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Sustainable Urban Development System Measurement Based on Dissipative Structure Theory, the Grey Entropy Method and Coupling Theory: A Case Study in Chengdu, China

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Abstract: With the rapid advancement of urbanization, the sustainable development of the city has received more and more attention. The measurement of the sustainable development of a city can provide an important reference for the development of the city. Therefore, this paper firstly constructs an index system for five dimensions: society, the economy, the environment, resources, and technology. Then, a sustainable development measurement model is established based on dissipative structure theory, grey entropy and coupling theory, and the evolution trend and coordinated development of the city are measured. Finally, Chengdu, an important central city in the western region of China, is selected for sustainable development measurement research, from which it was found that the city became more sustainable and more orderly, the development level was constantly improving, and the coordination was continuously improving, which was consistent with the actual situation and indicated that the proposed measurement model could effectively measure and evaluate sustainable urban development.

Keywords: urban sustainability; dissipative structure theory; grey entropy; coupling theory

1. Introduction

The world urbanization growth rate is expected to reach 60% by 2030 and 70% by 2050 [1], and the increasing urbanization growth rate has caused more and more residents to enter the city. As urban areas have grown, cities have become centers for social and economic development and the driving forces behind sustainable development efforts [2]. As urban changes inevitably affect a city's level of social development, economic growth, environmental change, resource consumption, and technological progress speed [3], it is a huge challenge to meet the needs of the current urban populations without compromising the needs of future generations [4]. Therefore, there has been increasing research focused on sustainable urban development. However, as sustainable urban development is a complex multi-dimensional system that has both external system and internal subsystem interactions [5], evaluating sustainable urban development is complex. To promote sustainable urban system development, it is necessary to assess the sustainability of existing practices, measure sustainable urban development system evolution, and analyze the impact mechanisms to ensure efficient, coordinated and orderly overall development.

As sustainable urban development assessments require a comprehensive, accurate approach and a scientific, rational index system, there has been significant academic research focused on index system construction and evaluation methods.

Due to different domestic and foreign situations and the differences in urban development levels, the construction of the sustainable urban development measurement indexes for measurement index systems has varied significantly. However, in general, urban sustainability has been based around the three dimensions of the economy, society, and the environment [6,7]. Mori et al. [8] established an index system to analyze the sustainability of these three systems and explored whether they were able to achieve simultaneous sustainability, and Ghalib et al. [9] developed indexes for these three systems based on second-hand data collected from 2004 to 2014 to establish a reasonable index system to evaluate the sustainable urban development in Lahore, Rawalpindi. As research deepened, there have been attempts to develop a more comprehensive evaluation index system. For example, Tanguay et al. [10] and Zheng et al. [11] examined the overlaps between the three different systems and divided sustainable development into seven dimensions: social, economic, environmental, livable (intersection of environmental and social dimensions), fairness (intersection of economic and social dimensions), feasibility (intersection of environmental and economic dimensions), and sustainability (intersection of social, economic, and environmental dimensions). Li et al. [12] introduced a measure for human well-being to improve the traditional sustainable three-dimensional index system, and Wu et al. [13] and Jiang et al. [14] developed an sustainable urban development capability index assessment systems with five dimensions—resource security, social development, ecological environment, economic efficiency, and innovation—which was found to more comprehensively reflect the main issues in sustainable urban development.

Various sustainable urban development measurement methods have also been developed. The most frequently used methods have been comprehensive index evaluations and multivariate statistical analyses, with some research having used supervisory assignment qualitative analyses and analytic hierarchy processes such as factor analysis [15,16], the analytic hierarchy process [17], principal component analysis methods [18], and the multi-criteria decision-making (MCDM) approach [19,20]. However, as these methods tend to have strong subjectivity, this can influence the scientific rationality of the research results. When using comprehensive index evaluation and multivariate statistical methods to study the status of sustainable urban development, most research has been confined to macro-level analyses and discussion, with few studies having also considered the internal mechanisms or evolutionary trends. However, providing a comprehensive, accurate reflection of a city's sustainable development system requires an assessment of the sustainable coordination of the society, the economy, the environment, resources, and technology as well as the respective interactions between these subsystems and the external environment.

Qiao et al. [21] developed an improved entropy method to quantitatively analyze the sustainable development capability in Henan Province, China and assess the importance of the various system components. Liang et al. [22], based on principal component analysis (PCA) and grey TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), constructed a sustainable urban development capability measurement model which is a convenient and comprehensive measure of the sustainability of cities in Jiangsu Province. William et al. [23] used data envelopment analysis to estimate and assess the environmental, social, and economic efficiencies of Colombian cities to determine the changes that had occurred between 2005 and 2013, which revealed that there were significant differences between the cities, effective urban resource utilization, small environmental impacts, improving social conditions, and guaranteed economic growth and development. Guo et al. [24] objectively analyzed the sustainable development capabilities of cities with the view to establishing a DEA (Data Envelopment Analysis)-based index system. After the construction of a sustainable index system, Munier [25] proposed a methodology based on information entropy to assess urban sustainable development. While the information entropy calculation method in dissipative structure theory is easy to operate, it is often difficult to apply to social sciences [26]. While grey relational analysis can be used to calculate the average value of associated measures point by point and to assess the degree of relevance, it has two shortcomings: (1) local point association tendency—when the point-related measure value distribution is discrete, the point at which the point-correlated measure value is largest determines the tendency of the overall correlation accuracy; and (2) information loss—the average tends to overwhelm the many point-related measures and therefore does not take advantage of the rich information provided by the point-related measures [27].

Therefore, to overcome these problems, this paper uses grey relational entropy analysis to scientifically and objectively weight the sustainable urban development measurement indexes, dissipative structure theory to deeply explore and analyze the evolutionary sustainable urban development system trends and coupling theory to analyze the internal subsystem coordination. To empirically test the effectiveness of the assessment system, it is then applied to a comprehensive analysis of Chengdu, Sichuan Province, China. Therefore, this paper develops a valuable reference for related research into sustainable urban development. The innovations in this article are as follows:

(1) A sustainable urban development measurement analysis based on systems theory is developed. The sustainable urban development system has five subsystems: society, the economy, the environment, resources and technology. The measurement index system for each subsystem is constructed based on the actual urban development situation, and the principles of quantity, totality, purposiveness, systematicity, and scientificity, the weights for the overall development level score and each subsystem development level score are determined based on the grey correlation coefficient calculated using the grey relational analysis method, and the index weights are calculated using grey entropy;
(2) Information entropy theory and the grey relational analysis method are combined to analyze the sustainable urban development system, and system entropy change is used to analyze the structure and order of the internal system index mechanism and assess the evolution in the sustainable urban development system;
(3) Sustainable urban development system evolutionary analysis is conducted based on the annual grey entropy change, the system development level, the coordination scores, a time series analysis of the orderly evolutionary trends, and the development level and coordination status.

2. Structural Characteristics of the Sustainable Urban Development System

2.1. Dissipative Characteristics of the Sustainable Urban Development System

Prigogine [28] proposed dissipative structure theory in 1973 to reflect a nonlinear open system far from an equilibrium state that continuously exchanges matter and energy with the external environment. When the system conditions change to a certain threshold, the system transforms from the previous disordered state to a new state that is temporally, spatially, and functionally more ordered, and which also needs to constantly exchange materials or energy with the outside world to maintain its structure. The sustainable urban development system is an open composite system with five subsystems—society, the economy, technology, the environment, and resources—the mechanism for which is shown in Figure 1. Sustainable urban development systems have the following characteristics: openness, non-equilibrium, non-linear effects, and fluctuations between the system elements. Therefore, dissipative structure theory is suitable for the analysis of sustainable urban development and evolution.

