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Quantitative simulation and verification of upgrade law of sustainable development in Beijing-Tianjin-Hebei urban agglomeration

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Abstract The natural formation and development of urban agglomerations is a process in which core cities continue to unite their neighboring cities to enhance sustainability for their own sustainable development. The upgrade mechanism of sustainable development urban agglomeration is a nonlinear composite upgrade curve that is a function of time, increasing with the number of cities. In this paper, the sustainable upgrade function curve, upgrade rate, and upgrade speed of urban agglomerations were solved using a geometrical derivation, and the index system for measuring the upgrade capability of sustainable development of urban agglomerations was established. The dynamic change in economic sustainable upgrade capability, social sustainable upgrade capability, environmental sustainable upgrade capability, and comprehensive sustainable upgrade capability of a Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015 was measured by technique for order preference by similarity to an ideal solution and a grey correlation method, and a comprehensive, intercity unite strength model and a unite threshold calculation method for urban agglomerations were established. The research shows that the economic sustainable upgrade capability, social sustainable upgrade capability, environmental sustainable upgrade capability, and comprehensive sustainable upgrade capability of the Beijing-Tianjin-Hebei urban agglomeration all show a wave-like rising trend. The average annual upgrade speeds during 2000–2015 are, respectively, 2.4%. 1.67%, 1.1%, and 1.74%, with the intercity comprehensive unite strength of urban agglomerations maintaining a general increase; but there is a limit to the joint threshold. From 2000 to 2015, as the core city of the Beijing-Tianjin-Hebei urban agglomeration, Beijing, to enhance its sustainable upgrade capability, jointly developed with Tianjin, Langfang, and Baoding before 2000, Tangshan in 2002, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2012, and Chengde in 2014. By 2015, the comprehensive unite strength between Beijing and four cities (Handan, Qinhuangdao, Hengshui, and Xingtai) was still lower than the unite threshold of 6.14. These four cities are relatively far from Beijing, and offer no substantial contribution to the sustainable upgrade capability of Beijing. Through multiple fittings of the upgrade curve using the long-term sequence index of the comprehensive sustainable upgrade capability of Beijing (the core city of the Beijing-Tianjin-Hebei urban agglomeration) from 2000 to 2015, it was found that the simulated curve of the comprehensive sustainable upgrade function of the agglomeration was very similar to the curve of the comprehensive sustainable upgrade capability, which indicates that the simulation results are satisfactory. The future comprehensive sustainable upgrade capability of the agglomeration can be analyzed and predicted by the comprehensive sustainable upgrade function model. This study provides quantitative decision-supporting evidence for promoting the coordinated development of the Beijing-Tianjin-Hebei urban agglomeration and provides theoretical guidance and algorithms for determining the number of cities joined with the sustainable development of national urban agglomerations.

Keywords Sustainable upgrade law of urban agglomeration, Sustainable upgrade strength of urban agglomeration, Quantitative simulation and verification, Beijing-Tianjin-Hebei urban agglomeration

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1. Introduction

The idea of sustainable development was first defined by the World Commission on Environment and Development in its report "Our Common Future" as "meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). In order to achieve sustainable development of the world, the United Nations has formulated the 2030 Agenda for Sustainable Development[1)] which was unanimously approved by world leaders at the Development Summit in 2015, and seventeen sustainable development goals and 169 sub-goals (Lu et al., 2015) were proposed. Many problems were encountered during the process for achieving these sustainable development goals. As the main area of world population agglomeration and an important entity for social, economic, and environmentally sustainable development, the development of cities is very complicated (Uchiyama and Mori, 2017). It is estimated that, about 70% of the world population will live in cities by 2050[2)]. While meeting the needs of excessive population and production, cities will inevitably suffer serious ecological problems (Koop, 2017), and social conflicts will be further intensified; moreover, the problem of disease will become increasingly prominent. Major cities around the world have developed sustainable city development plans to alleviate disease in cities, so as to guide the urbanization process toward the ideal conditions of sustainable cities. A sustainable development strategy was incorporated into the national planning of China in 2000, and the white paper China's Population and Development in the 21st Century (State Council, 2000) was prepared to promote the coordination of population, economy, society, resources, and environment. Rapid urbanization and industrialization bring increasing pressure on resources and the ecological environment, and challenge the sustainable development of cities in many respects (Normile, 2016). The main manifestations include severe air pollution (Xia et al., 2014), traffic jams (Rana, 2011), water quality deterioration (Seilheimer et al., 2007), ecological security crises and a lack of resources. In particular, air pollution problems (such as $PM_{2.5}$) have seriously impaired the daily life and physical health of people (Fang et al., 2017). Therefore, the Chinese government is paying more and more attention to the sustainable development of cities. The government has implemented multiple policies to promote the healthy and sustainable development of cities in a new urbanization model (Bai et al., 2014). The State Council issued the notice of the "The Development Plan of China's Innovation Demonstration Zone for the Implementation of the 2030 Agenda for Sustainable Development" (Document No 69, 2007, the State Council), with a view to promoting the city's sustainable development. A wide range of social, economic, cultural, institutional, and environmental issues should be investigated for promoting the sustainable development of cities (Reid et al., 2010). Since the 1980s, the globalization of transportation, information technology, and clean energy has changed the urban landscapes of the world (Wible, 2012).

Interdisciplinary, cross-disciplinary, and multi-directional studies based on these issues are required for the sustainable development of cities (Hadorn et al., 2007). In the field of sustainable theory, Lynch (1981) proposed the urban form theory which included three main aspects: urban function, decision-making, and normative theory. The function theory focused on the urban spatial system; the decision-making theory discussed urban development policies; and the normative theory was aimed at the urban material environment. This theory reflects the needs of sustainable urban development; the double-layer sustainable balance theory reflects that economic, social, and environmental elements are dynamic and interactive and are correlated with each other. The realization of social sustainable development requires a combined action of multidimensional elements, such as economy, environment and society (Lozano, 2008).

According to the theory of a coupled system comprising humans and nature, the system shows complexity in organization, space, and time coupling. The coupling types include direct and indirect, near and remote, local and global, and simple and complex coupling. Multidisciplinary research on different urban development models is helpful for the sustainable development of economy, society, and environment in different types of cities (Liu et al., 2007). As for the development of sustainable models, there are mainly coupling models (Huang and Fang, 2003) that use parameters such as ecological footprint (Gu et al., 2015), three-dimensional (3D) ecological footprint (Niccolucci et al., 2009), energy analysis (Chen et al., 2014), and ecological network (Zhang et al., 2017), etc. Comprehensively, the

1) United Nations Research Institute For Social Development. 2030 Agenda for Sustainable Development. http://unrisd.org/80256B3C005BB128/(httpProjects)/38DF80F450689724C1257A7D004BD04B, 2015

2) The United Nations . China's urban population will increase by 255 million in 2050. https://news.un.org/zh/story/2018/05/1008862, 2018-05-16

existing theories mainly consider the internal effect of the city, the one-way development of elements, and the mutual coupling of systems but seldom consider the fusion effect between cities, the spatial flow of elements, and the comprehensive development of the system; the existing models are mainly single element models or dual-element models. There is no comprehensive model that considers multiple objectives and multiple factors, such as population, resources, environment, economic and social development. Therefore, it is difficult to establish a model based on the theory of sustainable development.

The above theories and models are mainly aimed at urban areas, and there is currently little in the literature on the sustainable development of urban agglomerations. An urban agglomeration is an aggregate of cities in a specific region, centered on a megacity, consisting of at least three or more metropolitan areas (districts) or large and medium-sized cities and relying on infrastructure networks (such as developed transportation and communication). Urban agglomerations are relatively compact, closely linked to each other in economic activity, and ultimately integrated (Fang and Ren, 2017; Fang and Yu, 2017). In the 21st century, the urban agglomeration has become a new regional unit that participates in global competition and the international division of labor, and it has become the main form of new urbanization in China (Fang, 2014a), bearing the historical responsibility of the world economic center. Based on the four-stage law of urbanization development (Fang, 2014b), China is currently in a period of strategic transformation, in a stage of rapid urbanization, and will soon pass through a mid-stage to enter a stage of slow growth and quality improvement in the later stage of urbanization. In this stage, there are still serious pressures on resources, in addition to the existence of ecological stressors (Fang et al., 2017). It is urgent to conduct in-depth research on urban agglomeration, such as theoretical, model, and empirical analysis, to explore the agglomeration (grouping) effects exhibited during the development of urban agglomerations, synergistic effects (Fang, 2017) , straw effect (Fang, 2011), diffusion effect (Wang and Fang, 2011), catch-up effect (Fan et al., 2017), polarization effect (Cai et al., 2017), scale effect (Wang et al., 2013), edge effects (Zhang et al., 2018), heat island effect (Zhou et al., 2018), reflow effect (Chen and Mark, 2013), etc. Additionally, It is also urgent to explore the pattern of established urban agglomeration (Fang et al., 2019), urban body (Wang et al., 2017a), urban agglomeration "dividends"(Zhou, 2015), urban agglomeration "sickness" (Fang,2015), urban agglomeration engine (Fang et al., 2015b) and urban agglomeration linkage management model (Wang et al., 2017b), etc., so as to interpret the mechanism and rule of urban agglomeration formation and sustainable development (Fang et al., 2018).

2. Theoretical analysis and geometric expression of the sustainable upgrade law of urban agglomeration

2.1 The basic principle of the sustainable upgrade law of urban agglomeration

The natural formation and development of urban agglomerations is a process in which a number of cities unite their neighboring cities to promote mutual sustainability for their own sustainable development. This process occurs as follows: When city A cannot enhance its sustainable development capability relying on its own ability, it will naturally unite to a second city, B, for cooperation to create this enhancement; when the enhancement cannot be maintained through union with city B, it will naturally unite with a third city, C; when its sustainable development capability cannot be maintained through its union with city C, it will naturally unite with a fourth city D, and it continues to maintain the sustainable development capacity at the update level through uniting the 4th city, and so on. The sustainable development capability of city A cannot be maintained by uniting the $n-1$ and $N-1$ cities, and city A will naturally unite cities n and N through cooperation to maintain the sustainable development capability of city A at a higher level by uniting cities n and N (Figure 1). City A will continuously unite with cities B, C, ..., N to form a community of common destiny for sustainable development in city A and n cities, and eventually develop into an urban agglomeration.

With an increasing number of joint cities, the sustainable development capability of a city shows a step-by-step upgrade trend with time, like a stepped conveyor belt, which is the gradient upgrade law followed by the sustainable development of urban agglomerations.

The number of cities with which a city needs to unite to maintain its sustainable development is not unlimited, which is objectively constrained by the unite threshold and limited by the unite strength. When the number of other cities that unite with the core city exceeds a certain threshold, the sustainable development capability of the core city cannot be improved upon.

