD model of city scale eco-efficiency assessment.

The Beijing Social Governance Development Report (2015–2016) showed that the population flows frequently among the three regions of Beijing, Tianjin and Hebei, and the floating population of Hebei accounts for one-fifth of Beijing’s floating population, with an increasing trend year by year. The migration of population in Beijing-Tianjin-Hebei region not only leads to the disharmony of regional development, but also affects the environmental quality. Therefore, in the first-layer model (urban agglomeration scale), we consider the flow of population factors between cities, and the evaluation system of urban agglomeration eco-efficiency is shown in Figure 4 below.

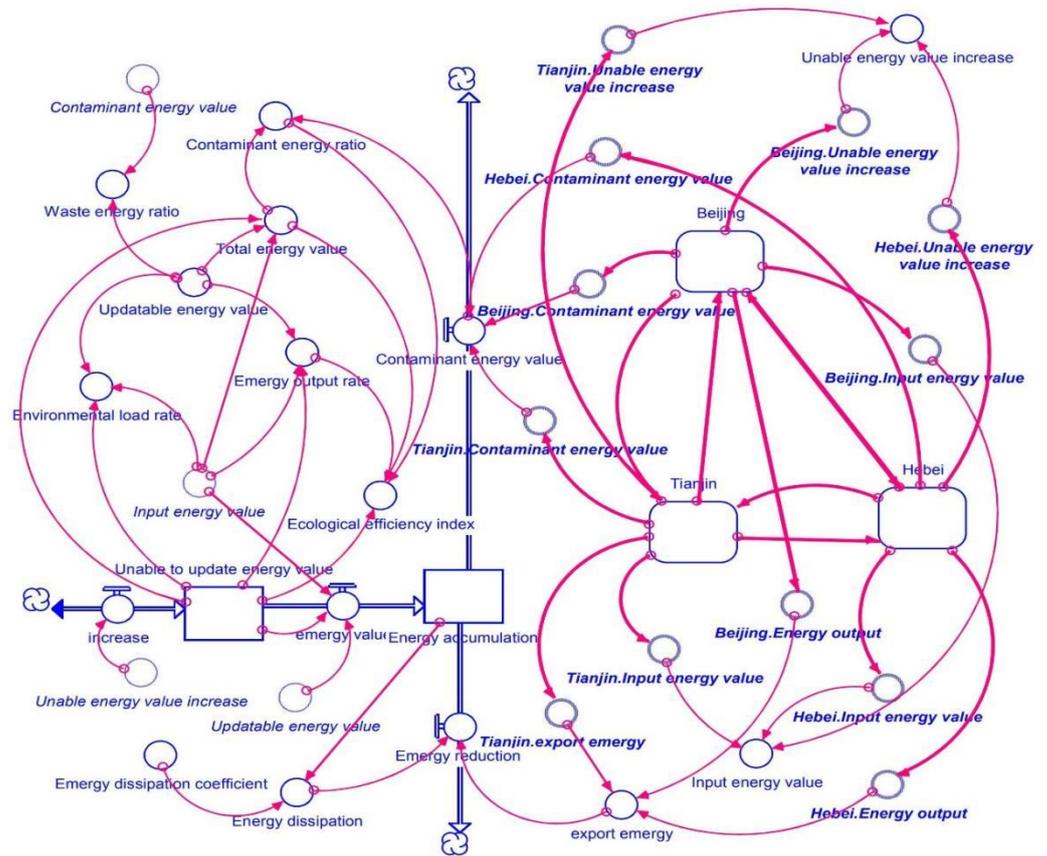


Figure 4. The first-level SD model of eco-efficiency assessment of urban agglomeration scale.

3.2. Model Development and Formulas

The subsystems of the first-layer eco-efficiency module are its urban components: Beijing, Tianjin and Hebei Province.

The second layer gives the SD model of the eco-efficiency evaluation of each subsystem. Figure 3 shows the stock flow diagram of the subsystem, which includes population flow, currency flow and energy flow. The total population is predicted from the previous year’s total population, births, deaths, and immigration and emigration figures. An analysis of trends in previous data on births and deaths reveals small changes in birth and death rates in the three regions.

$$Population_{jt} = Population_{j(t-1)} + Birth_{jt} + Death_{jt} + Immigration_{jt} + Outmigration_{jt}$$

This expression is a numerical equation. We use it to describe how the total population is calculated. $Population_{j(t-1)}$ represents the number of people in area j in the $(t - 1)$ year.

The relationship between regional GDP, labor force and capital was calculated with reference to the Cobb-Douglas production function. The Cobb-Douglas production function is a production function created by American mathematician Cobb and economist Douglas

when they discuss the relationship between input and output. The relationship between output (GDP) and input labor (L) and capital (K) can be expressed as follows:

$$GDP = A \cdot K^\alpha \cdot L^\beta \cdot e^\mu$$

The index α represents the capital elasticity, indicating that when the production capital increases by 1%, the output increases by $\alpha\%$ on average; β is the elasticity of labor force, which means that when the labor force input into production increases by 1%, the output increases by $\beta\%$ on average; A stands for comprehensive productivity and represents technological progress, and μ is the random disturbance term.