2.1.1. Sustainable Urban Development System Dissipative Characteristics

The sustainable urban development system must be open to maintain orderly evolution and ensure system survival and development. During system evolution, the subsystems develop interactively in terms of the transfers and transformations in the flow of people, logistics, energy, information, and technology, and therefore are mutually dependent and mutually restrained. At the same time, the overall system continues to expand its connections with external systems based on development needs to ensure positive continuous external system input that assists the system moving towards a new, more orderly structure. Because the system also continues to actively affect the external environment, it needs to constantly adapt to external environmental changes. Through selective input and output, the sustainable urban development system continually introduces negative entropy to offset the entropy increases caused by the internal interactions generated by the external environment interactions, thereby achieving sustainable development.

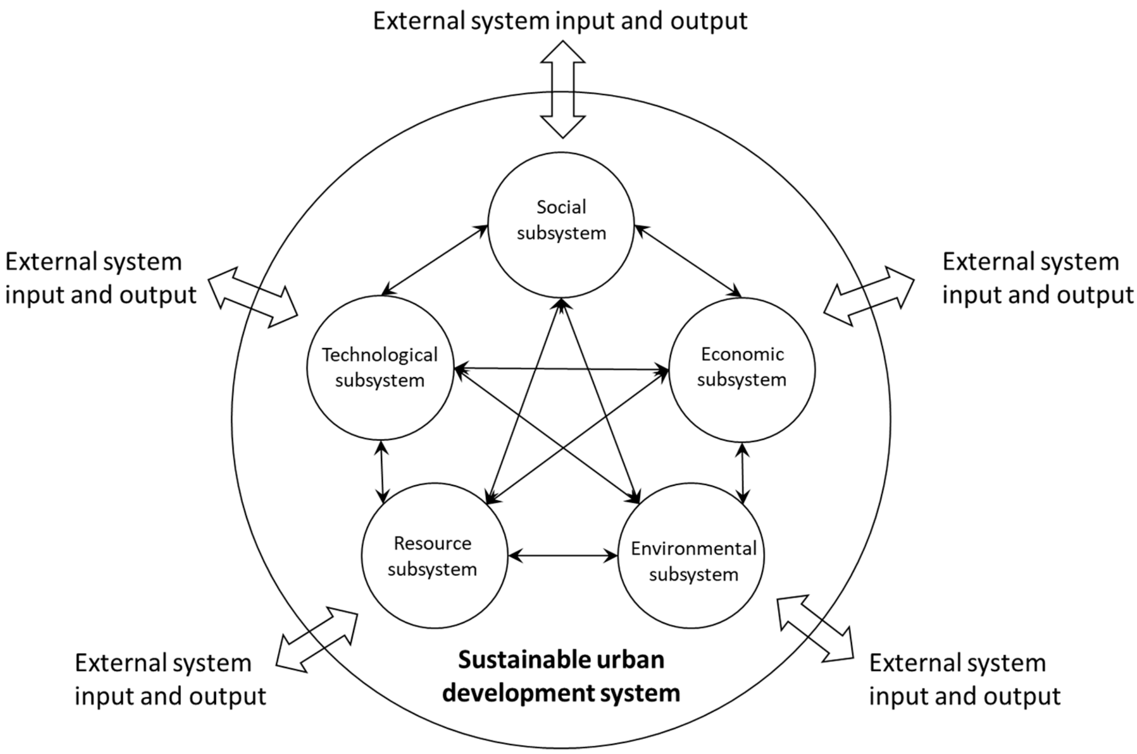

Figure 1. Dissipative structure for the sustainable urban development system.

2.1.2. A System Far from Equilibrium

As sustainable urban development is a dynamic evolutionary process, the system needs to go through an initial-stage, a growth-stage, and a mature-stage life cycle. Therefore, the original equilibrium system state is being continuously disrupted because of the internal and external interactions, which drives it towards a higher development level. Further, as the various sustainable urban development subsystems have imbalances between resource, information and technical forces due to interest conflicts and are also dealing with external environmental influences, they are unable to maintain an equilibrium state; therefore, a more orderly structure develops from this unbalanced dynamic interactivity.

2.1.3. System Nonlinearity

As the sustainable urban development system has several subsystems, the subsystem development models are different and the development levels imbalanced. When the external environment interactions on the sustainable urban development system move it away from the equilibrium state to a certain state, the internal subsystems function normally. However, when the functions in each subsystem are less than the total system functions, the sustainable urban development system enters a non-linear region of the non-equilibrium state. While at any moment, the relationship between the system and the external environment is simply linear, there are nonlinear relationships because of the organic interactions, the positive feedback multiplication effects, and the negative feedback saturation effects.

2.1.4. System Fluctuations

During system development and evolution, the elements in each subsystem (finance, technology, talent, knowledge, etc.) are continually changing in quantity and quality, which results in random "fluctuations". Because of these constant fluctuations in the system, when the impact reaches a certain level, the system begins to mutate because of the constant self-organization and catalysis and autocatalysis. The system revolves around its development goals by recombining its resources and elements, which causes a new "fluctuation", and moves the system from its previous state to a more orderly state and into a new dissipative structure.

2.2. Grey Characteristics of Sustainable Urban Development Systems

Cities are complex, open, giant composite systems, and for this paper, cities are made up of five subsystems—society, the economy, the environment, resources, and technology—therefore, due to the diversity, complexity and variability in the social, economic, environmental, resource and technical conditions and the limitations of human understanding and mastery of the evolutionary laws of these systems, there are a large number of objective uncertainties and inaccuracies, each of which have both a certain fuzzy feature and a certain grey feature. Therefore, sustainable urban development systems are also fuzzy grey systems.

3. Index System Construction

The main factors leading to entropy increases in the dissipative sustainable urban development system structure are resource consumption and environmental damage, and the main factors leading to entropy reduction are financial support, technological upgrading, and environmental governance. Entropy increase is a spontaneous process that goes from order to disorder, and entropy reduction promotes the development of a new, ordered system state because of the negative entropy flow. To study the entropy increase and entropy reduction factors in the sustainable urban development system, the negative entropy flow is selectively introduced to promote more orderly and coordinated system development.

When constructing the index system, this paper strictly followed the principles of quantity, totality, purposiveness, systematicity, and scientificity [29,30] and drew upon existing achievements and the actual situation in developed cities to identify the main factors affecting the dissipative sustainable urban development system structure. Then, a measurement evaluation index system based on a socio-economic–environmental–resource–technological (SEERT) framework for the sustainable urban development system was established which is shown in Table 1.

Table 1. Measurement evaluation index system for the sustainable urban development system.