2.2 Function model of sustainable upgrade curve of urban agglomeration

2.2.1 Geometric expressions of sustainable upgrade curves for urban agglomerations

The upgrade mechanism of the sustainable development of urban agglomerations is a nonlinear compound upgrade curve which is a function of time, increasing with the number of cities. We call it the "sustainable upgrade function curve of urban agglomerations". According to the principle of upgrade, in order to express the dynamic evolution of the upgrade capability of urban agglomeration, the upgrade

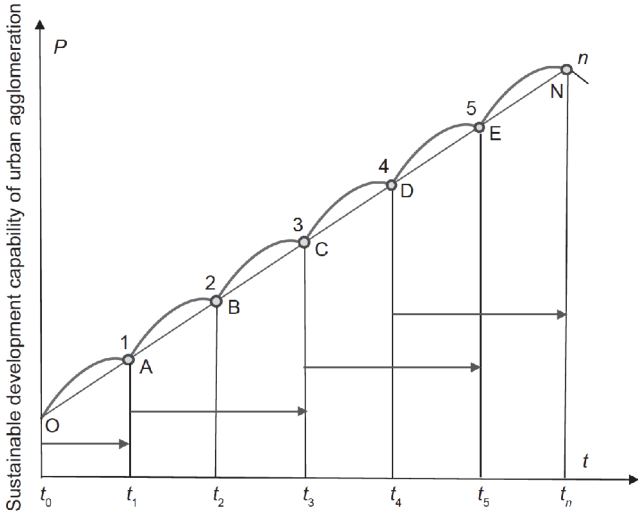

Figure 1 Schematic diagram of the evolution law of sustainable upgrade capability of urban agglomeration.

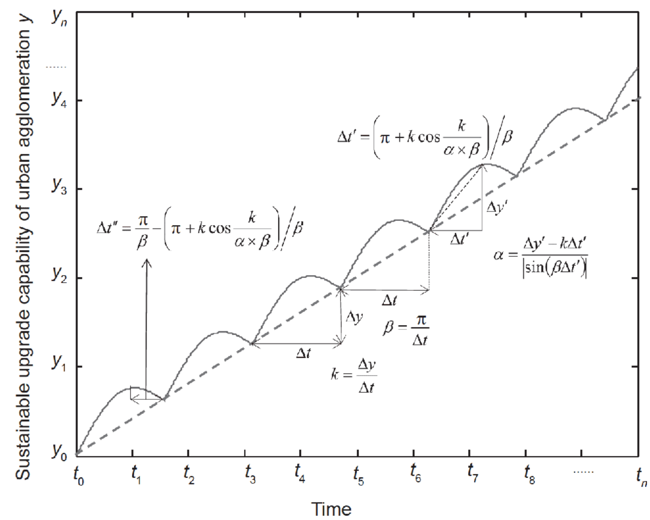

Figure 2 Quantitative analysis of the sustainable upgrade capability curve of urban agglomeration.

function curve formula can be expressed as:

$$y_t = k + |\alpha \sin(\beta t)|, \tag{1}$$

$$k = \frac{\Delta y}{\Delta t}, \tag{2}$$

where y_t represents the value of the sustainable upgrade capability of the urban agglomeration at time t; α is the amplitude of the trigonometric function indicating the antagonistic coefficient of synergistic development of urban agglomeration; β/π is the frequency of the trigonometric function; β represents the periodic coefficient of synergistic development of urban agglomeration; k is the slope of the linear function, called the upgrade rate, which represents the rate of change of a city's sustainable upgrade capability; and $\Delta t = \pi/\beta$ is the fluctuation period of the function.

2.2.2 *Calculation formula for optimization of sustainable upgrade capability curve of urban agglomeration*

The core cities of urban agglomerations have the ability to achieve sustainable development in the early stages of development. The paper assigns the core cities the values t_0 and y_0 for the initial time and initial sustainable development capability of the urban agglomeration respectively. The simulation curve of the sustainable upgrade capacity of the urban agglomeration is shown in Figure 2. The model of the upgrade function curve is optimized as:

$$y_t = y_0 + k(t - t_0) + \left|\alpha \sin(\beta(t - t_0))\right|, \tag{3}$$

$$y' = k + \alpha\beta\cos(\beta t - \beta t_0), \tag{4}$$

$$\Delta t'' = \frac{\pi}{\beta} - \left(\pi + k\cos\frac{k}{\alpha \times \beta}\right) / \beta, \tag{5}$$

where y' represents the expansion velocity of urban agglomeration; and $\Delta t''$ represents the time of antagonism in the development of the urban agglomeration.

When $(n-1) \times \frac{\pi}{\beta} < t < (n-1) \times \frac{\pi}{\beta} + \left(\pi + k\cos\frac{k}{\alpha \times \beta}\right) \div \beta$, the synergistic effect is significant between core city and n united cities in the urban agglomeration, and the core city is also affected by the small overflow effect of the surrounding cities.

When $(n-1) \times \frac{\pi}{\beta} + \left(\pi + k\cos\frac{k}{\alpha \times \beta}\right) \div \beta < t < n \times \frac{\pi}{\beta}$, the core city in the urban agglomeration unites with the (n+1)th city for synergistic development, and there is a relatively obvious antagonistic effect at the end stage of joint development of the city.

2.2.3 *Quantitative analysis of sustainable upgrade rate of urban agglomeration*

There is a specific interval for the sustainable upgrade rate of urban agglomerations, namely between the minimum upgrade rate and the maximum upgrade rate. During the initial development period of urban agglomeration, there is no connection between the core city and surrounding cities, but the core city can itself achieve sustainable development, making the minimum upgrade rate 0 at this time. The maximum upgrade value refers to the maximum value of sustainable development capability obtained by the core city of the urban agglomeration when uniting with n surrounding cities. Beyond this value, even the core city of the urban agglomeration unites with the (n+1)th city, and its sustainable development capability will not be improved further, having reached the maximum capacity of sustainable upgrade for the urban agglomeration. The maximum upgrade value of the urban agglomeration per unit time is called the "maximum upgrade rate of the sustainable development capability of the urban agglomeration". The formula is:

$$k_{\max} = \frac{\max\Delta y}{\Delta t}, k_{\min} = \frac{\min\Delta y}{\Delta t}, \tag{6}$$

$$\overline{k} = \frac{\Delta y_t - \Delta y_{\min}}{\Delta y_{\max} - \Delta y_{\min}}, \tag{7}$$

$$s = (\sqrt[t-t_0]{\frac{y_t}{y_0}} - 1) \times 100, \tag{8}$$

where $\overline{k}$ represents the average rate of change of the sustainable upgrade of the urban agglomeration, that is, the average rate of upgrade; $k_{\max}$ represents the maximum rate of change of the sustainable upgrade of the urban agglomeration, that is, the maximum rate of upgrade; $k_{\min}$ represents the minimum rate of change of the sustainable upgrade of the urban agglomeration, that is, the minimum rate of upgrade; and S represents the sustainable upgrade rate of urban agglomerations during the period $t-t_0$.

3. The calculation of sustainable upgrade capability of Beijing-Tianjin-Hebei urban agglomeration

3.1 Measuring index system for sustainable upgrade capability of urban agglomerations

The indicators for sustainable city development are helpful in determining the performance level of strategies and policies implemented in the process of achieving sustainable development (Shen et al., 2011). Previous work built an indicator system from the multi-dimensional perspectives of economic, social, and environmental development (Li and Zhang, 2014), resource security, innovation drives (Wu and Miao, 2017), government efficiency and people's lives (Zhang et al., 2014; Millennium Ecosystem Assessment, 2003). This paper establishes a measuring index system for the sustainable upgrade capability of urban agglomerations from three dimensions (economy, society, and environment), while taking into account the principles of a scientific, systematic, and comprehensive selection of indicators (Zeng and Bi, 2015). From the dimension of economy, six indicators are selected from two areas: the economic sustainable development level and the economic structure. From the dimension of society, nine indicators are selected from three areas: the population development and urbanization level, infrastructure, and social progress. From the dimension of environment, nine indicators are selected from three areas: environmental pollution, ecological construction, and recycling development. The specific measuring index system is shown in Table 1.

3.2 Calculation method of sustainable upgrade capability of urban agglomeration

In a comprehensive evaluation of the sustainable upgrade capability of urban agglomeration, standardized treatment methods are adopted to eliminate the influence of different dimensions and orders of magnitude on the evaluation indexes, so as to reduce the interference of random factors. In the weighting process of indexes, a 1–9 scale is adopted, and the principle of information entropy is adopted, which is the larger the entropy value, the more balanced the system structure, and the smaller the difference coefficient, the smaller the weight of the index. Finally, the comprehensive weight is calculated by averaging. The evaluation methods for the sustainable upgrade capability of urban agglomerations include the Delphi method (Huang et al., 2000), environmental sustainability index method (Du, 2006), and the DEA method (Zeng, 2000). In order to obtain relatively objective evaluation results, this paper combines the technique for order preference by similarity to an ideal solution concept and grey relation theory to construct a comprehensive evaluation model of sustainable upgrade capability of urban agglomerations and to approximate the degree between the sustainable upgrade capability of different cities and the ideal state in these areas, which can be reflected by Euclidean distance and the grey relation degree.

(1) Solve the weighted normalization matrix:

$$U = (u_{ij})_{m*n} = (w_j * x'_{ij})_{m*n} = \begin{bmatrix} u_{11} & u_{12} & \cdots & u_{1n} \\ u_{21} & u_{22} & \cdots & u_{2n} \\ \cdots & \cdots & \cdots & \cdots \\ u_{m1} & u_{m2} & \cdots & u_{mn} \end{bmatrix}. \tag{9}$$

(2) Determine the positive and negative ideal solutions for different cities:

$$\text{Positive ideal solution: } U^+ = \{u_{01}^+, u_{02}^+, ..., u_{0n}^+\}, \tag{10}$$

$$\text{Negative ideal solution: } U^- = \{u_{01}^-, u_{02}^-, ..., u_{0n}^-\}, \tag{11}$$

where the positive ideal solution is the collection of ideal optimal values of indexes for the same city, and the negative ideal solution is the collection of the worst values of indexes for the same city.

(3) Solve the relative similarity degree of gray relation: Assume ρ_{ij}^+ is the grey relation coefficient between the j index and positive ideal solution in the i evaluation unit. u_{oj}^+ is the positive ideal value of the j index, ξ is the resolution coefficient; the significance of the difference between correlations can be improved. $\xi \in [0,1]$, and ξ is usually set to 0.5. The grey relation coefficient between the i index and positive ideal solution in the j evaluation unit is

$$\rho_{ij}^+ = \frac{\min\limits_{1\le j\le n}\min\limits_{1\le i\le m}\left(\left|u_{oj}^+ - x'_{ij}\right|\right) + \xi\max\limits_{1\le j\le n}\max\limits_{1\le i\le m}\left(\left|u_{oj}^+ - x'_{ij}\right|\right)}{\left|u_{oj}^+ - x'_{ij}\right| + \xi\max\limits_{1\le j\le n}\max\limits_{1\le i\le m}\left(\left|u_{oj}^+ - x'_{ij}\right|\right)}. \tag{12}$$

Table 1 Measuring index system for sustainable upgrade capability of urban agglomeration

Criteria layer	Sub-criteria layer	Indicator layer
Economic sustainable upgrade capability	Economic continuous development level	GDP (%)
		GDP growth rate (Yuan)
		Per capita GDP (100 Million Yuan)
	Economic structure	Proportion of value-added of tertiary industry (%)
		Proportion of fixed assets investment in GDP (%)
		Proportion of total retail sales of social consumer goods in GDP (%)
Social sustainable upgrade capability	Population development and urbanization level	Natural growth rate (%)
		Population density (Person per square kilometer)
		Urbanization level (%)
	Infrastructure	Number of health workers and technicians per 10,000 people (Ten thousand)
		Number of Internet users
		Total telecommunications business (100 Million Yuan)
	Social progress	Percentage of tertiary industry labor (%)
		Investment in research and development (100 Million Yuan)
		Number of college students per 10000 people
Environmental sustainable upgrade capability	Environmental pollution	Industrial wastewater discharge (10000 tons)
		Industrial SO_2 emissions (tons)
		$PM_{2.5}$ concentration (μg m^{-3})
	Ecological construction	Green coverage rate in built-up areas (%)
		Percentage of ecological space land area (%)
		Risk degree of ecosystem (%)
	Cyclic development	Percentage of sewage centralized treatment (%)
		Percentage of harmless treatment of domestic garbage (%)
		Percentage of urban wastewater treatment (%)