Among them, $Labor = total\ population * labor\ coefficient$

$Increase\ in\ fixed\ assets = investment\ in\ fixed\ assets * 0.95$. Since there will inevitably be some loss and waste in the process from the beginning to the final use of an investment, which cannot reach 100% utilization, this paper assumes that the utilization efficiency of fixed asset investment is 95%. The depreciation method of all assets adopts the straight-line method, and the depreciation rate of fixed assets was set as 9.6% [33].

$$K_{j,t} = I_{j,t}/P_{j,t} + (1 - \delta_{j,t})K_{j,t-1}$$

$K_{j,t}, I_{j,t}, P_{j,t}, \delta_{j,t}$ represent fixed asset stock, fixed asset investment amount, fixed capital investment price index and fixed capital depreciation rate in year t in j region. The initial stock of fixed asset comes from the existing literature [34].

The equation in this paper is set based on the existing research and the research object. The main variable equations are shown in Table 1.

Table 1. Relationship of main variables.

Serial Number	Relational Formula		
	Beijing	Tianjin	Hebei
1	Increment of fixed assets = [469.89 × (TIME-2000) + 602.66] × 95%	Increment of fixed assets = [76.491 × (TIME-2000) ² − 315.35 × (TIME-2000) + 1079.1] × 95%	Increment of fixed assets = [146.44 × (TIME-2000) ² − 327.4 × (TIME-2000) + 2016.5] × 95%
2	Depreciation of fixed assets = fixed assets × 9.6%	Depreciation of fixed assets = fixed assets × 9.6%	Depreciation of fixed assets = fixed assets × 9.6%
3	lg(GDP) = −1.899 + 0.823 × lgL + 0.813 × lgK	lg(GDP) = −1.484 + 1.054 × lgL + 0.565 × lgK	lg(GDP) = −9.573 + 3.296 × lgL + 0.433 × lgK
4	Labor = population × labor rate	Labor = population × labor rate	Labor = population × labor rate
5	IF population > 23,000,000, Immigrant population = population × 0.002; ELSE = population × 0.02	Immigrant population = population × 0.003	Immigrant population = population × 0.002
	Emigration population = population × 0.001	Emigration population = population × 0.002	Emigration population = population × 0.002
6	Wastewater emergy value = population × 2.574 × 10 ¹⁴ /Person + GDP × 6.95 × 10 ⁸ /GDP	Wastewater emergy value = population × 1.53 × 10 ¹⁴ /Person + GDP × 1.92 × 10 ⁹ /GDP	Wastewater emergy value = population × 8.32 × 10 ¹³ /Person + GDP × 4.23 × 10 ⁹ /GDP
7	Emergy value of exhaust gas = GDP × 5.19 × 10 ⁶	Emergy value of exhaust gas = GDP × 1.16 × 10 ⁷	Emergy value of exhaust gas = GDP × 3.03 × 10 ⁷
8	Emergy input = emergy_of_foreign_direct_investment + import_emergy + international_tourism_foreign_exchange_earnings_emergy		
9	Emergy reduction = emergy × 0.05 + emergy output		
10	Energy value of waste = exhaust gas emergy value + waste water emergy value		

3.3. Calculation Method of Emergy

The emergy analysis method regards the research system as an energy system, takes emergy as the benchmark, and transforms the heterogeneous and non-comparable energy as well as various non-energy forms such as energy flow, capital flow, information flow and

population flow in the system into the same standard energy for processing and analysis. Since all kinds of energy come from solar energy, solar energy is often used to measure a certain energy value in energy analysis [35]. The formula is as follows: $E_m = \tau E_x$.

E_m represents the energy of a material or energy; E_x represents the number of joules of material or energy available; τ represents the conversion of the energy value of a material or energy, or the amount of solar energy required to produce one joule of services or products (unit: sej/J or sej/g).

The urban eco-efficiency energy stream was divided into local renewable energy (R), local non-renewable energy (N), and imported energy from external systems (IMP). In order to minimize the risk of double counting, this paper selects the maximum renewable flow (sunshine, wind, rain, river and earth cycle) to calculate the renewable resource energy of the Beijing-Tianjin-Hebei region. The solar conversion data were taken from previous studies [24,36–38]. The energy values of the main variables in Beijing, Tianjin and Hebei province in 2000 are shown in Table A1 of the Appendix A.

3.4. Eco-Efficiency Evaluation Indicators

Zhang and Yang constructed an indicator to evaluate the sustainable development ability of the system from the perspective of metabolism, namely the ecological efficiency index (UEI) [25]. It is a function of energy yield ratio, energy-value ratio of non-renewable resources and contaminant energy ratio, the higher the ecological efficiency index, the higher the social and economic benefits of the system under unit environmental pressure (see Table 2). Therefore, this paper makes a dynamic evaluation of the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration by referring to the existing research and ecological efficiency index (UEI) [25,39,40], as well as based on the actual situation of the Beijing-Tianjin-Hebei urban agglomeration.