Target-Grade	First-Grade Index	Second-Grade Index	Third-Grade Index	Index Properties	Data Source
Urban sustainable development system	Social sustainability subsystem S	Life quality S_1	Average employee wages (CNY) S_{11}	+	[31]
			Year-end balance of urban and rural resident savings (10^4 CNY) S_{12}	+	[31]
		Consumption capacity S_2	Social consumer goods retail sales of (10^4 CNY) S_{21}	+	[31]
		Infrastructure S_3	Total library books in public libraries (10^3 units) S_{31}	+	[31]
			Actual urban road area at the end of the year (10^4 m^2) S_{32}	+	[31]
			Number of hospitals and health centers (units) S_{33}	+	[31]
			Number of operating public steam (electric) vehicles at the end of the year (units) S_{34}	+	[31]
	Economic sustainability subsystem E	Economic scale E_1	Per capita GDP (CNY) E_{11}	+	[31]
			Gross production value (current price) (10^4 CNY) E_{12}	+	[31]
		Industrial structure E_2	Three production ratio (%) E_{21}	+	[31]
		Economic vitality E_3	Gross domestic product growth rate (%) E_{31}	+	[31]
			Total fixed assets investment (10^4 CNY) E_{32}	+	[31]
			Total population at the end of the year (10^4 person) E_{33}	+	[31]
			Financial general public budget revenue (10^4 CNY) E_{34}	+	[31]
	Environmental sustainability subsystem N	Pollutant emission N_1	Per capita industrial wastewater discharge (t) N_{11}	−	[31]
			Per capita sulfur dioxide emissions (t) N_{12}	−	[31]
			Per capita smoke emissions (t) N_{13}	−	[31]
		Pollution control N_2	Environmental protection expenditure in fiscal expenditure (10^8 CNY) N_{21}	+	[32]
			General industrial solid waste comprehensive utilization rate (%) N_{22}	+	[31]
			Sewage treatment rate (%) N_{23}	+	[31]
			Harmless treatment rate of domestic garbage (%) N_{24}	+	[31]
	Resource sustainability subsystem R	Resource use R_1	Per capita water supply (t) R_{11}	−	[31]
			Per capita electricity consumption (kwh) R_{12}	−	[31]
			Per capita air supply (m^3) R_{13}	−	[31]
		Resource condition R_2	Per capita green area (m^2) R_{21}	+	[31]
			Per capita administrative area (m^2) R_{22}	+	[31]
		Energy consumption level R_3	Energy consumption per unit of GDP (t/10^4 CNY) R_{31}	−	[33]
			Unit industrial added value energy consumption (t/10^4 CNY) R_{32}	−	[33]
	Technological sustainability subsystem T	Technological support T_1	Number of ordinary institutions of higher learning (units) T_{11}	+	[31]
			Number of students in ordinary colleges and universities (person) T_{12}	+	[31]
			Number of undergraduate and above employees in scientific and technological institutions (person) T_{13}	+	[34]
			Total public finance expenditure in science and technology and education (10^4 CNY) T_{14}	+	[31]
		Technological output T_2	Number of invention patents (units) T_{21}	+	[35]
			Number of output technology contracts (units) T_{22}	+	[34]
			Output technology amount (10^4 Yuan) T_{23}	+	[34]

4. Method for Measuring the Sustainable Urban Development System

4.1. Measurement Model

The sustainable urban development system is a composite system with several subsystems, each of which has its own development and evolutionary rules and constraints; therefore, the sustainable urban development system structure embodies complex mutual connections, mutual restraints, and mutual support relationships, all of which affect the system's operating mechanisms and evolution.

Orderly social, economic, environmental, resource and technological sustainable development can be achieved if these subsystems are able to maintain a certain order and a dynamic coordinated balance, which would eventually result in benign development, circulation, and evolution in the sustainable urban development system. However, achieving a dynamic but orderly evolution from a low-ordered state to a new high-ordered state is not certain as both orderly and disorderly transformations are possible. Therefore, when studying the system evolution, it is first necessary to describe the order of the system.

When quantitatively and scientifically analyzing the status of the sustainable urban development system based on dissipative structure theory, the grey relational analysis method and the information entropy weight method can be used to calculate the grey entropy of the index and the year-end information. The grey information entropy of the index information can then be used to determine the index weights for the calculation of the system development level score and the coordination development level score, both of which provide an effective, reasonable evaluation of the sustainable urban development system. Using the grey entropy year-end information, the evolutionary trends and order degree for the sustainable urban development system can be assessed from the time series. The measurement model used in this paper is shown in Figure 2.

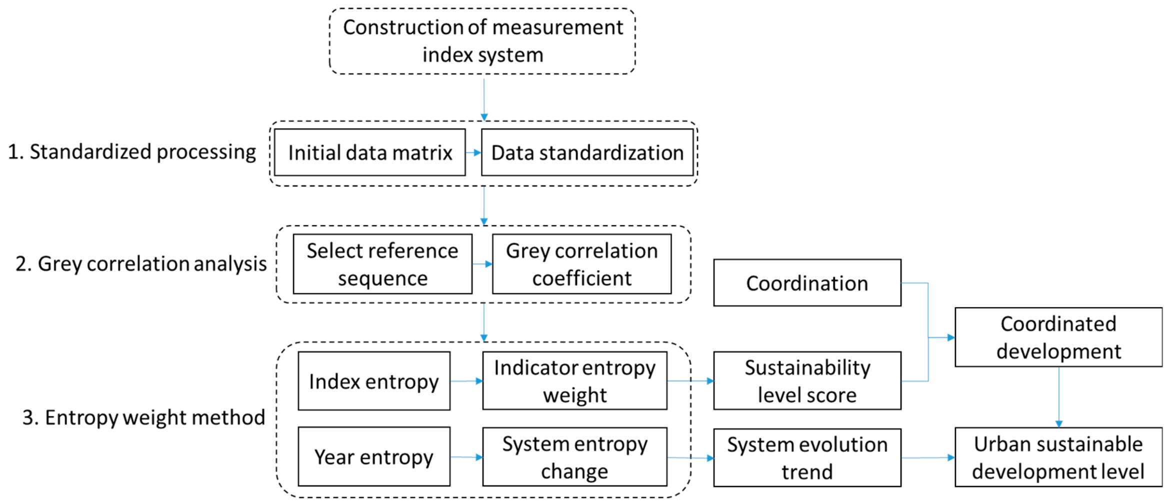

Figure 2. Measure model.

4.2. Measurement Steps

4.2.1. Build the Initial Matrix

This paper studies the sustainable development of a city in m years, which has n indexes in the evaluation index system, the mathematical model for which was built as follows:

The domain is $U = \{u_1, u_2, \ldots, u_i\}, i = 1, 2, \ldots, m$;

The number of indexes for each u_i is characterized by $u_i = \{x_{i1}, x_{i2}, \ldots, x_{ij}\}, j = 1, 2, \ldots, n$;

In this way, the initial measurement data matrix is obtained as $X = \{x_{ij}\}_{m \times n}$, where x_{ij} represents the value of the j_{th} evaluation index in year i. As there are dimensional and order-of-magnitude differences between each index in the initial data matrix, the next step is to standardize the data.

4.2.2. Data Standardization

To ensure the reliability of the measurement results, this paper uses the extremum method to perform dimensionless processing and eliminate the influences of the different dimensions and order of magnitude on the initial data. The entropy increase and entropy decrease indexes in the evaluation index dimensions were respectively eliminated using the maximum and minimum values.