Then the grey relation coefficient matrix of each evaluation unit and the positive ideal solution is

$$p^+ = \begin{bmatrix} \rho_{11}^+ & \rho_{12}^+ & \cdots & \rho_{1n}^+ \\ \rho_{21}^+ & \rho_{22}^+ & \cdots & \rho_{2n}^+ \\ \cdots & \cdots & \cdots & \cdots \\ \rho_{m1}^+ & \rho_{m2}^+ & \cdots & \rho_{mn}^+ \end{bmatrix}. \quad (13)$$

The grey relation degree between the i evaluation unit and the positive ideal solution is

$$p_i^+ = \frac{\sum_{j=1}^{n} \rho_{ij}^+}{n}, \quad (i = 1, 2, ..., m). \quad (14)$$

Similarly, the grey relation between the i evaluation unit and the negative ideal solution is

$$p_i^- = \frac{\sum_{j=1}^{n} \rho_{ij}^-}{n}, \quad (i = 1, 2, ..., m). \quad (15)$$

The relative similarity degree of grey relation is

$$C_i = \frac{p_i^+}{p_i^- + p_i^+}. \quad (16)$$

The greater the degree of similarity, the higher the sustainable upgrade capability of the city in the period of interest, and the better the system conditions; conversely, the smaller the degree of similarity, the lower the sustainable upgrade capability of the city in the period of interest, and the worse the system conditions. After calculating the index value, the results are subjected to dimensionless processing using standardized processing methods. The sustainable upgrade capability index is the arithmetic mean of the economic, social, and environmental sustainable upgrade capability index values.

3.3 Analysis of calculation results of sustainable upgrade capability and upgrade speed of urban agglomeration

Using the above formulas, the economic, social, and environmental sustainable upgrade capability and comprehensive sustainable upgrade capability of thirteen cities above the prefecture level in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015 were calculated.

3.3.1 Analysis of economic sustainable upgrade capability and upgrade speed

From 2000 to 2015, the economic sustainable upgrade capability of the Beijing-Tianjin-Hebei urban agglomeration showed a wave-like upward trend. The economic sustainable upgrade capability index increased from 70.03 in 2000 to 100 in 2015, and the average annual upgrade speed during the 15-year period was 2.4%. The economic sustainable upgrade capability of the thirteen cities showed an overall upward trend, but the upgrade amplitude and speed showed significant differences, where the economic sustainable upgrade capability index of Beijing, Langfang, Tianjin and Hengshui in 2015 reached 100, 95.57, 91.59 and 84.83, respectively. The average upgrade speed in 2000–2015 was 2.4%, 2.74%, 2.11% and 2.07%, respectively. The economic sustainable upgrade capability in Zhangjiakou and Xingtai was the lowest, and the upgrade capability index values were only 63.72 and 63.86, respectively. The upgrade speed in Chengde was the slowest (Figure 3), and the average upgrade speed was only 0.07% over the years.

3.3.2 *Analysis of social sustainable upgrade capability and upgrade speed*

From 2000 to 2015, the social sustainable upgrade capability of the Beijing-Tianjin-Hebei urban agglomeration showed an upward trend. The social sustainable upgrade capability index increased from 76.8 in 2000 to 98.46 in 2015, and the average annual upgrade speed during the 15-year period was 1.67%. The social sustainable upgrade capability of the thirteen cities showed an overall upward trend, but the upgrade amplitude and speed showed significant differences, where the sustainable upgrade capability index of Beijing and Tianjin in 2015 reached 100 and 83.4, respectively; the average upgrade speed in 2000–2015 was 1.78% and 1.25%, respectively. The social sustainable upgrade capability in Chengde was the lowest (63.42), and the upgrade speed in Zhangjiakou was the slowest (0.34%) (Figure 4).

3.3.3 *Analysis of environmental sustainable upgrade capability and upgrade speed*

From 2000 to 2015, the environmental sustainable upgrade capability of the Beijing-Tianjin-Hebei urban agglomeration showed an upward trend. The environmental sustainable upgrade capability index increased from 83.31 in 2000 to 98.13 in 2015, and the average annual upgrade speed during the 15-year period was 1.1%. The environmental sustainable upgrade capability of the thirteen cities showed an overall upward trend, but the upgrade amplitude and speed showed significant differences, where the environmental sustainable upgrade capability index of Chengde, Beijing and Zhangjiakou in 2015 reached 99.85, 98.13 and 94.38, respectively; the average upgrade speed in 2000–2015 was 1.09%, 1.29% and 1.19%, respectively. The environmental sustainable upgrade capability in Hengshui was the lowest (72.46), and the upgrade speed in Qinhuangdao was the slowest (0.56%) (Figure 5).

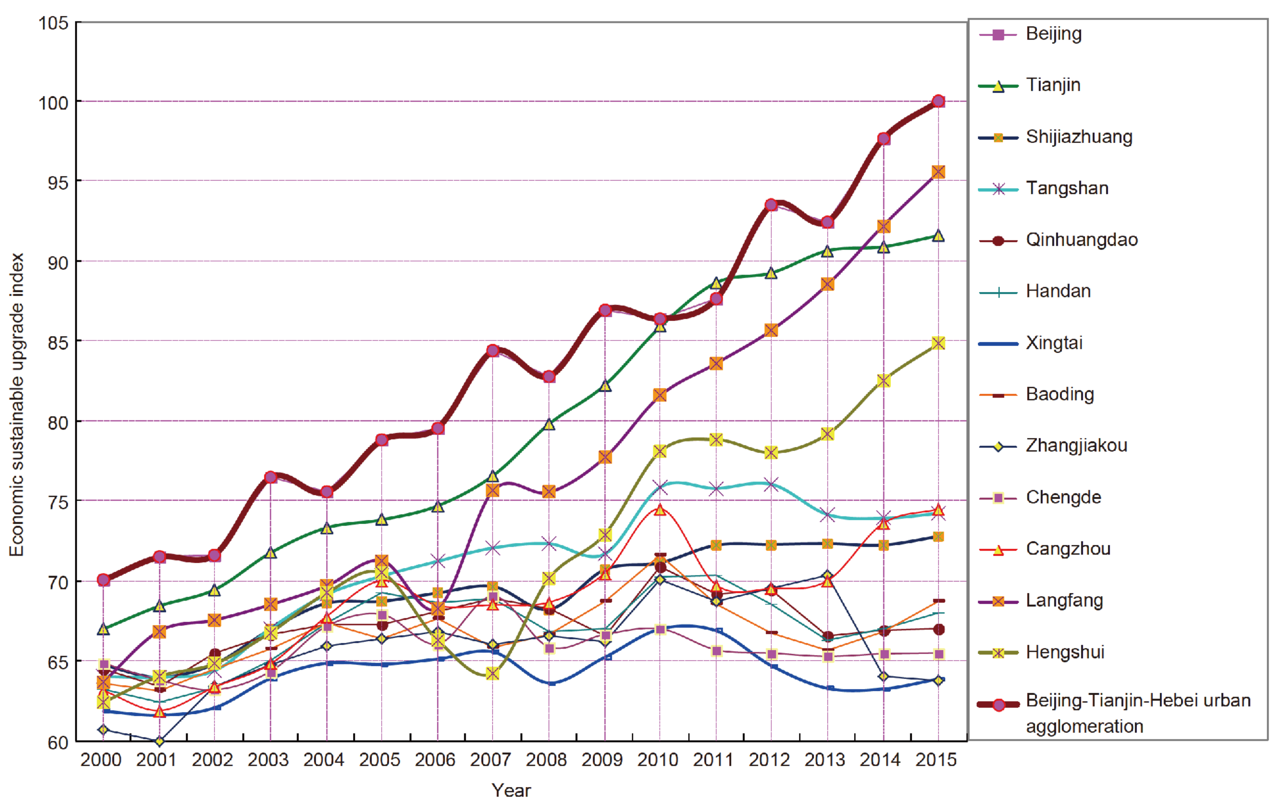

Figure 3 Change in economic sustainable upgrade capability of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

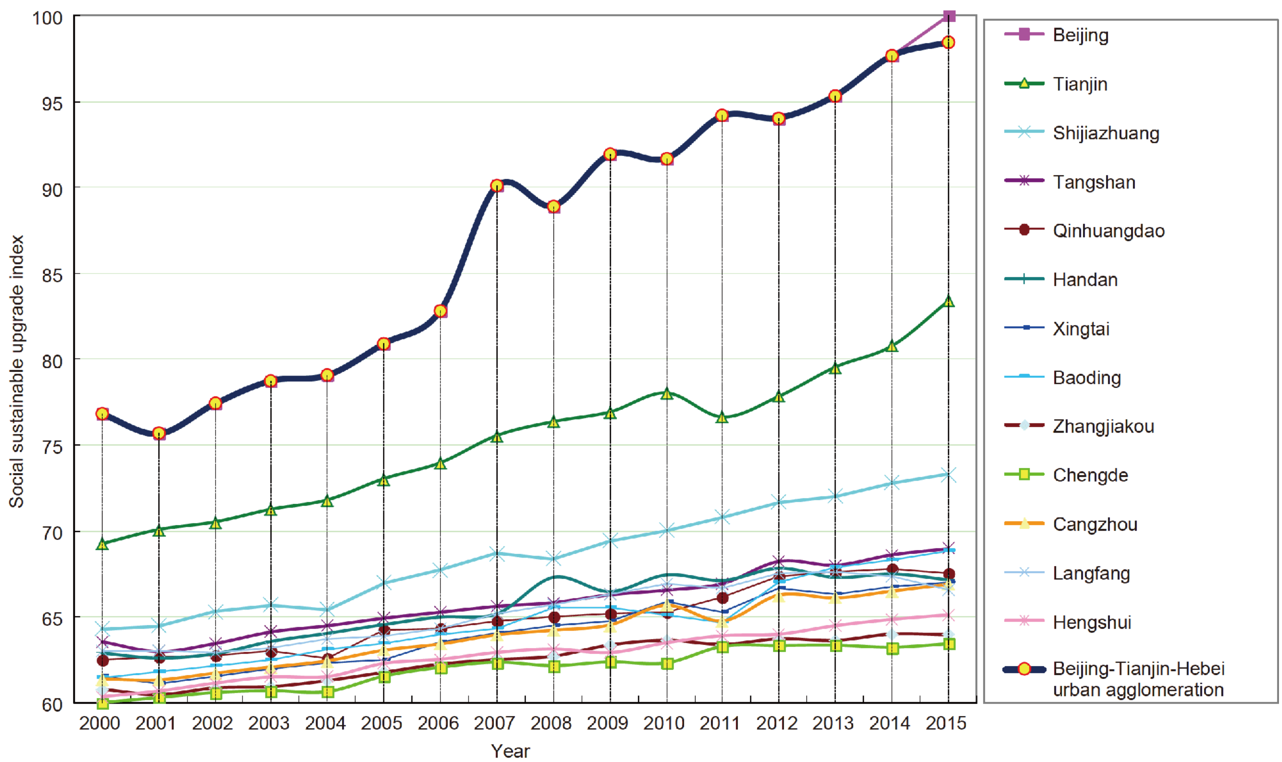

Figure 4 Change in social sustainable upgrade capability of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