Table 2. Energy evaluation index system of eco-efficiency.

Classification	Energy Indicators	Calculation Formula	Unit
The energy flow	Updatable Resource Energy (R)	R	sej/a
	Non-updatable resource Energy (N)	N	sej/a
	Import Energy (IMP)	I	sej/a
	Export Energy (EXP)	E	sej/a
	Waste energy value (W)	W	sej/a
	Total energy (U)	$R + N + IMP$	sej/a
The energy efficiency	Energy Self-sufficiency Ratio (ESR)	$(N + R)/U$	%
	Energy Waste Ratio (EWR)	W/R	%
	Environment load ratio (ELR)	$(U - R)/R$	%
	Energy Yield Ratio (EYR)	$(R + N + IMP)/IMP$	%
	Contaminant energy ratio (W')	W/U	%
	Non-updatable resource energy ratio (N')	N/U	%
Eco-efficiency index [25]	UEI	$EYR \times (1 - W/U)^2 \times (1 - N/U)^2$	-

4. Results and Discussion

Taking 2000 as the base year, the time step is one year, and the operation cycle is 2000–2035, this paper used STELLA software to simulate the high-quality development level of Beijing-Tianjin-Hebei urban agglomeration.

4.1. Model Validity Verification

Model validity analysis is a necessary step of system simulation, which can be judged by comparing the difference between simulation value and existing statistical data. The system dynamics model constructed in this paper is a concrete abstract and approximate description of the real system. Whether the model can accurately present the real system is the key to the trend prediction and policy analysis of the system. Therefore, we judged the

reliability of the model by comparing the difference between the simulation value and the existing statistical data [41].

The inspection period of this article is from 2015 to 2018, and the selected indicators include population, GDP, etc. Since they are the main indicators for the result analysis, and they can be calculated with a subset of historical data, the feasibility of the actual inspection is ensured. The results show that there is a certain difference in the fitting degree between the simulation data and the statistical data, which is directly related to the accuracy of historical data and the logical structure of the model itself. The relevant literature indicates that when the system dynamics model is used for trend prediction, the error is acceptable within 30% [42]. Therefore, effectiveness analysis in Table 3 shows that the model can accurately describe the high-quality development status of the Beijing-Tianjin-Hebei region and has a good prediction function.

Table 3. Reliability test of the eco-efficiency simulation system of the Beijing-Tianjin-Hebei urban agglomeration.

	Year	The Real Value			Simulation Value			Error		
		Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei	Beijing	Tianjin	Hebei
Total Population (10,000)	2015–2018	2167.25	1556.50	7492.75	2133.75	1489.67	7474.74	(0.0154)	(0.0429)	(0.0024)
GDP (billion)	2015–2018	26,918.81	17,957.16	33,330.15	25,400.10	19,758.86	33,552.27	(0.0564)	0.1003	0.0067
International tourist foreign exchange earnings (US \$10,000)	2015–2018	508,030	353,548	56,991.75	471,500	368,461.65	70,281.46	(0.0719)	0.0422	0.2332
Actual utilization of foreign investment (US \$10,000)	2015–2018	1,691,623	1,167,307	853,895.3	1,317,312	1,000,000	1,009,490.8	(0.2213)	(0.1433)	0.1822
Total exports (US \$10,000)	2015–2018	5,979,500	5,773,075	3,221,700	5,679,745	6,796,826	2,948,552	(0.0501)	0.1773	(0.0848)
Total import (US \$10,000)	2015–2018	27,473,500	7,456,900	1,823,300	34,969,494	8,093,880	2,268,320	0.2728	0.0854	0.2441

4.2. Analysis of Simulation Results

4.2.1. Eco-Efficiency of Beijing-Tianjin-Hebei Urban Agglomeration

The eco-efficiency index (UEI) is a sustainable development index that reflects urban resource efficiency, environmental efficiency and economic efficiency. As can be seen from Figure 5, although the Beijing-Tianjin-Hebei region advocates green production, the overall eco-efficiency index was not high, with an average of 0.3786 from 2000 to 2035. During the simulation period, the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration showed a trend of increasing first and then decreasing, reaching a maximum value in 2011. This is similar to the conclusion of Ren and Fang on the county-scale evaluation of eco-efficiency in the Beijing-Tianjin-Hebei urban agglomeration; that is, that the overall level of eco-efficiency is low, and most eco-efficiency values are below 0.4 [43]. This may be due to the fact that in the early stage of the development of the Beijing-Tianjin urban agglomeration, there were relatively few residents and resource-intensive industries, resulting in less waste discharge. With the continuous expansion of urbanization, the migration of residents and enterprises leads to the massive consumption of renewable resources such as hydropower, wind energy and geothermal energy, as well as the increase in waste emissions. Therefore, UEI shows a trend of rising first and then falling.