For the entropy reduction index x_{ij}, the larger the value, the better:

$$x'_{ij} = \frac{x_{ij}}{max\{x_{1j}, x_{2j}, \ldots, x_{ij}\}}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{1}$$

For the entropy increase index x_{ij}, the smaller the value, the better:

$$x'_{ij} = \frac{min\{x_{1j}, x_{2j}, \ldots, x_{ij}\}}{x_{ij}}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{2}$$

Then, the normalized value is $y_{ij} = x'_{ij}$.

Thus, the standardized matrix is obtained as $y = \{y_{ij}\}_{m \times n}$.

4.2.3. Grey Correlation Analysis

First, determine the comparison sequences and the reference sequences.

The comparison sequence is $y_i = \{y_{1j}, y_{2j}, \ldots, y_{ij}\}, i = 1, 2, \ldots, m; j = 1,\ 2, \ldots,\ n.$

The reference sequence consists of the optimal index values. As the dimensionless indexes now belong to the interval $[0,\ 1]$, the maximum value for each index is selected as the comparison sequence $y_0 = \{1, 1, \ldots 1\}$.

Next, calculate the correlation coefficient, and the grey correlation coefficient indicates

$$\zeta_{ij} = \frac{\min_i \min_j |y_{ij} - 1| + \rho \max_i \max_j |y_{ij} - 1|}{|y_{ij} - 1| + \rho \max_i \max_j |y_{ij} - 1|}, i = 1, 2, \ldots, m; j = 1, 2, \ldots, n \tag{3}$$

where ρ is the resolution coefficient, $\rho \in [0, 1]$, and $\rho = 0.5$ to achieve a higher resolution.

4.2.4. Calculating the Grey Entropy Value and Grey Entropy Weight

As the information entropy in the information system is a measure of the degree of information disorder, the information entropy can be used to evaluate the order degree and the utility value of the obtained system information. The larger the information entropy, the higher the information disorder, and the smaller the information utility value, the smaller the weight. On the contrary, the smaller the information entropy, the lower the information disorder, and the greater the information utility value, the greater the weight. The entropy method can accurately determine the utility value of the index information entropy value and allow for the construction of a judgment matrix by evaluating the index numerical values to determine the index weights. Therefore, as the entropy method eliminates evaluator subjectivity and objectively determines the indexes based on survey data, the results are more in line with reality.

From the information entropy definition, the information entropy value of the *j*th index is

$$E_j = -K \sum_{i=1}^{m} p_{ij} \ln p_{ij}, j = 1, 2, \ldots, n \tag{4}$$

where $p_{ij} = \frac{\zeta_{ij}}{\zeta_j} = \frac{\zeta_{ij}}{\sum_{i=1jj}^{m}}$, $j = 1, 2, \ldots, n$. K is a constant, and the value is related to the number of system samples., When the system information is completely disordered, the order degree is 0, the entropy value is the largest, and $E = 1$. When there are m samples in a completely disordered state, $p_{ij} = \frac{1}{m}$, at this time, $K = \frac{1}{\ln m}$, $0 \leq E \leq 1$ [36–38].

Based on Shannon's information entropy definition and the Boltzmann function, the difference coefficient for the jth evaluation index entropy under the ith subsystem can be calculated [39].

$$d_j = 1 - E_j, j = 1, 2, \ldots, n \tag{5}$$

The weight coefficient of the index information is used to calculate the weight of each index; therefore, the entropy weight of the jth index is

$$w_j = \frac{d_j}{\sum_{j=1}^{n} d_j}, j = 1, 2, \ldots, n \tag{6}$$

The system's sustainable development level score and the system's coordination degree are used to analyze the coordinated development of the sustainable urban development system. As the measurement system has a multi-layer structure, according to the information entropy weight additivity, the entropy weight for each subsystem is calculated as

$$W_k = \sum_{j=1}^{l} w_j \tag{7}$$

where k is the number of subsystems in the system, and l is the number of measurement indexes for the subsystem.

The weight of the measurement indexes of the subsystem is calculated as

$$W_j = \frac{w_j}{W_k} \tag{8}$$

4.2.5. Calculating the Year Entropy Changes Using Grey Correlation

This paper reflects the orderly system development degree and evolutionary trends using the year-end entropy changes in the sustainable urban development system. The year-end entropy change is calculated for each year's sequence [40], the formula for which is

$$dS_i = K \sum_{j=1}^{n} q_{ij} \ln q_{ij}, i = 1, 2, \ldots, m \tag{9}$$

where $q_{ij} = \frac{\zeta_{ij}}{\zeta_i} = \frac{\zeta_{ij}}{\sum_{j=1}^{n} \zeta_{ij}}, i = 1, 2, \ldots, m$.

4.2.6. Coordinated Development Level

Based on the entropy weight for each index W_j and w_j, and the grey correlation coefficient, the system development level score D and each subsystem development level score D_k are calculated.

$$D_{ik} = \sum_{j=1}^{n} w_j \zeta_{ij}, i = 1, 2, \ldots, m \tag{10}$$

$$D_i = \sum_{j=1}^{n} w_j \zeta_{ij}, i = 1, 2, \ldots, m \tag{11}$$

The coordinated development of each system is expressed by the coupling degree, which is the degree to which the system and the system elements are mutually consistent in the development process and the orderly system development trend. The coupling degree [41], derived from physics, refers to the phenomenon when two or more systems interact through various forms of motion. The coupling degree is used to measure the interaction degree between systems or elements, while the degree of coordination is the relationship of the coordination and virtuous cycle between systems or elements. The coupling degree formula is as follows:

$$C_i = \left[\frac{\prod_{k=1}^{5} D_{ik}}{\left(\frac{\sum_{k=1}^{5} D_{ik}}{5} \right)^5} \right]^{1/5}, i = 1, 2, \ldots, m \quad (12)$$

The larger the C_i, the higher the coordination degree of each subsystem in the year. When $C_i = 1$, the three systems have reached the optimum coordination state; however, when $C_i = 0$, the various elements within the system are totally uncoordinated and the system is disorderly.

However, when the coupling degree is simply used to judge the interaction relationship between the various subsystems in the sustainable urban development system, it can result in pseudo-coordination and low subsystem development but a high coupling degree [42], which does not truly reflect the comprehensive development level of the society, the economy, technology, the environment and resource. Therefore, the coordinated development model is as follows:

$$CD_i = \sqrt{C_i \times D_i}, i = 1, 2, \ldots, m \quad (13)$$

where D_i is the total system development level score.

Referring to study [43], the classification for the coordinated development is shown in the following Table 2.

Table 2. Coordinated development hierarchy.

Coordination Value	Coordination Level	Coordination Degree
0.0000~0.0999	Level 1	Extreme imbalance
0.1000~0.1999	Level 2	Serious imbalance
0.2000~0.2999	Level 3	Moderate imbalance
0.3000~0.3999	Level 4	Mild imbalance
0.4000~0.4999	Level 5	Near imbalance
0.5000~0.5999	Level 6	Reluctant coordination
0.6000~0.6999	Level 7	Primary coordination
0.7000~0.7999	Level 8	Intermediate coordination
0.8000~0.8999	Level 9	Good coordination
0.9000~1.0000	Level 10	Quality coordination

5. Case Study

5.1. Research Area

Considering that the earthquake in Sichuan in 2008, we selected the data from 2009 to 2016 for analysis to ensure that the time span is long enough. Based on the requirements of our index system, the original data used for this case were extracted from the China city statistical yearbooks (2010~2017) [31], Chengdu yearbooks (2010~2017) [32], Sichuan statistical yearbooks (2010~2017) [33], Chengdu statistical yearbooks (2010~2017) [34], China Intellectual Property Statistics Report (2010~2017) [35]. Relevant data were extracted to obtain the index data, with the small number of missing values being processed through interpolation.