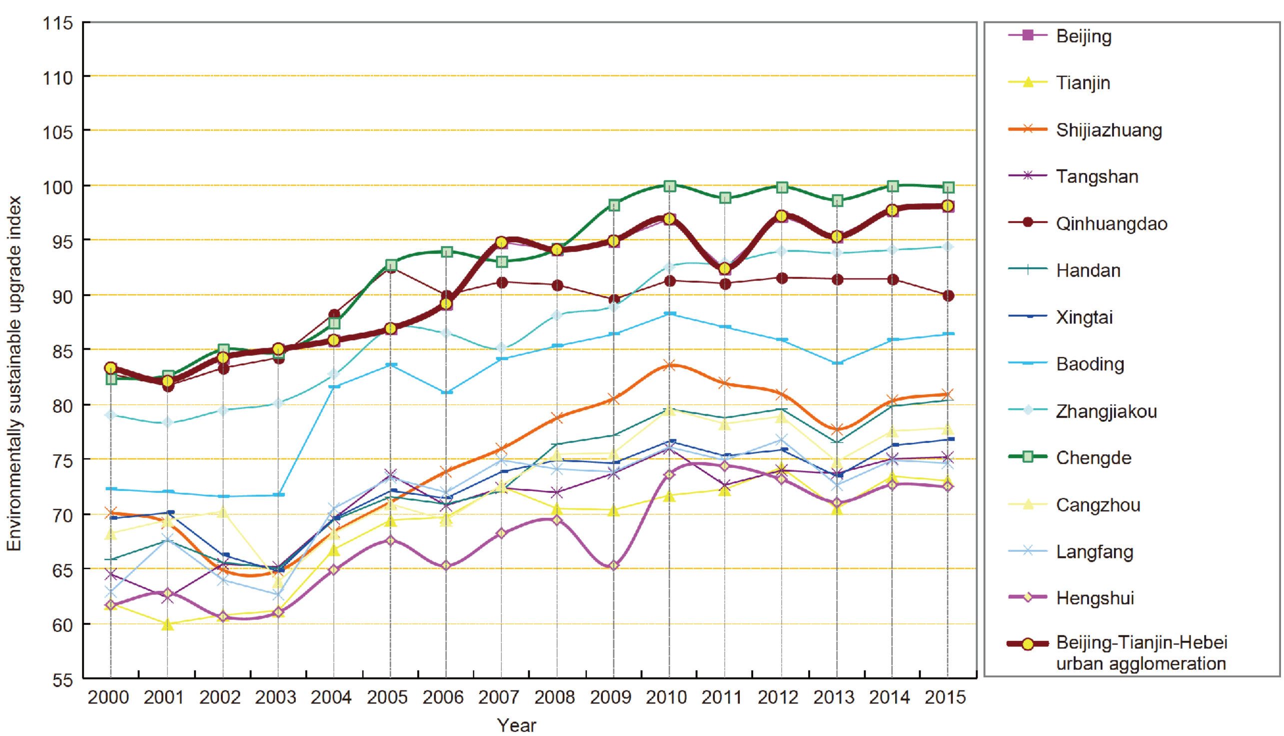

Figure 5 Change in environmental sustainable upgrade capability of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

3.3.4 Analysis of comprehensive sustainable upgrade capability and upgrade speed

The comprehensive sustainable upgrade capability of the Beijing-Tianjin-Hebei urban agglomeration showed an overall upward trend (Table 2), from 76.71 in 2000 to 99.38 in 2015, and the average annual upgrade speed during the 15-year period was 1.74%. Comprehensive sustainable upgrade capability of thirteen cities showed an overall upward trend, but the upgrade amplitude and speed showed significant differences, where the comprehensive sustainable upgrade capability index of Beijing and Tianjin in 2015 reached 99.38 and 82.67, respectively; the average upgrade speed in 2000–2015 was 1.74% and 1.51%, respectively. The comprehensive sustainable upgrade capability in Xingtai was the lowest (69.22), and the upgrade speed in Qinhuangdao was the slowest (0.45%) (Figure 6).

4. Quantitative analysis of sustainable upgrade intensity of Beijing-Tianjin-Hebei urban agglomeration

4.1 Unite strength and unite threshold of sustainable upgrade of urban agglomerations

4.1.1 Unite strength of sustainable upgrade of urban agglomeration

The unite strength of the sustainable upgrade between cities

Table 2 Calculation of comprehensive sustainable upgrade capability index of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average annual upgrade speed (%)
Beijing	76.71	76.16	77.76	80.06	80.14	82.19	83.88	89.76	88.61	91.26	91.67	91.39	94.90	94.37	97.68	99.38	1.74
Tianjin	65.99	66.16	66.90	68.03	70.62	72.07	72.76	74.87	75.52	76.48	78.56	79.16	80.44	80.22	81.68	82.67	1.51
Shijiazhuang	66.36	65.87	64.98	65.81	67.44	68.90	70.26	71.41	71.78	73.54	74.89	74.98	74.96	74.04	75.11	75.65	0.87
Tangshan	64.01	63.10	64.42	65.41	67.70	69.57	69.08	70.00	70.05	70.54	72.81	71.75	72.73	71.95	72.51	72.77	0.86
Qinhuangdao	69.92	69.24	70.53	71.31	72.72	74.63	74.13	74.93	74.70	73.77	75.79	75.48	76.11	75.21	75.37	74.82	0.45
Handan	63.96	64.20	63.87	64.51	66.92	68.44	68.15	68.71	70.14	70.24	72.39	72.06	71.95	70.04	71.46	71.82	0.78
Xingtai	64.32	64.25	63.28	63.51	65.59	66.43	66.67	67.81	67.67	68.17	69.83	69.14	69.07	67.66	68.74	69.22	0.46
Baoding	65.75	65.63	66.04	66.63	70.66	71.14	70.86	71.42	72.50	73.55	74.97	73.43	73.22	72.38	73.62	74.65	0.85
Zhangjiakou	66.83	66.26	67.89	68.60	69.96	71.65	71.84	71.19	72.46	72.82	75.41	75.00	75.74	75.92	74.02	74.02	0.68
Chengde	69.05	68.89	69.58	69.92	71.74	74.07	74.00	74.82	74.07	75.75	76.43	75.94	76.22	75.76	76.19	76.25	0.66
Cangzhou	64.24	64.22	65.10	63.54	66.13	67.99	67.07	68.33	69.42	70.18	73.23	70.89	71.57	70.27	72.55	73.05	0.86
Langfang	63.19	65.82	64.78	64.75	67.98	69.48	68.18	71.91	71.80	72.63	74.86	75.03	76.67	76.25	78.15	78.92	1.49
Hengshui	61.46	62.48	62.17	63.08	65.19	66.75	64.67	65.11	67.55	67.03	71.72	72.37	71.72	71.57	73.33	74.13	1.26
Beijing-Tianjin-Hebei urban agglomeration	76.71	76.16	77.76	80.06	80.14	82.19	83.88	89.76	88.61	91.26	91.67	91.39	94.90	94.37	97.68	99.38	1.74

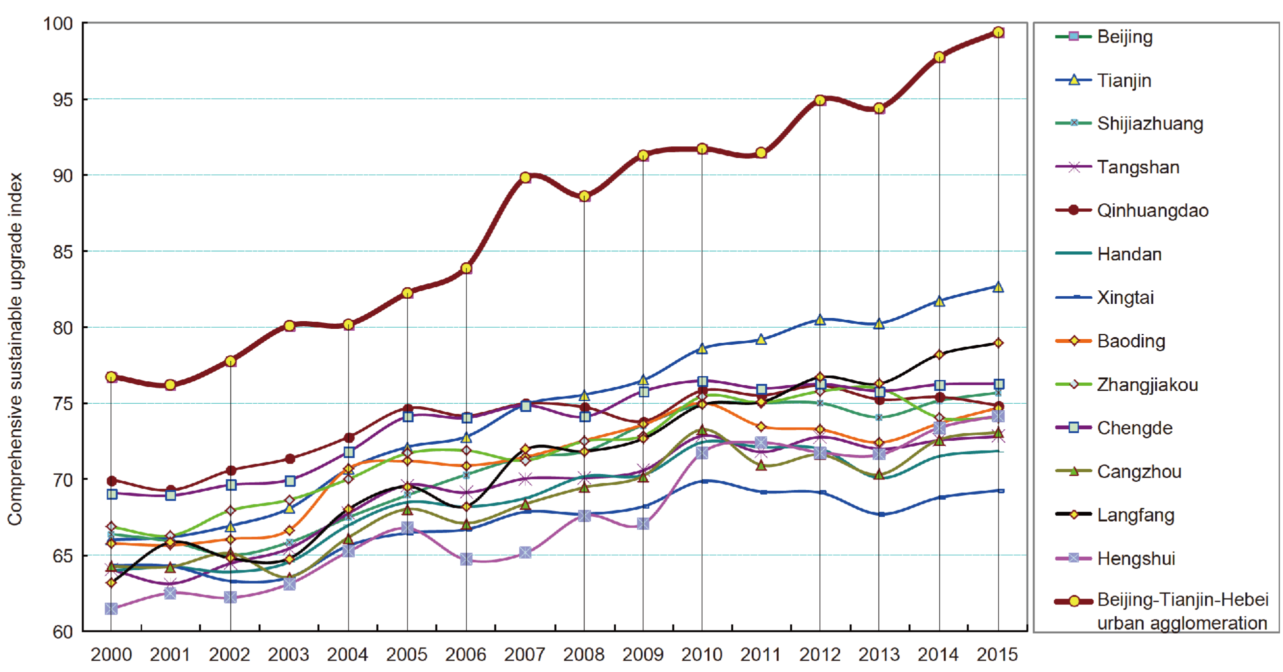

Figure 6 Change of comprehensive sustainable upgrade capability of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

is positively correlated with the economic scale of the city, and negatively correlated with the distance between cities. The unite strength of the sustainable upgrade of urban agglomerations can be reflected through establishing an upgrade intensity model between cities. The unite strength model and the comprehensive unite strength model of economic, social, and environmental sustainable upgrade in the Beijing-Tianjin-Hebei urban agglomeration are as follows:

$$\left.\begin{aligned} f_{ij} &= \frac{\sqrt{P_i \cdot P_j} \cdot \sqrt{G_i \cdot G_j}}{d_{ij}^2} \\ f'_{ij} &= \frac{\sqrt{P'_i \cdot P'_j} \cdot \sqrt{G'_i \cdot G'_j}}{d_{ij}^2} \\ f''_{ij} &= \frac{\sqrt{P''_i \cdot P''_j} \cdot \sqrt{G''_i \cdot G''_j}}{d_{ij}^2} \end{aligned}\right\}, \quad (17)$$

$$\left.\begin{aligned} F_{ij} &= \frac{f_{ij} - \min(f_{ij})}{\max(f_{ij}) - \min(f_{ij})} \times 100 \\ F'_{ij} &= \frac{f'_{ij} - \min(f'_{ij})}{\max(f'_{ij}) - \min(f'_{ij})} \times 100 \\ F''_{ij} &= \frac{f''_{ij} - \min(f''_{ij})}{\max(f''_{ij}) - \min(f''_{ij})} \times 100 \end{aligned}\right\}, \quad (18)$$

$$F'''_{ij} = \frac{F_{ij} + F'_{ij} + F''_{ij}}{3}, \quad (19)$$

where F_{ij} and f_{ij} represent the unite strength of the economic sustainable upgrade of city i and city j; F'_{ij} and f'_{ij} represent the unite strength of the social sustainable upgrade of city i and city j; F''_{ij} and f''_{ij} represent the unite strength of the environmental sustainable upgrade of city i and city j. f_{ij}, f'_{ij} and f''_{ij} are the index values; F_{ij}, F'_{ij} and F''_{ij} are the standardized values. F'''_{ij} represents the unite strength of the comprehensive sustainable upgrade of city i and city j. P_i and P_j represent the population of city i and j, respectively; G_i and G_j represent the GDP of city i and city j, respectively; P'_i and P'_j represent the population of city i and city j, respectively; G'_i and G'_j represent the urban population of city i and city j, respectively; P''_i and P''_j represent the population of city i and city j, respectively; G''_i and G''_j represent the urban domestic wastewater discharge of city i and city j, respectively; and d_{ij} is the distance between city i and city j.