Next, we further analyzed the changes of the eco-efficiency index under different situations. As shown in Figure 6, when the actual utilization of foreign investment, international tourism foreign exchange earnings and import value of Beijing, Tianjin, and Hebei increase by 10%, it is conducive to the improvement of eco-efficiency. On the contrary, a 10% decrease in birth rate and fixed asset investment of Beijing Tianjin and Hebei contributed to the increase in eco-efficiency. Previous studies have also shown that population agglomeration in the Beijing-Tianjin-Hebei region has a significant negative impact on eco-efficiency [44]. Therefore, the Beijing-Tianjin-Hebei urban agglomeration must pay attention to the synchronous improvement of weight and quality in the process of introducing actual utilization of foreign capital. In addition, tourism is a “smoke-free industry”,

and the foreign exchange income from tourism is compatible with the development of green industries, so it should be vigorously advocated. The data show that, in 2019, the international tourism foreign exchange income of Beijing, Tianjin and Hebei Province accounted for about 5.42% of the national international tourism foreign exchange income. At the same time, in the process of coordinated development of Beijing-Tianjin-Hebei, how to adjust the population scale and reasonably arrange the fixed asset investment to achieve the improvement of eco-efficiency is a problem that needs to be discussed.

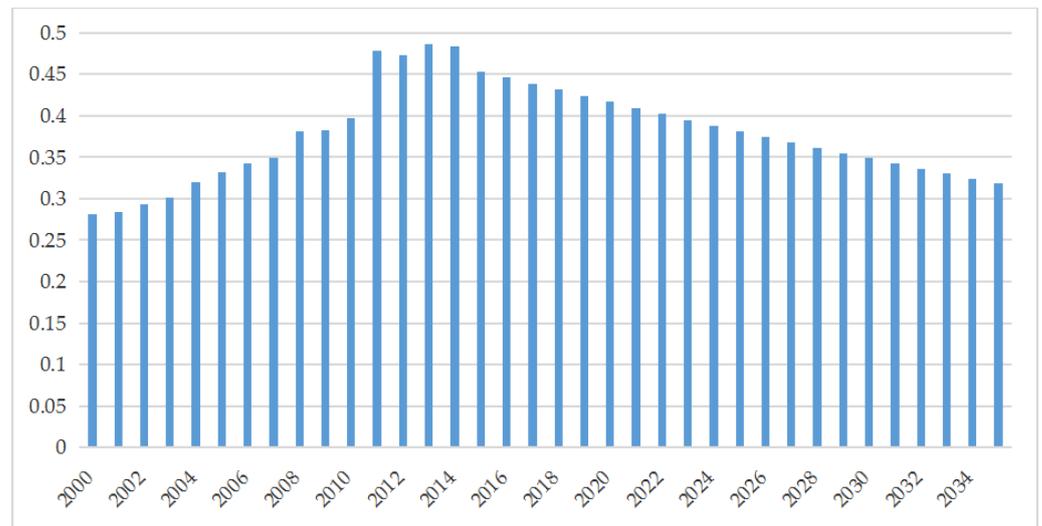


Figure 5. Eco-efficiency index of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2035.

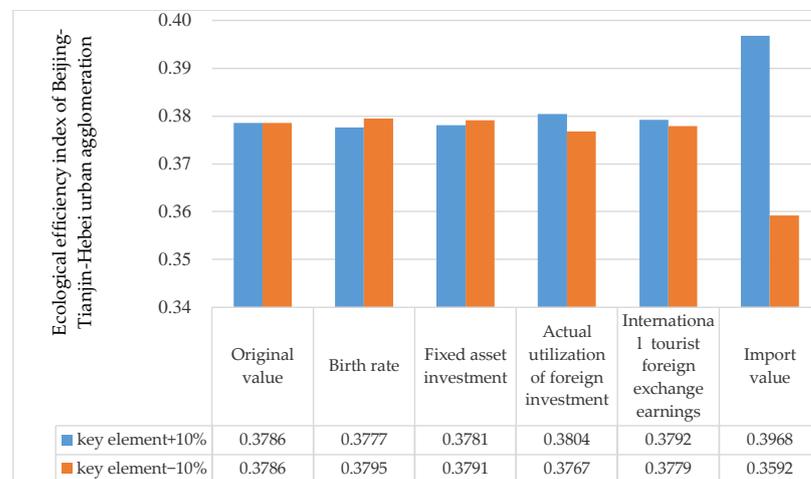


Figure 6. Changes of average eco-efficiency index from 2000 to 2035 under different simulation scenarios. Note: The horizontal axis represents the parameters adjusted in different simulation scenarios.

4.2.2. Analysis of Eco-Efficiency Indicators of Beijing-Tianjin-Hebei Urban Agglomeration

(1) Energy waste ratio (EWR)

The energy waste rate (EWR) is the ratio of waste energy to renewable resource energy, which is used to evaluate the availability of waste discharged by the system and the recycling capacity of the system. As shown in Figure 7, the waste rate of energy is increasing from 2000 to 2035. The simulation results of energy waste rate under different scenarios show that when the birth rate and fixed asset investment in Beijing, Tianjin and Hebei province increase by 10%, the energy waste rate of Beijing-Tianjin-Hebei urban agglomeration increases.