Using Formulas (1)–(8) on the original data, the grey entropy and entropy weights for each index in Chengdu's sustainable development system were calculated, which were then used to calculate the system coordination and development levels. The data are shown in Table 3.

Table 3. Grey entropy and entropy weights for the Chengdu sustainable development system indexes.

Target Layer	Criteria layer		Index Layer			
	Index Code	Grey Entropy Weight W_k	Index Code	Entropy Weight W_j	Entropy Weight ω_j	Grey Entropy Variation Coefficient
Sustainable urban development system	S	0.2080	S_{11}	0.1786	0.0371	0.0155
			S_{12}	0.1969	0.0410	0.0171
			S_{21}	0.2151	0.0447	0.0187
			S_{31}	0.1250	0.0260	0.0108
			S_{32}	0.0759	0.0158	0.0066
			S_{33}	0.0729	0.0152	0.0063
			S_{34}	0.1357	0.0282	0.0118
	E	0.1828	E_{11}	0.2127	0.0389	0.0162
			E_{12}	0.2166	0.0396	0.0165
			E_{21}	0.0080	0.0015	0.0006
			E_{31}	0.2246	0.0411	0.0171
			E_{32}	0.1627	0.0297	0.0124
			E_{33}	0.0321	0.0059	0.0024
			E_{34}	0.1433	0.0262	0.0109
	N	0.2318	N_{11}	0.1424	0.0330	0.0138
			N_{12}	0.3331	0.0772	0.0322
			N_{13}	0.2328	0.0540	0.0225
			N_{21}	0.2258	0.0523	0.0218
			N_{22}	0.0288	0.0067	0.0028
			N_{23}	0.0181	0.0042	0.0018
			N_{24}	0.0189	0.0044	0.0018
	R	0.1116	R_{11}	0.1390	0.0155	0.0065
			R_{12}	0.1561	0.0174	0.0073
			R_{13}	0.0267	0.0030	0.0012
			R_{21}	0.1719	0.0192	0.0080
			R_{22}	0.1345	0.0150	0.0063
			R_{31}	0.1613	0.0180	0.0075
			R_{32}	0.2104	0.0235	0.0098
	T	0.2658	T_{11}	0.0340	0.0090	0.0038
			T_{12}	0.0378	0.0101	0.0042
			T_{13}	0.0671	0.0178	0.0074
			T_{14}	0.1548	0.0411	0.0172
			T_{21}	0.2670	0.0710	0.0296
			T_{22}	0.0886	0.0235	0.0098
			T_{23}	0.3508	0.0932	0.0389

5.2. Results Analysis

5.2.1. Analysis of the Orderly Degree and Evolution Trend of Sustainable Development in Chengdu

Using the proposed method and the grey entropy changes each year, the evolutionary trend and orderly development degree of the sustainable urban development system in Chengdu was determined. Figure 3; Figure 4 show the evolutionary trend and order degree for each subsystem and the overall system. As can be seen in Figure 3, the entropy in each subsystem from 2009 to 2015 was reducing at varying degrees, indicating that Chengdu's social, economic, environmental, resource, and technological subsystems were developing in an orderly direction. The entropy deceleration in the resource subsystem was slowing and the entropy deceleration in the environmental subsystem was increasing, which indicated that the government policy measures had had significant success in improving the Chengdu environment. It can be seen that the improvement of Chengdu's sustainable development capacity is greatly affected by policy factors, such as the state's strong ecological environmental protection supervision, the establishment of independent innovation pilot zones and national central cities, etc. However, the impact of industrial structure, technological structure transfer and transformation factors is relatively small.

From Figure 4, it can be clearly seen that from 2009 to 2016, the entropy of the overall sustainable urban development system in Chengdu was gradually decreasing, with the rate of decline flattening out from 2014 to 2016, which indicated that through continuous development and evolution, the sustainable urban development system in Chengdu was becoming more orderly, with the whole system moving towards a state of dynamic balance. It can be seen that from the 12th to the 15th that Chengdu's development and construction has achieved great results, providing favorable support for the 13th Five-Year Plan to build the western economic center, the beautiful Chinese model city, and the happy city.

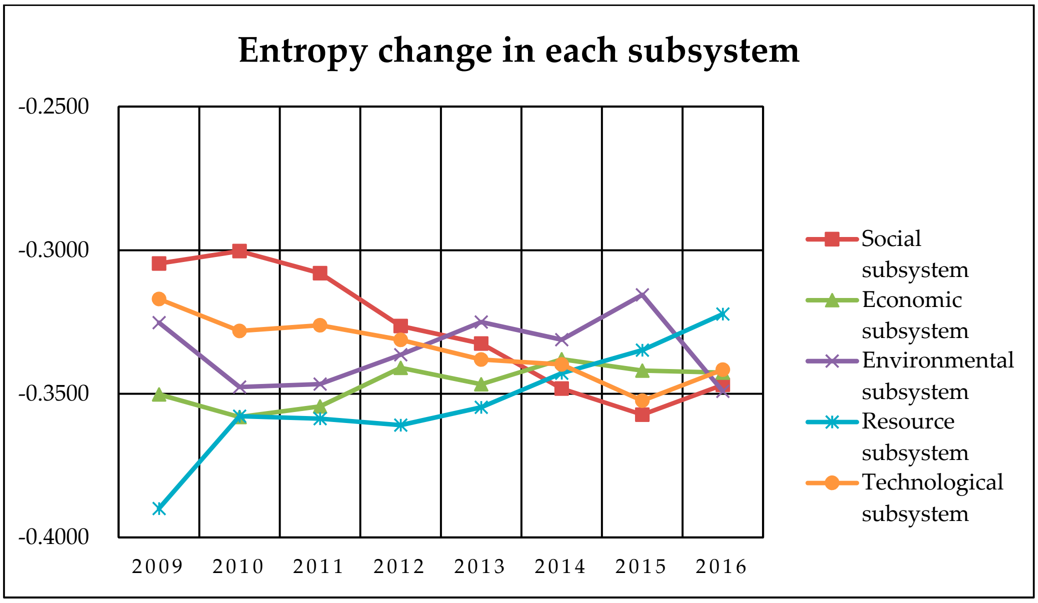

Figure 3. Entropy change in each subsystem.