4.1.2 Unite threshold for sustainable upgrade of urban agglomerations

The unite strength of sustainable upgrade between cities can be calculated by a gravity model. Half the unite threshold of the urban economic, social and environmental sustainable upgrade and the average value of the comprehensive unite strength, that is η_{ij}, η'_{ij}, η''_{ij} and η'''_{ij}, are adopted for measuring the unite threshold of the economic sustainable upgrade, unite threshold of the social sustainable upgrade, unite threshold of the environmental sustainable upgrade, and the unite threshold of the sustainable upgrade of urban agglomeration. The formula is as follows:

$$\left.\begin{aligned} \eta_{ij} = \frac{1}{2} \times \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} F_{ij}}{i \times j}, \quad \eta'_{ij} = \frac{1}{2} \times \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} F'_{ij}}{i \times j} \\ \eta''_{ij} = \frac{1}{2} \times \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} F''_{ij}}{i \times j}, \quad \eta'''_{ij} = \frac{1}{2} \times \frac{\sum_{i=1}^{m}\sum_{j=1}^{n} F'''_{ij}}{i \times j} \end{aligned}\right\}, \quad (20)$$

where η_{ij}, η'_{ij}, η''_{ij} and η'''_{ij} represent the urban economic unite development threshold, the social unite development threshold, the environmental unite development threshold, and the comprehensive unite development threshold, respectively. F_{ij}, F'_{ij}, F''_{ij} and F'''_{ij} represent the economic, social, environmental, and comprehensive unite strengths of city i and city j. i represents the number of years evaluated, and j the number of cities evaluated.

4.2 Analysis of unite strength calculation results for sustainable upgrade of Beijing-Tianjin-Hebei urban agglomeration

4.2.1 Analysis of economic unite strength and unite threshold

According to the analysis of the economic unite strength of Beijing-Tianjin-Hebei urban agglomeration (Figures 7 and 8), in the development process of Beijing, due to the limitation in local resources and the market, to enhance its economic sustainable upgrade capability, Beijing jointly developed with Tianjin and Langfang before 2000, Baoding and Tangshan in 2005, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2011, and Chengde in 2014. By 2015, the comprehensive unite strength between Beijing and four cities (Handan, Qinhuangdao, Hengshui and Xingtai) was still lower than the unite threshold of 5.03. These four cities are relatively far from Beijing, offering no substantial contribution to Beijing's sustainable upgrade capability; this shows that Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration, has no close economic and technological links with the four cities, and theoretically, the cities can be excluded from the Beijing-Tianjin-Hebei urban agglomeration.

4.2.2 Analysis of social unite strength and unite threshold

The social unite strength analysis of the Beijing-Tianjin-Hebei urban agglomeration (Figures 9 and 10) shows the

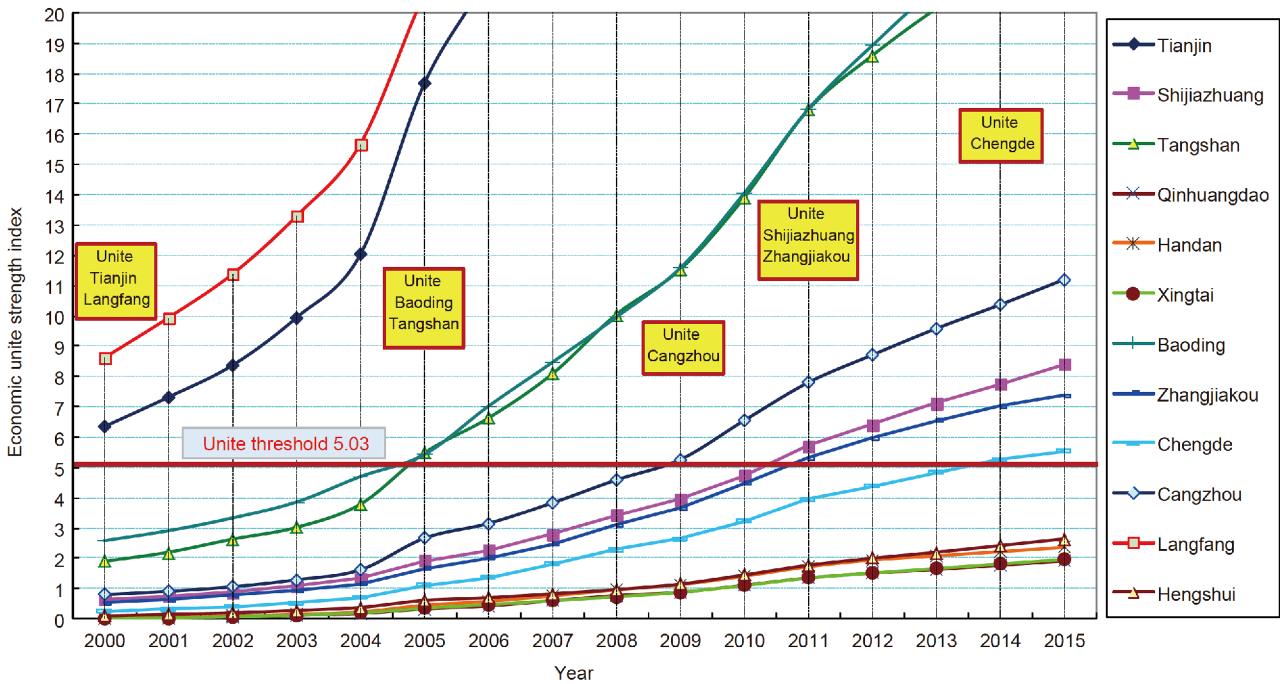

Figure 7 Change of the economic unite strength between Beijing and other cities in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

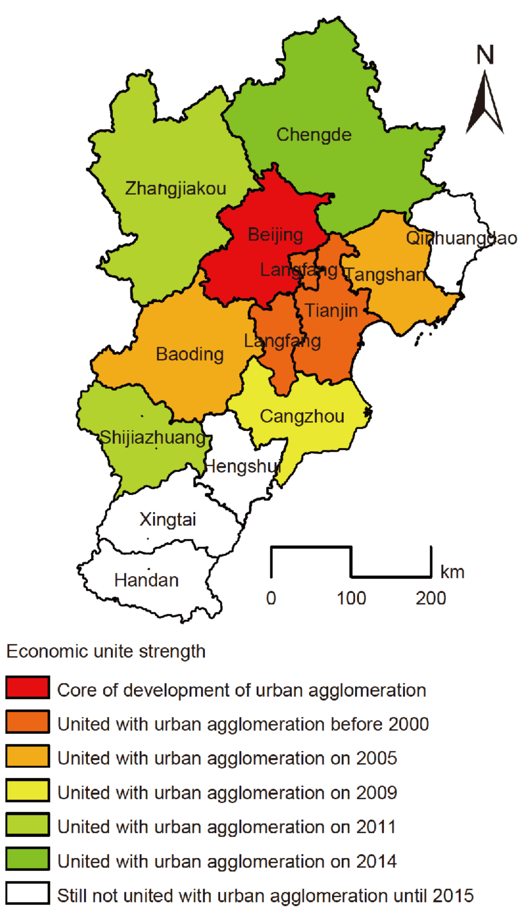

Figure 8 Schematic diagram of economic unite strength of Beijing-Tianjin-Hebei urban agglomeration.

social sustainable upgrade capability index and the unite development process of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015. Regarding Beijing's social development, because of a high local population density and limited social resources, to enhance the social sustainable upgrade capability of its society, Beijing jointly developed with Tianjin, Langfang and Baoding before 2000, Tangshan in 2002, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2011, and Chengde in 2013. By 2015, the social unite strength between Beijing and the four cities of Handan, Qinhuangdao, Hengshui, Xingtai and Chengde was still lower than the unite threshold of 7.58. These five cities are relatively far from Beijing and offer no substantial contribution to Beijing's social sustainable upgrade capability. This shows that Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration, has no close social connection with these five cities.

4.2.3 Analysis of environmental unite strength and unite threshold

According to the analysis of the environmental unite strength of the Beijing-Tianjin-Hebei urban agglomeration (Figures 11 and 12), in the process of environmental protection and ecological construction in Beijing, due to the high efficiency of joint prevention and control of local cross-regional, inter-organizational and inter-disciplinary areas, as well as a high local population density and limited social resources, Beijing, to enhance the social sustainable upgrade capability of its society, jointly developed with Tianjin, Langfang and

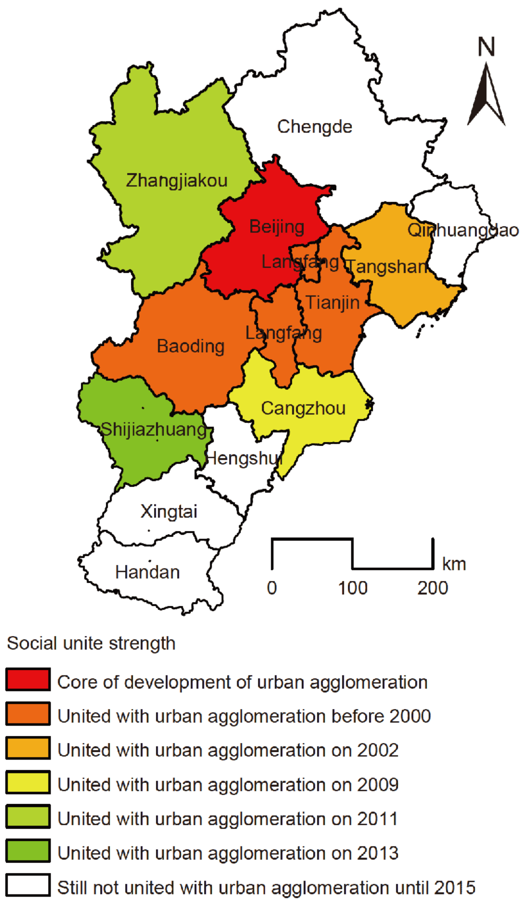

Figure 9 Schematic diagram of social unite strength of Beijing-Tianjin-Hebei urban agglomeration.

Baoding before 2000, Tangshan in 2002, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2012, and Chengde in 2014. By 2015, the environmental unite strength between Beijing and the four cities Handan, Qinhuangdao, Hengshui and Xingtai was still lower than the unite threshold of 5.53. These four cities are relatively far from Beijing and offer no substantial contribution to Beijing's environmental sustainable upgrade capability; this shows that Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration, has no close environmental connection with these six cities.

4.2.4 Analysis of comprehensive unite strength and unite threshold

According to the analysis of the comprehensive unite strength of the Beijing-Tianjin-Hebei urban agglomeration (Table 3, Figures 13 and 14), in the process of economic and social development and environmental protection in Beijing, due to local resources, space and market restrictions, etc., to enhance its sustainable upgrade capability, Beijing jointly developed with Tianjin, Langfang and Baoding before 2000, Tangshan in 2002, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2012, and Chengde in 2014. By 2015, the social unite strength between Beijing and the four cities, Handan, Qinhuangdao, Hengshui and Xingtai was still lower than the unite threshold of 6.05. These four cities are relatively far from Beijing and offer no substantial contribution to Beijing's sustainable upgrade capability; this shows that Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration, has no close economic or social, ecological, and environmental links with these four cities.