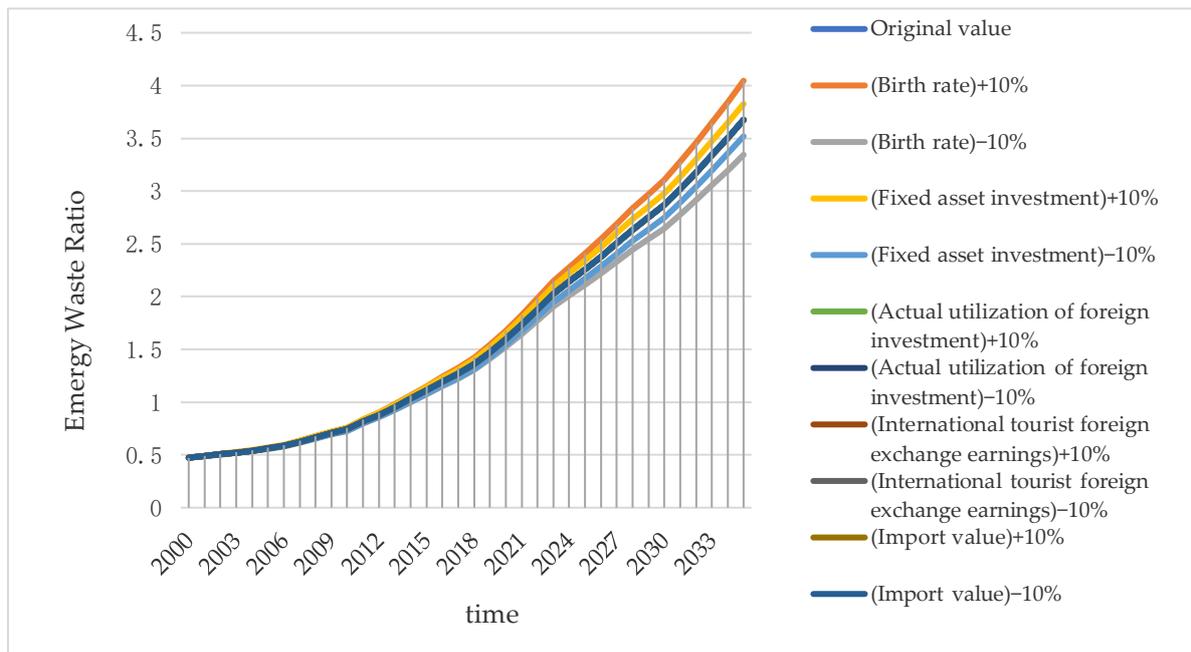


Figure 7. Simulation results of emergy waste rate of the Beijing-Tianjin-Hebei urban agglomeration.

(2) Contaminant emergy ratio

The contaminant emergy ratio is the ratio of the sum emergy of the “three wastes” to the total emergy, which is used to measure the burden of waste on the entire system. The larger the contaminant emergy ratio is, the larger the amount of waste discharged from the system is, and the greater the degree of utilization of waste from the system is [45]. It can be seen from Figure 8 that the contaminant emergy ratio in the Beijing-Tianjin-Hebei region decreased first and then increased during the simulation period. In the case of original value, the contaminant emergy ratio in 2011 and 2035 are 0.0097 and 0.026, respectively.

The simulation results of the waste emergy ratio under different scenarios show that the contaminant emergy ratio increases when the birth rate and fixed asset investment increase by 10%, and the actual utilization of foreign investment, tourism foreign exchange income, and imports decrease by 10%. The sustainability of economic development is affected by the recycling rate of waste. Therefore, there are still some urgent tasks for environmental regulation, such as energy conservation under the guidance of urban transformation.

(3) Emergy yield ratio (EYR)

Emergy yield ratio (EYR) is an indicator that measures the contribution of system output to economic development. The higher the EYR, the higher the emergy return rate of the system. It also means under the same economic input, the higher emergy output will be obtained, that is, the higher the production efficiency of the system. As shown in Figure 9, the emergy yield ratio of the Beijing-Tianjin-Hebei urban agglomeration fluctuated between 1.5 and 5.5 from 2000 to 2035, and has been on the rise since 2011, indicating that the economic efficiency of energy and resource utilization of Beijing-Tianjin-Hebei urban agglomeration has been improved recently. When the actual utilization of foreign capital, the foreign exchange income of international tourism and the import volume decreased by 10%, the emergy yield ratio increased.