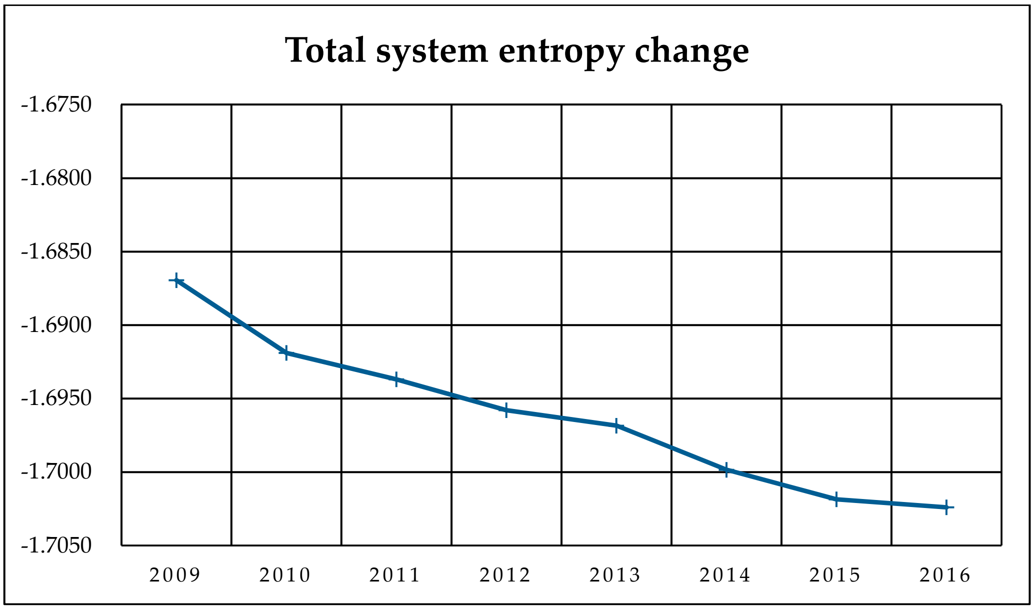

Figure 4. Sustainable urban development system entropy change.

5.2.2. Analysis of the Development Status of the Sustainable Urban Development System in Chengdu

(1) Total system sustainability analysis

It can be seen from Figure 5; Figure 6 that from 2009–2016, the sustainable urban development system in Chengdu was evolving towards high-quality coordination, from a moderate coordination of 0.7100 to a quality coordination of 0.9701. The comprehensive sustainable development score also had a gradual upward trend from 0.5124 in 2009 to 0.9422 in 2016, an average annual growth rate of 5.37%. This was mainly because the government began to focus more attention on environmental protection and technology, therefore introducing a series of policies and increasing investment such as conducting environmental inspections, establishing national-level science and technology research and development centers, etc., which led to a rapid development in the environmental and technological subsystems, especially from 2015 to 2016, at which time the growth rate in the environmental subsystem score was 41.05%. From 2014 to 2016, the growth rate in the technology subsystem score was 16.60%. Therefore, as can be seen, Chengdu's urban development was becoming more coordinated and more sustainable.

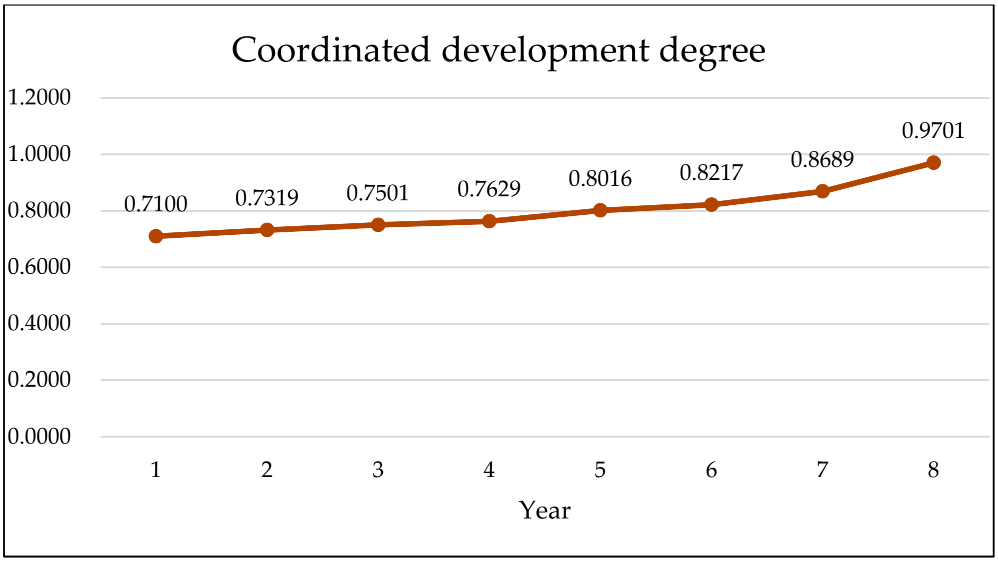

Figure 5. Chengdu's coordinated development.

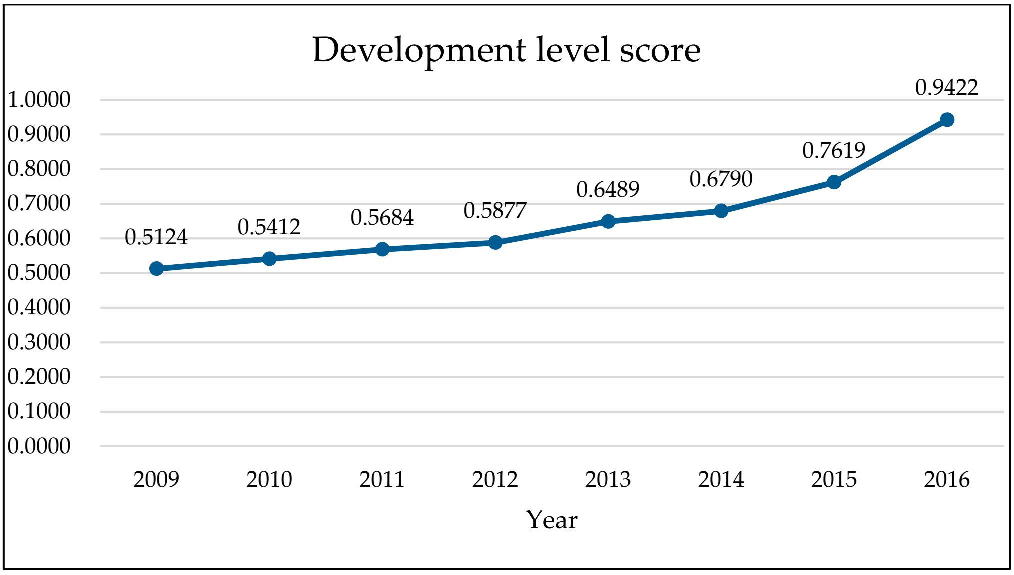

Figure 6. Chengdu's development level rating.

(2) Social subsystem sustainable development level

From Figure 7, it can be seen that the social subsystem sustainable development level continuously increased from 0.5002 to 0.9468, an average annual growth rate of 5.58%. In 2016, the social consumer goods retail sales reached 574.236 million CNY, the average employee wages reached 74,408 yuan, the year-end balance of urban and rural resident savings reached 108.08 billion CNY, and the level of urban infrastructure also gradually improved. This is due to the Chengdu government's focus on comprehensively improving people's well-being, raising the income level of residents and increasing investment in infrastructure. The quality of life was improving, which boosted consumption power, and lay the foundation for further social subsystem development.