5. Simulation and verification of the sustainable upgrade curve of the Beijing-Tianjin-Hebei urban agglomeration

5.1 Analysis of change in the sustainable upgrade curve of urban agglomeration

As shown in the results, the economic sustainable upgrade capability index of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015 increased from 70.03 to 100, the social sustainable upgrade capability index increased from 76.8 to 98.46, the environmental sustainable upgrade capability index increased from 83.31 to 98.13, and the comprehensive sustainable upgrade capability index increased from 76.71 to 99.38 (Table 4). The average annual upgrade speed during the 15-year period was 2.4%, 1.67%, 1.10%, and 1.74%, respectively. The economic sustainable upgrade capability index was the lowest in 2000, but the upgrade speed was fast, indicating that the cities in the Beijing-Tianjin-Hebei urban agglomeration accelerated their economic development through unification. The integration of industrial development and layout was good, but in contrast, the environmental sustainable upgrade capability index was highest in 2000; but the upgrade speed was the slowest, indicating that improvement in the environmental quality of the cities in the Beijing-Tianjin-Hebei urban agglomeration was relatively slow, and that the integration of ecological construction and environmental protection in the urban agglomeration required further improvement. The social sustainable upgrade capability was in the mid-range, indicating that integration of the social development and basic public service desks of the urban agglomeration was at a medium level, leaving much room for improvement in future integrated development. The economic, social, environmental, and comprehensive sustainable upgrade curves are shown in Figure 15.

5.2 Simulation and verification of sustainable upgrade curve of urban agglomeration

5.2.1 Simulation and verification of economic sustainable upgrade curve

According to the long-term sequence index value of the economic sustainable upgrade capability of Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration

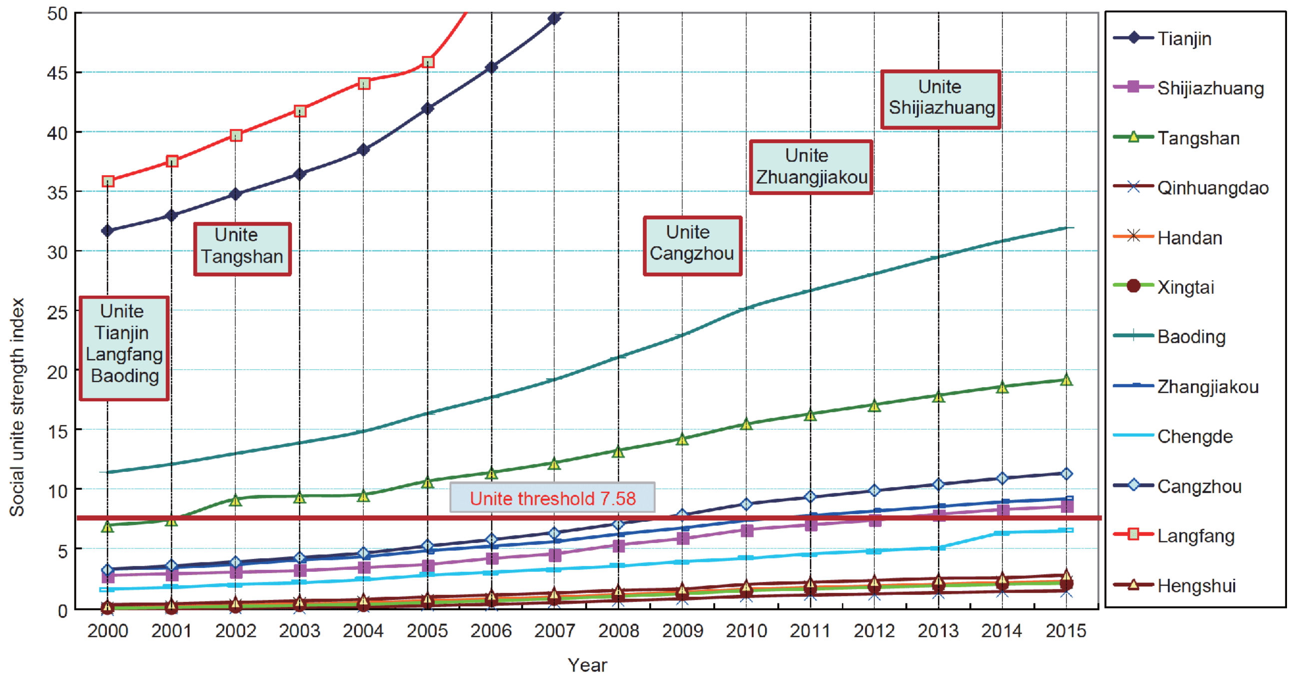

Figure 10 Change trend of social joint strength between Beijing and other cities in Beijing Tianjin Hebei Urban Agglomeration from 2000 to 2015.

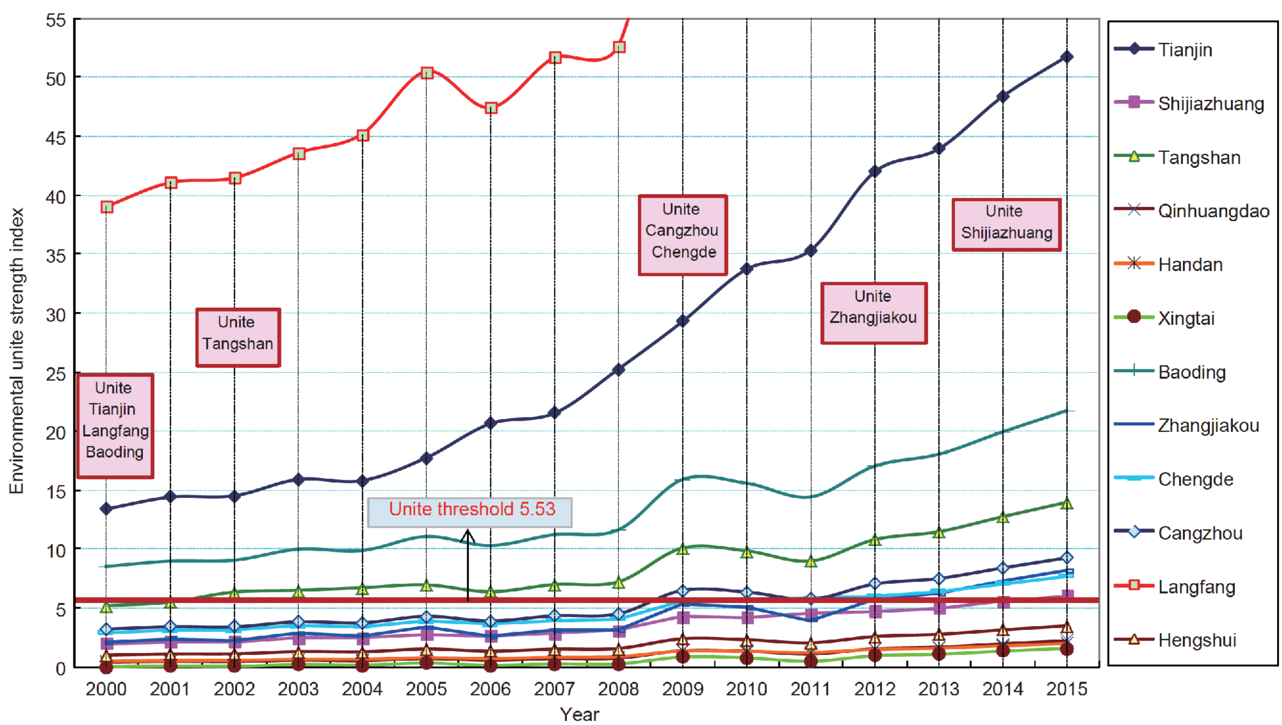

Figure 11 Change trend of environmental joint strength between Beijing and other cities in Beijing Tianjin Hebei Urban Agglomeration from 2000 to 2015.

from 2000 to 2015, multiple upgrade curves were fitted using the economic sustainable upgrade function, $y_t = y_0 + k(t - t_0) + |\alpha\sin(\beta(t - t_0))|$, to obtain the optimum function for the economic sustainable upgrade curve of the Beijing-Tianjin-Hebei urban agglomeration, as follows:

$$y_t = -404.1 + 0.2565 \times (t - 125.3) + |0.5438\sin(0.4467(t - 125.3))|. \qquad (21)$$

According to the economic sustainable upgrade function curve formula of the urban agglomeration, the simulated economic upgrade curve is shown in Figure 16. The program

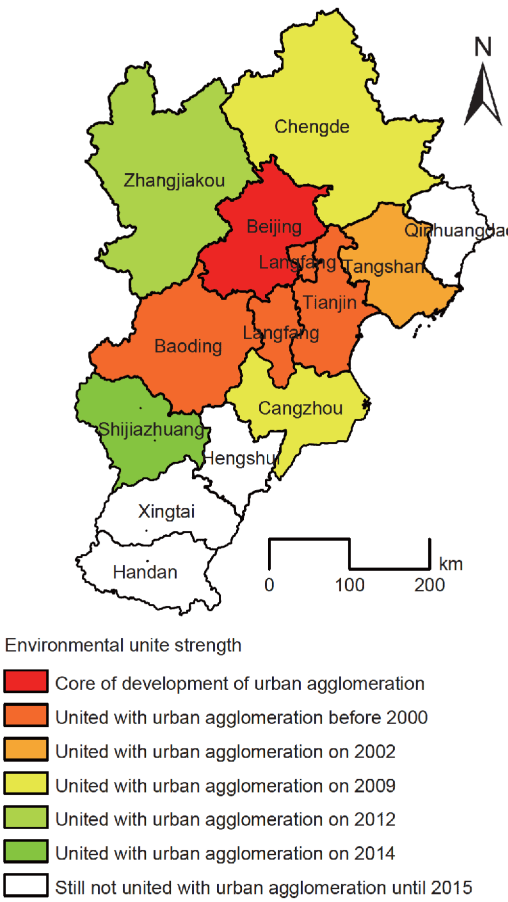

Figure 12 Schematic diagram of environmental unite strength of Beijing-Tianjin-Hebei urban agglomeration.

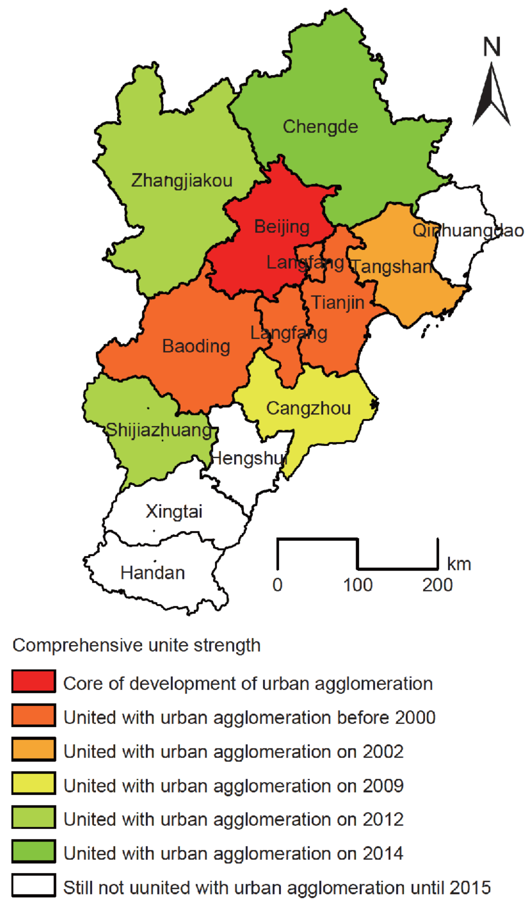

Figure 13 Schematic diagram of comprehensive unite strength of Beijing-Tianjin-Hebei urban agglomeration.