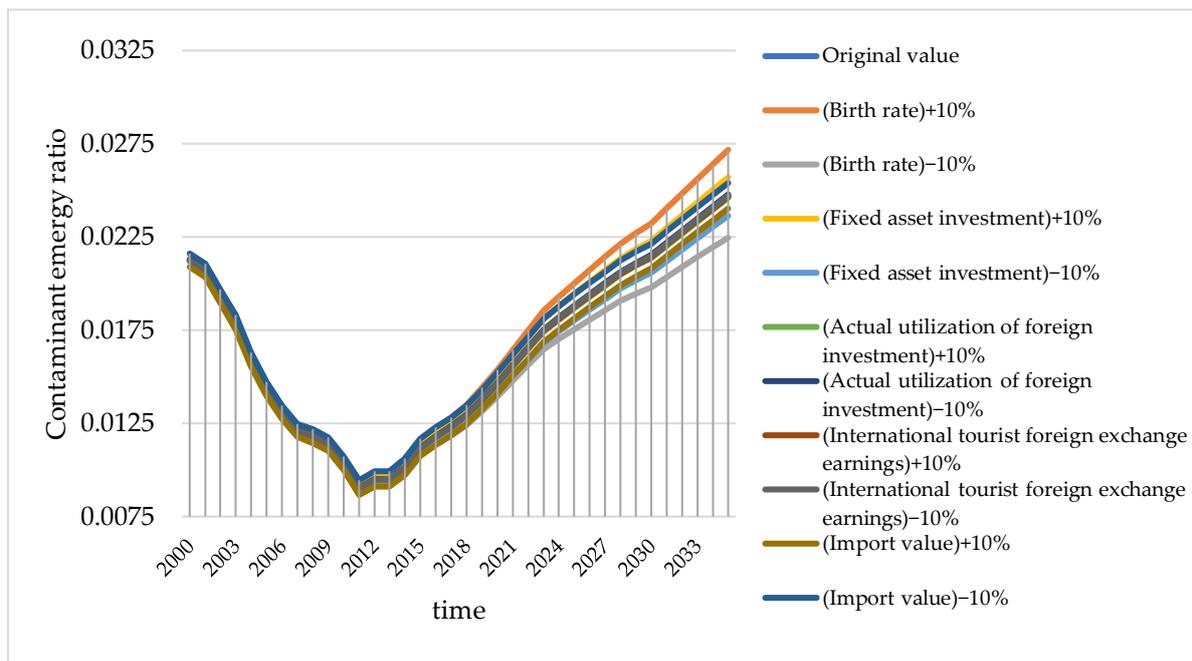


Figure 8. Simulation results of contaminant energy ratio of the Beijing-Tianjin-Hebei urban agglomeration.

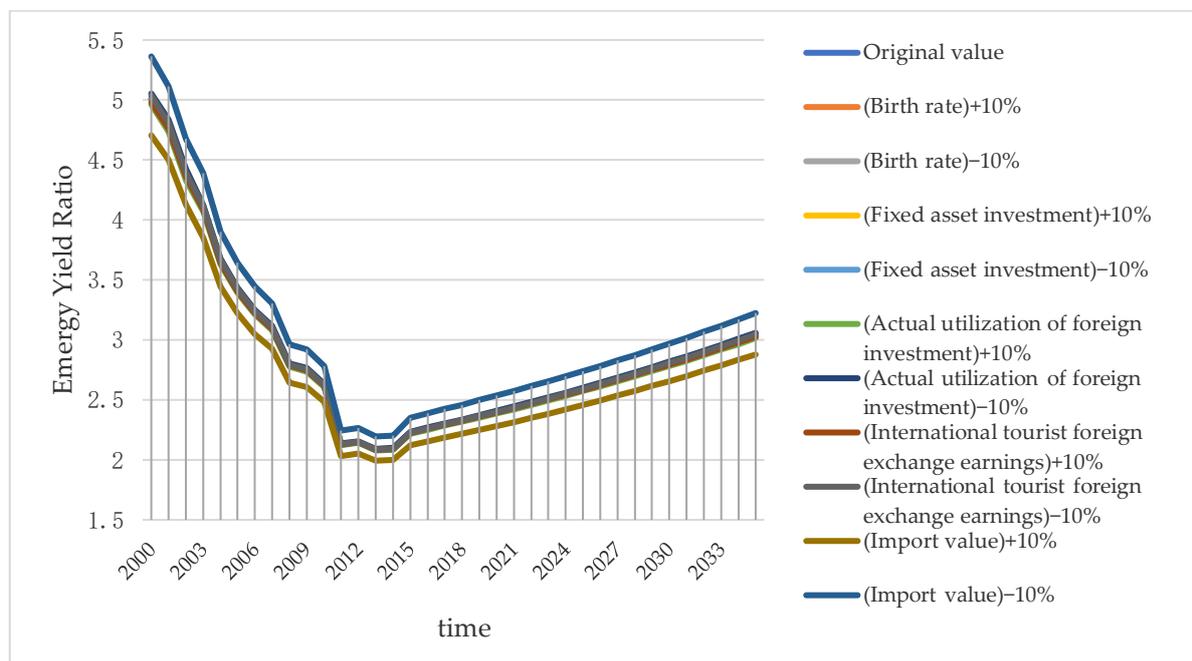


Figure 9. Simulation results of energy yield ratio of the Beijing-Tianjin-Hebei urban agglomeration.