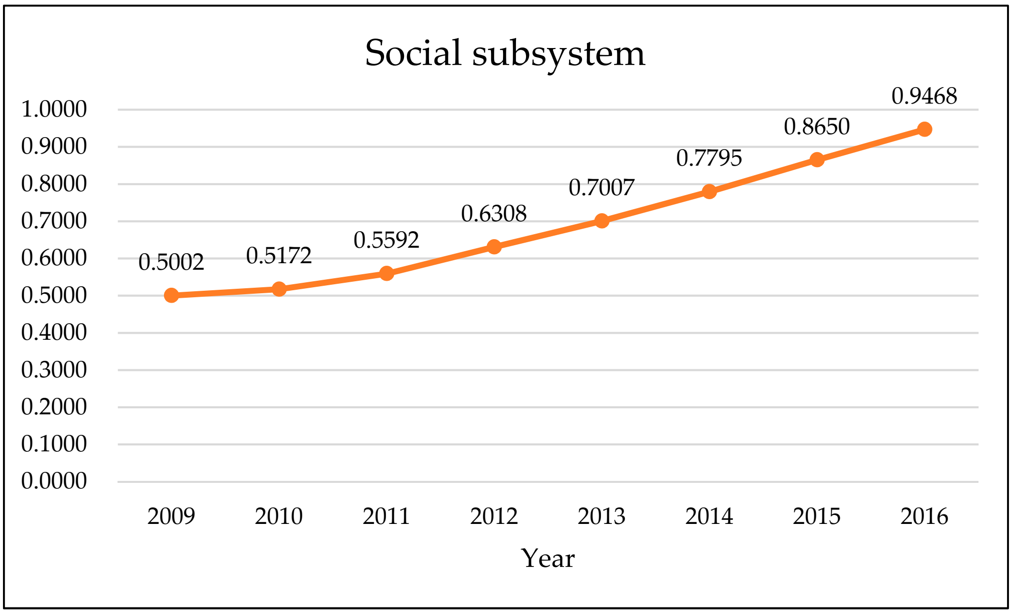

Figure 7. Social subsystem development level score

(3) Economic subsystem sustainable development level

From Figure 8, it can be seen that the economic subsystem development level was generally improving; however, there were varying degrees of decline during the assessment period. In 2012 and 2014, the system development level fluctuated, mainly because of a decrease in the GDP growth rate and the fiscal general public income in 2012, which resulted in lower economic vitality and a lower economic subsystem development level. However, since the 13th Five-Year Plan, Chengdu has focused on industrial restructuring and industrial transformation and upgrading. In 2016, the proportion of tertiary industry reached 53.11%, and the per-capita GDP reached 76,960 CNY, resulting in the continuous improvement of the economic subsystem development level. In addition, with the implementation of a series of national strategies such as the Chengdu–Chongqing city group and national central city, the government has increased investment in fixed assets and made efforts to build a western economic center, which has played a very important role in its economic development. It can be seen that the trend line has become more inclined from 2015 to 2016, indicating that the economic growth rate has increased, and the overall economic subsystem development level was gradually increasing.

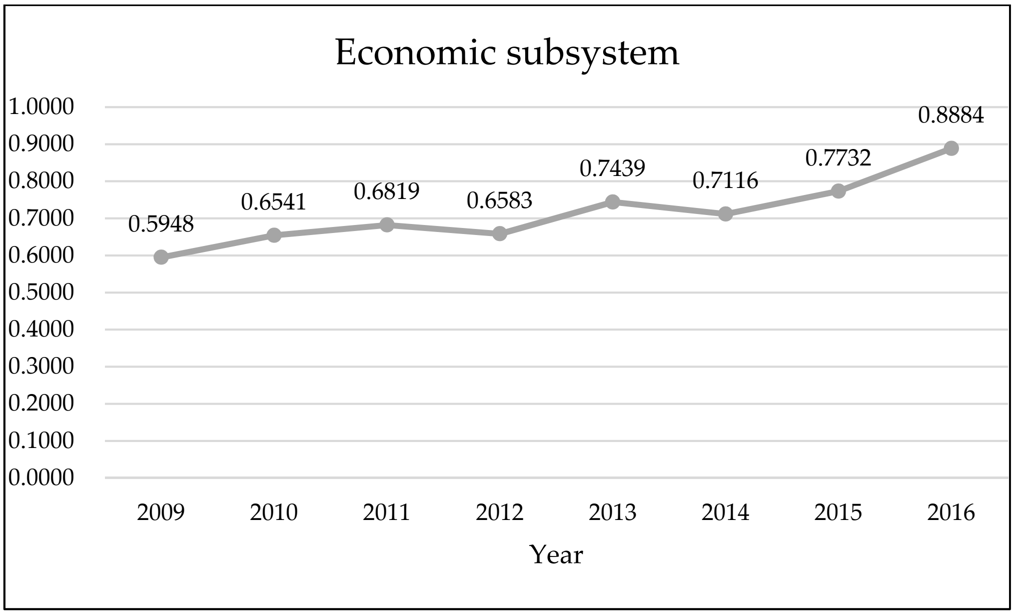

Figure 8. Economic subsystem development level score

(4) Environmental subsystem sustainable development level

From Figure 9, it can be seen that the environmental subsystem grew steadily from 2009 to 2015, and grew rapidly from 2015 to 2016, with a growth rate of 41.05%. Since the "13th Five-Year Plan", Chengdu has been promoting the construction and development of energy-saving and environmental protection industries, such as equipment manufacturing, and has focused on efficient resource use, energy-conservation and environmental protection services, and the construction of a "one main, three auxiliaries" industrial layout. These measures have resulted in a reduction in waste and emissions. From 2015 to 2016, the per-capita industrial wastewater discharge, per-capita sulfur dioxide emissions, per-capita soot emissions, and environmental expenditure rate increases were respectively 36.72%, 54.20%, 48.32%, and 31.60%, all of which are key to sustainable urban environmental development.

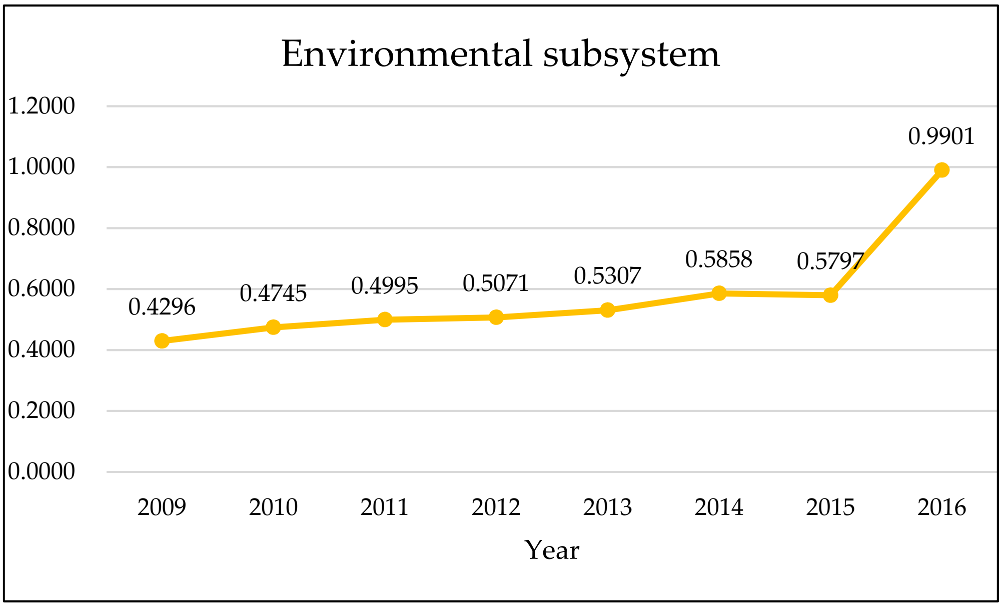

Figure 9. Environmental subsystem development level score.