Table 3 Calculation of comprehensive unite strength of Beijing and other cities in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015

Region	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Tianjin	17.13	18.22	19.19	20.75	22.09	25.75	29.08	32.33	37.62	43.21	50.48	56.85	64.25	69.18	76.27	80.83
Shijiazhuang	1.80	1.93	2.05	2.24	2.43	2.77	3.06	3.40	3.95	4.71	5.19	5.76	6.20	6.66	7.18	7.67
Tangshan	4.69	5.07	6.05	6.32	6.69	7.71	8.15	9.11	10.18	11.96	13.07	14.03	15.50	16.50	17.62	18.48
Qinhuangdao	0.13	0.17	0.20	0.27	0.30	0.43	0.46	0.61	0.73	1.04	1.17	1.20	1.43	1.55	1.72	1.88
Handan	0.21	0.26	0.32	0.40	0.47	0.63	0.71	0.86	1.01	1.29	1.46	1.58	1.78	1.91	2.07	2.21
Xingtai	0.02	0.08	0.11	0.20	0.24	0.40	0.42	0.57	0.68	0.99	1.13	1.16	1.42	1.55	1.73	1.90
Baoding	7.51	8.00	8.46	9.24	9.81	10.95	11.68	12.97	14.22	16.80	18.26	19.29	21.33	22.74	24.03	26.04
Zhangjiakou	1.96	2.16	2.26	2.61	2.71	3.28	3.27	3.74	4.13	5.25	5.65	5.69	6.64	7.13	7.74	8.26
Chengde	1.60	1.74	1.85	2.07	2.21	2.60	2.68	3.01	3.33	4.07	4.40	4.79	5.08	5.44	6.23	6.61
Cangzhou	2.44	2.64	2.80	3.14	3.34	4.07	4.28	4.85	5.41	6.54	7.22	7.62	8.54	9.16	9.90	10.60
Langfang	27.83	29.50	30.84	32.89	34.99	38.99	41.60	46.83	51.47	62.52	67.68	71.12	79.00	84.30	90.74	98.70
Hengshui	0.48	0.56	0.62	0.75	0.82	1.04	1.06	1.22	1.37	1.74	1.93	2.01	2.32	2.51	2.72	2.99

code is:

```
t=[2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015];
y=[68.63; 69.26; 70.15; 70.59; 69.91; 74.37; 76.74; 80.57; 78.98; 81.81; 81.44; 82.06; 88.57; 87.42; 91.10; 93.04];
p=fittype('y0+a*(t-t0)+abs(b*sin(c*(t-t0)))', 'independent', 't');
plot(f,t,y); f=fit(t,y,p).
```

As shown in Figure 16, the simulation curve of the economic sustainable upgrade function of the Beijing-Tianjin-Hebei urban agglomeration is very similar to the sustainable upgrade capacity curve of the agglomeration from 2000 to 2015, indicating that the simulation result of the economic

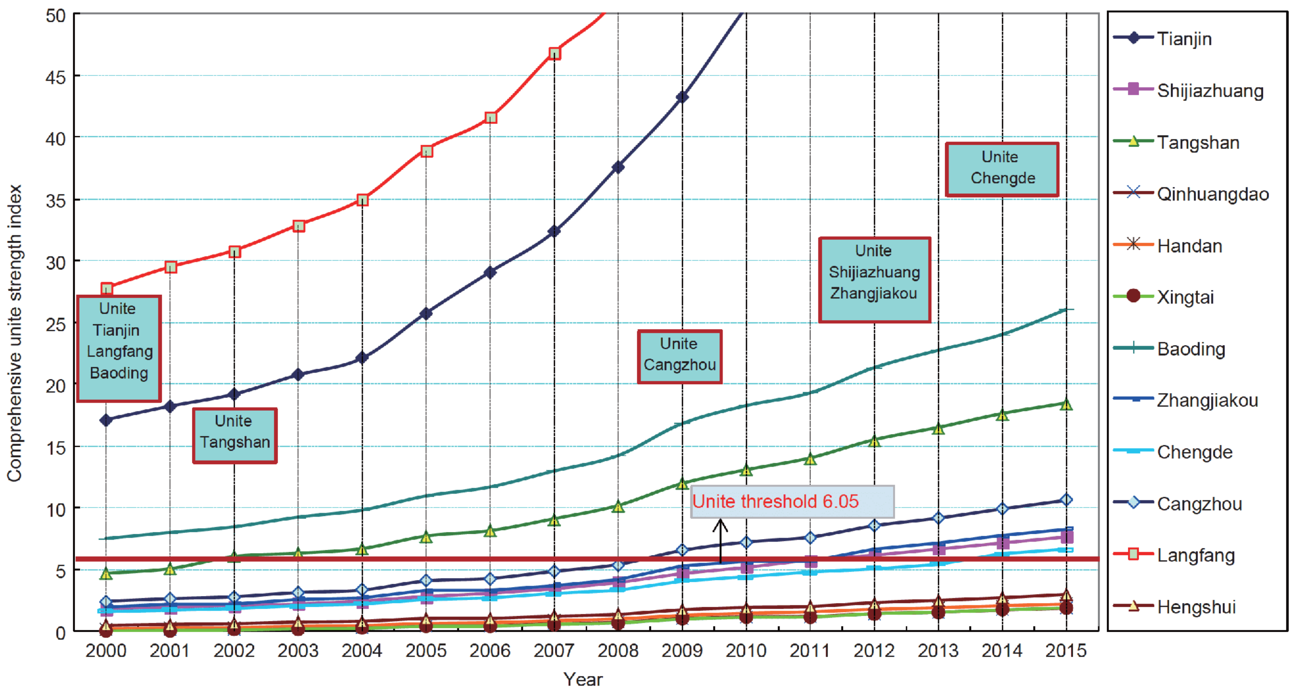

Figure 14 Change in comprehensive unite strength between Beijing and other cities in the Beijing-Tianjin-Hebei urban agglomerations from 2000 to 2015.

Table 4 Calculation of sustainable upgrade capability index of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015

Index	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	Average annual upgrade speed (%)
Economic sustainable upgrade index	70.03	71.47	71.64	76.45	75.52	78.78	79.56	84.37	82.8	86.92	86.38	87.62	93.49	92.47	97.62	100.0	2.40
Social sustainable upgrade index	76.80	75.65	77.39	78.74	79.07	80.91	82.84	90.08	88.94	91.91	91.70	94.17	94.06	95.36	97.67	98.46	1.67
Environmentally sustainable upgrade index	83.31	82.16	84.26	85.00	85.82	86.88	89.23	94.81	94.08	94.94	96.94	92.39	97.16	95.27	97.75	98.13	1.10
Comprehensive sustainable upgrade index	76.71	76.16	77.76	80.06	80.14	82.19	83.88	89.76	88.61	91.26	91.67	91.39	94.90	94.37	97.68	99.38	1.74

sustainable upgrade function curve is satisfactory, and that future economic sustainable upgrade capability can be predicted using the economic sustainable upgrade function model.

5.2.2 Simulation and verification of social sustainable upgrade curve

According to the long-term sequence index value of the social sustainable upgrade capability of Beijing, the core city of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015, multiple upgrade curves were fitted using the social sustainable upgrade function $y_t = y_0 + k(t - t_0) + |\alpha \sin(\beta(t - t_0))|$ to obtain the optimum function for the social sustainable upgrade curve, as follows:

$$y_t = -760.9 + 0.4318 \times (t - 45.69) + |1.643 \sin(0.1734(t - 45.69))|. \quad (22)$$

According to the social sustainable upgrade function curve formula of the urban agglomeration, the simulated social upgrade curve of the Beijing-Tianjin-Hebei urban agglomeration is shown in Figure 17.

The program code is:

```
t=[2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015];
y=[76.80; 75.65; 77.39; 78.74; 79.07; 80.91; 82.84; 90.08; 88.94; 91.91; 91.70; 94.17; 94.06; 95.36; 97.67; 100.00];
p=fittype('y0+a*(t-t0)+abs(b*sin(c*(t-t0)))', 'independent', 't'); plot(f,t,y);f=fit(t,y,p).
```

As shown in Figure 17, the simulation curve of the social sustainable upgrade function of the Beijing-Tianjin-Hebei

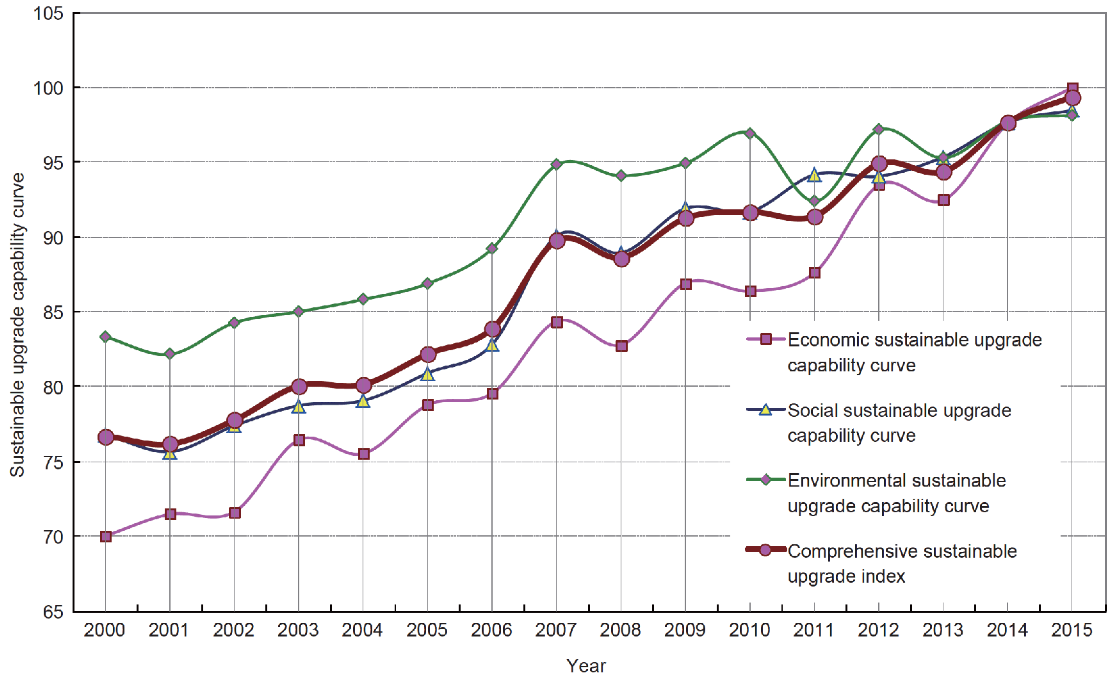

Figure 15 Schematic diagram of the sustainable upgrade curve of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