(4) Environmental load ratio (ELR)

Environmental load ratio (ELR) is the ratio of purchased and non-renewable local energy to free environmental energy (renewable resource energy). The environmental load rate represents the pressure on the environment caused by the economic activities of the system [46]. When $ELR < 3$, the system environment bears less pressure and belongs to a healthy state; when $3 < ELR < 10$, the system environment pressure is at a medium level and belongs to sub-health state, and when $ELR > 10$, the system environment pressure is too high, which is an unhealthy state [25]. As shown in Figure 10, the environmental load rate of the Beijing-

Tianjin-Hebei urban agglomeration showed an upward trend from 2000 to 2035, indicating that the pressure on the environment caused by system economic activities continued to increase. In the case of the original value, the average value of the environmental load rate from 2000 to 2035 is 94.57, which belongs to an unhealthy state. It shows that the pressure of urban ecosystem economic activities on the environment in the Beijing-Tianjin-Hebei urban agglomeration is too large and does not weaken with the development of the city.

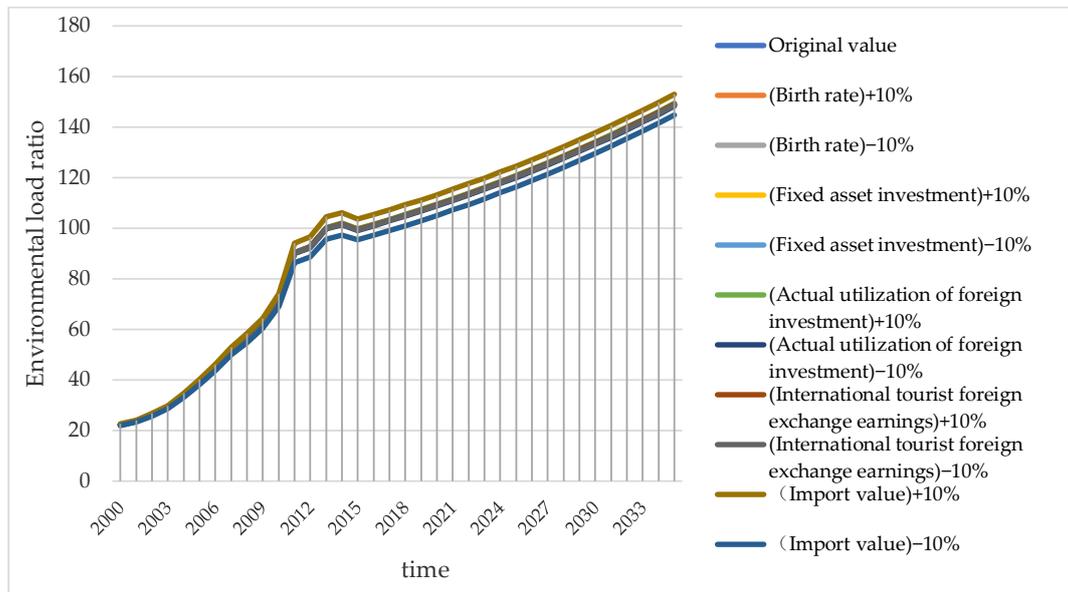


Figure 10. Simulation results of environmental load ratio of the Beijing-Tianjin-Hebei urban agglomeration.

The simulation results show that the environmental load rate is greatly affected by the amount of foreign capital, foreign exchange income from international tourism and imports, which is determined by the connotation of the environmental load rate. From the perspective of energy analysis, a large number of energy inputs from the outside and over-exploitation of local non-renewable resources are the main reasons of high environmental load rate.

5. Conclusions and Suggestion

In this paper, the energy analysis and system dynamics method are combined to establish the eco-economic system dynamics model of Beijing-Tianjin-Hebei urban agglomeration by using Stella software, and the development status and motivation of the system are analyzed through simulation. The results show that: (1) From 2000 to 2035, the eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration was not high, showing a trend of first rising and then falling. Compared with the value of eco-efficiency index in 2000, it increased by 13.28% in 2035. The analysis under different situations shows that the synchronous improvement of the quantity and quality of foreign capital actually utilized, as well as the adjustment of population scale and rational arrangement of fixed assets investment are conducive to the improvement of eco-efficiency; (2) The analysis of various indicators of eco-efficiency of the Beijing-Tianjin-Hebei urban agglomeration shows that the energy waste rate is rising, the environmental load rate is in an unhealthy state, and the decline of system energy output efficiency because of the environmental pressure on the growth of imported energy and non-renewable resource energy is rising. Therefore, high environmental pressure, low re-use rate of pollutants and low production efficiency of the system are important reasons for low eco-efficiency in regional economic development. According to the energy analysis theory, if the Beijing-Tianjin-Hebei urban agglomeration wants to truly realize the high-quality development of economy, some feasible approaches are to improve the utilization rate of renewable resources in the region, appropriately

limit the input of external feedback energy, and at the same time establish a recycling mechanism of waste resources and energy to improve the social and economic benefits exchanged by unit resources, energy and environment.