(5) Resource subsystem sustainable development level

From Figure 10, it can be seen that the resource subsystem development speed was relatively slow, primarily because the per-capita water electricity and gas use was increasing, which accelerated the resource consumption and reduced the resource sub system sustainable development level. In recent years, Chengdu has been accelerating industrial transformation and upgrades, deepening the elimination of backwardness and defusing excess capacity, accelerating the development of green and low-carbon industries, and strictly controlling the growth of high-energy-consuming industries, which plays an important role in reducing the energy consumption per unit of GDP. From 2014 to 2016, the energy consumption per unit of GDP(t/10^4 CNY) was reduced from 0.840 to 0.456, and the unit industrial added value energy consumption(t/10^4 CNY) was reduced from 1.385 to 0.826, which has promoted the development of the resource subsystem to a certain extent.

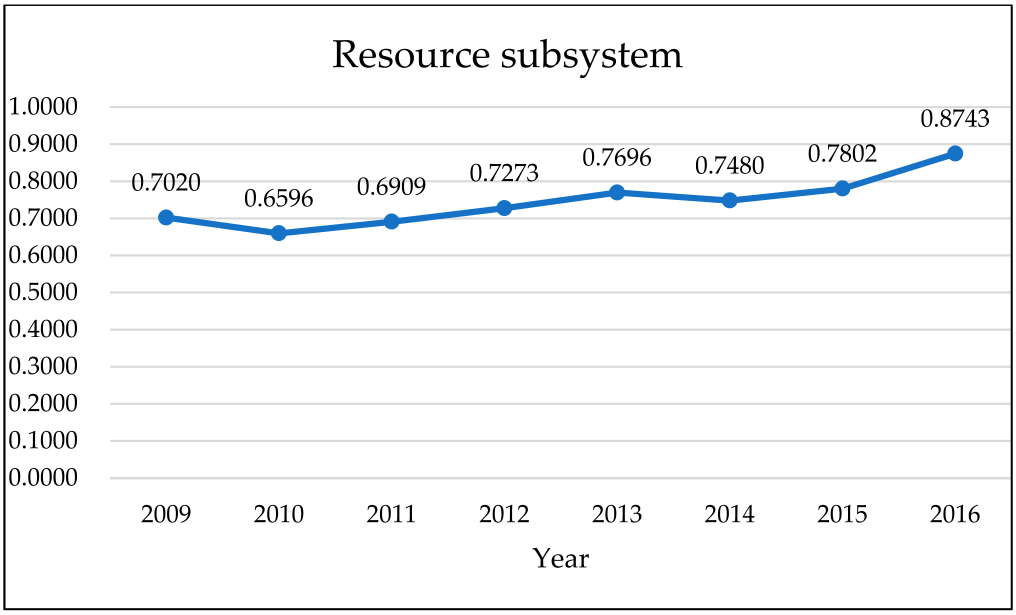

Figure 10. Resource subsystem development level score.

(6) Technological subsystem sustainable development level

From Figure 11, it can be seen that the average annual growth rate in the technological subsystem development level from 2009 to 2014 was 3.45%, after which the growth increased significantly from 2014 to 2016 at an average annual growth rate of 16.60%. Through the strengthening of policy support and the provision of increased financial assistance, Chengdu has gradually strengthened its scientific and technological development level and achieved remarkable results. From 2014 to 2016, the average annual growth rate in the number of invention patent grants in Chengdu was 23.43%, and the average growth rate for the output technological development was 23.27%. These results indicate that the strategic government science and technology measures have been promoting sustainable urban technological subsystem development.

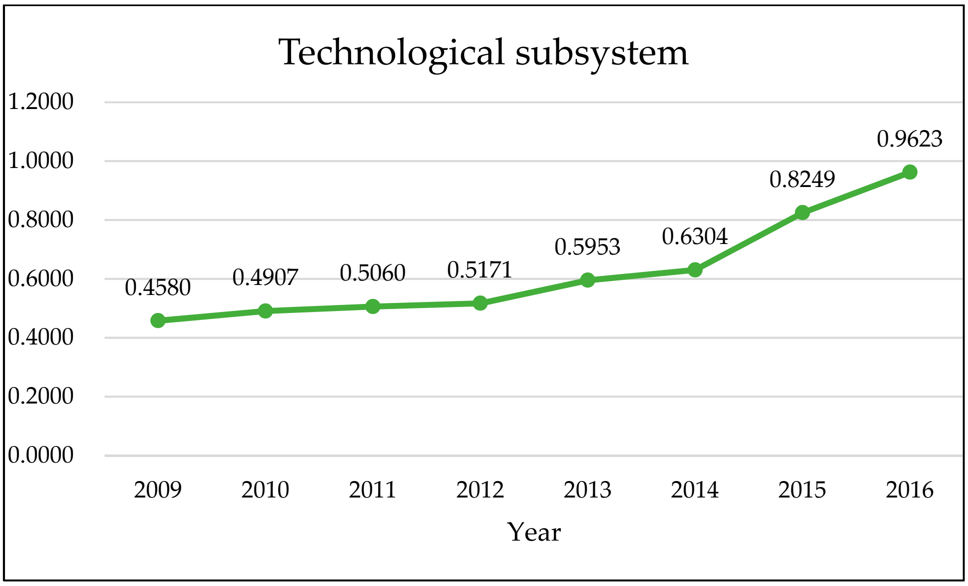

Figure 11. Technological subsystem development level score.

6. Conclusions and Prospects

This paper constructed a sustainable urban development measurement index based on the dissipative structure and grey relational entropy theories that included indexes in the five dimensions of the society, the economy, the environment, resources, and technology to conduct a quantitative measurement analysis of the sustainable development level, the coordinated development level, the evolutionary trends and the sustainable urban development system order. Using the developed index, the sustainable urban development in Chengdu was assessed from 2009 to 2016, from which the following conclusions were drawn.

The sustainable urban development system is a complex, giant system with five subsystems; the society, the economy, the environment, resources and technology. There are material-flow, information-flow and energy-flow interactions between the subsystems and between the total system and the external environment. As the evolutionary system direction is uncertain but has structural dissipative and grey features, dissipative structure theory and grey theory can be used to analyze the evolution in sustainable urban development systems.

Grey entropy theory was shown to effectively analyze the sustainable urban development system evolution, as the grey entropy in each year can indicate the evolutionary trends and system order degree, with a fall in the entropy value indicating system order enhancement and a movement towards benign evolution. Therefore, when assessing sustainable urban development system development trends, grey entropy was proven to be useful as the quantitative index. Further, the indexes have strong objectivity when weighted using the grey relational analysis method and the entropy weight method.

To effectively analyze the sustainable urban development system coordination, coupling theory was shown to be a good method. The coordinated development level analysis found that this method was able to accurately assess the degrees of consistency between the sustainable urban development system and the five subsystems.

The developed multi-dimensional and multi-faceted comprehensive analysis method was able to provide a valuable reference for sustainable urban development as it was able to assess the overall system development trends, identify the dynamics in the various subsystems, and promote all-round development.

This study, however, had certain limitations. While sustainability, coordination, and fairness are the three core sustainable development concepts, when establishing indexes, it is necessary to consider the multiple levels and aspects; however, for some indexes in this study, such as policy factors, there was insufficient information available on their effect on overall sustainable development. Therefore, in the future, these need to be further explored.

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