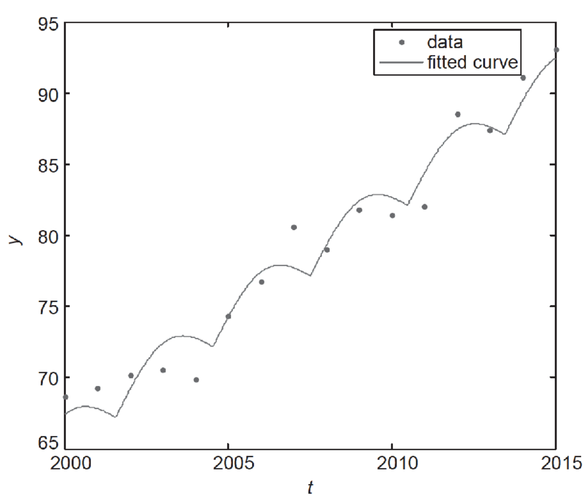

Figure 16 Simulation of economic sustainable upgrade curve of Beijing, as the core city in the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

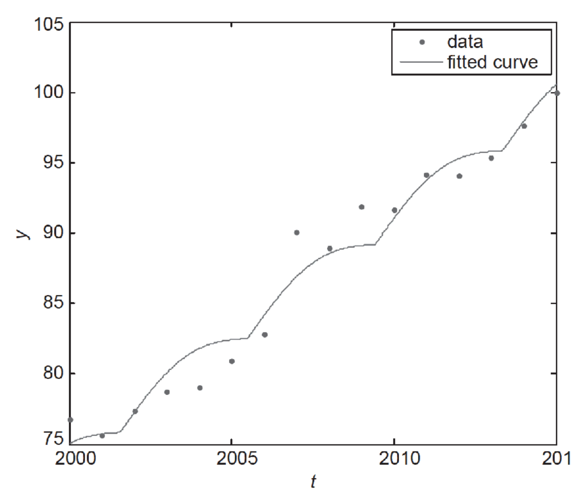

Figure 17 Simulation of social sustainable upgrade curve of Beijing, as the core city of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

urban agglomeration is very similar to the social sustainable upgrade capacity curve of the agglomeration from 2000 to 2015, indicating that the simulation result is satisfactory, and that future social sustainable upgrade capability can be predicted by the social sustainable upgrade function model.

5.2.3 Simulation and verification of environmental sustainable upgrade curve

According to the long-term sequence index value of the environmental sustainable upgrade capability of Beijing, the core city of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015, multiple upgrade curves were fitted using the environmental sustainable upgrade function, $y_t = y_0 + k(t - t_0) + \left|\alpha \sin(\beta(t - t_0))\right|$ to obtain the optimum function, as follows:

$$y_t = -1337 + 0.7853 \times (t - 190) + |0.6687 \sin(0.7511(t - 190))|. \quad (23)$$

According to the environmental sustainable upgrade function curve formula of the urban agglomeration, the simulated environmental upgrade curve is shown in Figure 18. The program code is

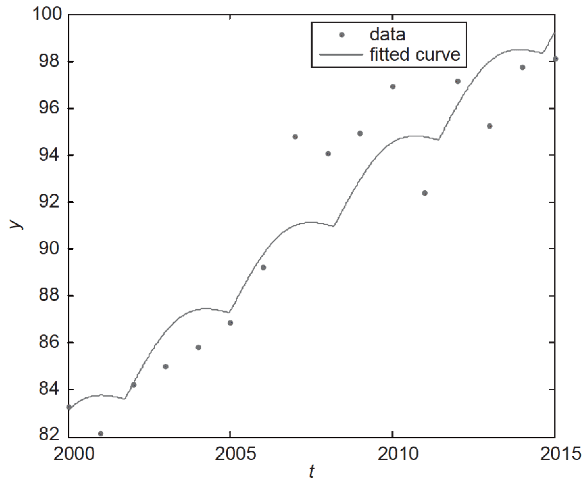

Figure 18 Simulation of environmental sustainable upgrade curve of Beijing, as the core city of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

t=[2000; 2001; 2002; 2003; 2004; 2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015];
y=[83.31; 82.16; 84.26; 85.00; 85.82; 86.88; 89.23; 94.81; 94.08; 94.94; 96.94; 92.39; 97.16; 95.27; 97.75; 98.13];
p=fittype('y0+a*(t-t0)+abs(b*sin(c*(t-t0)))', 'independent', 't');
plot(f,t,y);f=fit(t,y,p).

As shown in Figure 18, the simulation curve of the environmental sustainable upgrade function of the Beijing-Tianjin-Hebei urban agglomeration is very similar to the environmental sustainable upgrade capacity curve of the agglomeration from 2000 to 2015, indicating that the simulation result is satisfactory, and that future environmental sustainable upgrade capability of the agglomeration can be predicted using the environmental sustainable upgrade function model.

5.2.4 *Simulation and verification of comprehensive sustainable upgrade curve*

According to the long-term sequence index value of the comprehensive sustainable upgrade capability of Beijing, the core city of Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015, multiple upgrade curves were fitted using the comprehensive sustainable upgrade function $y_t = y_0 + k(t-t_0) + \left|\alpha\sin(\beta(t-t_0))\right|$to obtain the optimum function, as follows:

$$y_t = -2519 + 1.358*(t-89.34) + |0.5024\sin(0.9515(t-89.34))|. \quad (24)$$

According to the comprehensive sustainable upgrade function curve formula of the urban agglomeration, the simulated comprehensive upgrade curve of the Beijing-Tianjin-Hebei urban agglomeration is shown in Figure 19. The program code is

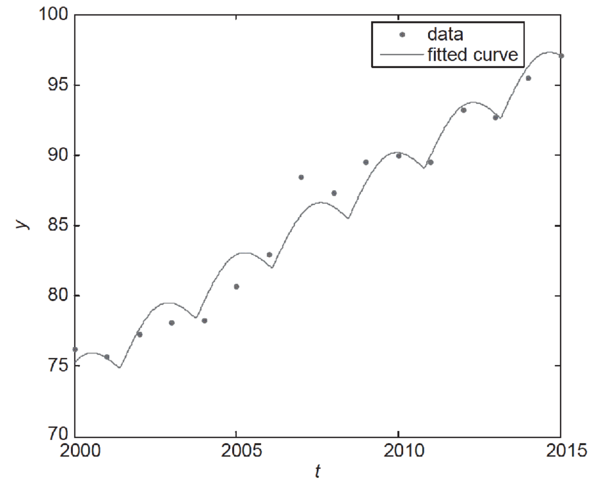

Figure 19 Simulation of comprehensive sustainable upgrade curve of Beijing, as the core city of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015.

t=[2000; 2001; 2002; 2003; 2004;2005; 2006; 2007; 2008; 2009; 2010; 2011; 2012; 2013; 2014; 2015];
y=[76.25; 75.69; 77.27; 78.11; 78.27; 80.72; 82.94; 88.49; 87.33; 89.55; 90.02; 89.54; 93.26; 92.68; 95.51; 97.06];
p=fittype('y0+a*(t-t0)+abs(b*sin(c*(t-t0)))', 'independent', 't');
plot(f,t,y);f=fit(t,y,p).

As shown in Figure 19, the simulation curve of the comprehensive sustainable upgrade function of the Beijing-Tianjin-Hebei urban agglomeration is very similar to the comprehensive sustainable upgrade capacity curve of the agglomeration from 2000 to 2015, indicating that the simulation result is satisfactory, and that future comprehensive sustainable upgrade capability of the agglomeration can be predicted using the comprehensive sustainable upgrade function model.

6. Discussion and conclusions

(1) An urban agglomeration is highly integrated, and the improvement in its sustainable development ability follows a wave gradient upgrade law. When a city cannot enhance its sustainable development capability, relying on its own ability, it will naturally unite with a second city for cooperation to continue to maintain its sustainable development capability; when the city can no longer maintain such a capability, it will naturally unite with a third city, and so on. Through continuously uniting with other cities, the city will form a community of sustainable development, and eventually develop into an urban agglomeration. Through geometric derivation, the sustainable upgrade law of urban agglomeration can be quantitatively expressed as a sustainable upgrade function curve, and the sustainable upgrade

speed, minimum upgrade rate, maximum upgrade value, and the maximum upgrade rate of urban agglomeration can be calculated. There is a maximum value for the sustainable upgrade capability of urban agglomeration that, when exceeded, prevents the improvement of sustainable development capability through the uniting of new cities. Therefore, the maximum number of cities for formation and development in an urban agglomeration can be determined.

(2) The sustainable upgrade capability of urban agglomerations includes the economic sustainable upgrade capability, social sustainable upgrade capability, environmental sustainable upgrade capability, and comprehensive sustainable upgrade capability. By establishing a sustainable upgrade capability measurement index system using TOPSIS and a grey relation method, after quantitative evaluation of the Beijing-Tianjin-Hebei urban agglomeration, it was found that the economic sustainable upgrade, social sustainable upgrade, environmental sustainable upgrade, and comprehensive sustainable upgrade capabilities of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015 all showed a wave-like rising trend. The average annual upgrade speeds over these years are, respectively, 2.4%, 1.67%, 1.1%, and 1.74%. The economic sustainable upgrade capability index value is the lowest in the early stage of upgrade, but the upgrade speed is high, which indicates that integration of the cities in the Beijing-Tianjin-Hebei urban agglomeration through uniting is satisfactory; on the contrary, the environmental sustainable upgrade capability index is the highest in the early stage of upgrade. However, the upgrade speed is the slowest, which indicates that the improvement in environmental quality of the cities in the urban agglomeration through uniting is slow; the integration of ecological construction and environmental protection needs to be further improved. The social sustainable upgrade capability derives from the economic sustainable upgrade capability and the environmental sustainable upgrade capability, which indicates that there is still much room for improvement in the integration of social development and basic public services of the Beijing-Tianjin-Hebei urban agglomeration.

(3) The unite strength and unite threshold of the sustainable upgrade of urban agglomerations can be calculated using the established inter-city unite strength model and unite threshold method. Studies have shown that the comprehensive unite strength of cities in urban agglomerations is increasing, but it is limited by the value of the unite threshold. Based on comprehensive unite strength analysis from 2000 to 2015, in order to enhance its sustainable upgrade capability, Beijing, as the core city of the Beijing-Tianjin-Hebei urban agglomeration, jointly developed with Tianjin, Langfang and Baoding before 2000, Tangshan in 2002, Cangzhou in 2009, Zhangjiakou and Shijiazhuang in 2012, and Chengde in 2014. By 2015, the comprehensive unite strength between Beijing and the four cities, Handan, Qinhuangdao, Hengshui and Xingtai, was still lower than the unite threshold of 6.14. These four cities are relatively far from Beijing, and offer no substantial contribution to the sustainable upgrade capability of Beijing, which indicates that the spatial composition of the Beijing-Tianjin-Hebei urban agglomeration may not include these four cities.

(4) The sustainable upgrade function curve of urban agglomerations has been verified in the Beijing-Tianjin-Hebei urban agglomeration. Through multiple fittings of upgrade curves using the long-term sequence index of the comprehensive sustainable upgrade capability of Beijing (the core city of the Beijing-Tianjin-Hebei urban agglomeration from 2000 to 2015), it was found that the simulated curve of the comprehensive sustainable upgrade function of the agglomeration is very similar to the curve of the comprehensive sustainable upgrade capability, which indicates that the simulation results of the comprehensive sustainable upgrade function are satisfactory. The future comprehensive sustainable upgrade capability of the agglomeration can be analyzed and predicted by the comprehensive sustainable upgrade function model. This study provides quantitative decision-supporting evidence for promoting the coordinated development of the Beijing-Tianjin-Hebei urban agglomeration, providing theoretical guidance and a computable model method for determining the number of joined cities with the sustainable development of national urban agglomerations.

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