This paper combines emergy analysis with the system dynamics method to show the relationship between the system structure and factors through the system dynamics model, and uses simulation technology to grasp the future high-quality development of urban agglomerations. In future work, more details can be considered in the model development to reduce the impact of data limitations and increase the integrity and authenticity of the system simulation.

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Appendix A

In this paper, the conversion rate of energy is mainly based on existing research [24,36–38], and the global energy reference line of 9.26×10^{24} sej/year is used as the standard for conversion. The 2000 energy value analysis table of the Beijing-Tianjin-Hebei urban agglomeration is calculated, as shown in Table A1 below.

Table A1. Main energy flow analysis table of Beijing-Tianjin-Hebei Eco-economic system in 2000.

Items		Initial Data			Energy Conversion Rate	Solar Energy Value			Reference
		Beijing	Tianjin	Hebei		Beijing	Tianjin	Hebei	
Updatable resource energy values (R)	The solar energy	9.33×10^{19}	7.12×10^{16}	1.06×10^{21}	1.00	9.33×10^{19}	7.12×10^{16}	1.06×10^{21}	[24]
	wind energy	1.28×10^{17}	9.77×10^{16}	1.46×10^{18}	6.32×10^2	8.09×10^{19}	6.17×10^{19}	9.22×10^{20}	[24]
	Chemical energy of rainwater	4.10×10^{16}	3.16×10^{16}	9.38×10^{17}	1.82×10^4	7.46×10^{20}	5.75×10^{20}	1.71×10^{22}	[24]
	The rain potential energy	2.54×10^{15}	2.07×10^{14}	7.58×10^{16}	8.89×10^3	2.26×10^{19}	1.84×10^{18}	6.74×10^{20}	[24]
Non-updatable resource energy values	Earth rotation energy subtotal	1.65×10^{16}	1.26×10^{16}	1.88×10^{17}	2.90×10^4	4.79×10^{20}	3.65×10^{20}	5.45×10^{21}	[36]
	Surface soil loss	1.05×10^{16}	1.35×10^{16}	2.19×10^{17}	7.40×10^4	7.77×10^{20}	9.99×10^{20}	1.62×10^{22}	[24]
	The raw coal (J)	5.68×10^{17}	5.17×10^{17}	2.53×10^{18}	4.00×10^4	2.27×10^{22}	2.07×10^{22}	1.01×10^{23}	[24]
	Crude oil (J)	3.15×10^{17}	2.97×10^{17}	3.12×10^{17}	5.40×10^4	1.70×10^{22}	1.6×10^{22}	1.69×10^{22}	[24]
	cement (t)	8.27×10^6	2.68×10^6	4.69×10^7	2.07×10^{15}	1.71×10^{22}	5.55×10^{21}	9.71×10^{22}	[37]
	Natural gas (J)	4.24×10^{16}	2.10×10^{16}	3.10×10^{16}	4.80×10^4	2.04×10^{21}	1.01×10^{21}	1.49×10^{21}	[38]
	steel (t)	6.97×10^6	3.16×10^6	1.31×10^7	1.40×10^{15}	9.76×10^{21}	4.42×10^{21}	1.83×10^{22}	[24]
	Thermal power subtotal	1.38×10^{17}	8.42×10^{16}	2.91×10^{17}	1.60×10^5	2.21×10^{22}	1.35×10^{22}	4.66×10^{22}	[36]
	imports	3.74×10^{10}	8.53×10^9	1.53×10^9	2.50×10^{12}	9.15×10^{22}	6.22×10^{22}	2.98×10^{23}	[38]
	International tourist foreign exchange earnings	2.77×10^9	1.42×10^8	2.32×10^8	2.50×10^{12}	9.36×10^{22}	2.13×10^{22}	3.82×10^{21}	[38]
Actual utilization of foreign investment subtotal	3.01×10	2.56×10	1.39×10	2.50×10^{20}	6.93×10^{21}	3.55×10^{20}	5.80×10^{20}	[38]	
Export Energy	exports	1.20×10^{10}	8.63×10^9	3.71×10^9	1.46×10^{12}	1.08×10^{23}	2.81×10^{22}	7.88×10^{21}	[38]
Waste energy value	Waste gas	7.74×10^{13}	4.20×10^{13}	2.37×10^{14}	4.80×10^4	3.72×10^{18}	2.01×10^{18}	1.14×10^{19}	[36]
	Waste water subtotal	4.47×10^{15}	2.04×10^{15}	7.40×10^{15}	8.60×10^5	3.85×10^{21}	1.75×10^{21}	6.36×10^{21}	[24]
						3.85×10^{21}	1.76×10^{21}	6.37×10^{21}	

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