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Article

An Integrated Approach to Modelling the Economy-Society-Ecology System in Urbanization Process

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Abstract: Urbanization has become a key part of social and economic progress in the 21st Century, but achieving healthy and safe urban development has a long way to go for many developed and developing countries. Urbanization has been recognized as a complex ecosystem which is affected by economic, social, and ecological factors. With this in mind, this paper looks at many factors to first evaluate based on the matter-element (ME) method and then model an Economy-Society-Ecology (ESE) subsystem using a hybrid method by a fuzzy analytical hierarchy process (FAHP), and then by using the entropy method (EM) to determine the relevant index weights. To avoid subjectivity when defining the model's boundaries, the technique for order preference by similarity to an ideal solution (TOPSIS) is introduced. Then, a coupling coordination degree model focusing on the degree of coordination in the ESE subsystem is established. Panel data collected from 2003 to 2012 for Chengdu, China, is then simulated to analyze the development process. The results show that: (1) The quality of urbanization continues to improve and the phasic features are presented; (2) The sensitivity analysis of subsystem weight shown that it had less effect on the coupling coordinated system; (3) The coordination in the ESE subsystem has also improved. However, the development rate of the economic subsystem is greater than that of the societal and ecological subsystem. The approach used here therefore, is shown to provide a promising basis for policy-making to support healthy urban development.

Keywords: urbanization; ESE; matter-element model; coupling coordination degree

1. Introduction

Urbanization, which refers to the increasing amount of people that live in urban areas, is a key index to measure the modernization, industrialization and sociological processes in a country [1]. There are, however, many definitions for urbanization [2–4]. The urbanization that is currently taking place in China, for instance, is classified as accelerated development [5]. The number and scale of cities has dramatically increased in China, an event which is unprecedented in human history [6]. As a result, the central government has taken urbanization as a key strategy for the country's development in the Eleventh and Twelfth five-year plans [7].

Urbanization has a significant influence on the national economic system. However, with the rapid development of industrialization and urbanization, it will be not only in terms of resource consumption but also environmental degradation. The evaluation of urban development quality can be helpful in city development planning, which has been found to an appropriate way to reduce the environmental impact. Since the urban environment is a complex system effected by many factors, it is impossible to find a way to master all the information from high-dimensional space-time. The economic-society-ecology (ESE) as a basic structure was preferred in this paper for reducing the dimensionality and analyzing city system.

The aim of this paper is to propose a comprehensive assessment model using a fuzzy-element method (FEM) and a hybrid weights algorithm to evaluate the level of urban health development. The remainder of this paper is organized as follows. Section 2 reviews the existing literature. Section 3 describes the urban conceptual framework, the methodology and modeling processes. Section 4 presents a numerical example to illustrate the proposed model. The validation of the proposed model is discussed in Section 5. Conclusions and suggestions for further research are discussed in Section 6.

2. Literature Review

As urbanization plays a major role in achieving economic and social progress, in particular, to pursue balanced development between urban and rural areas. However, people continue moving into cities to consume finite resources, such as land, soils and energy. Therefore, assessing urbanization quality has recently become a hot topic. Wang *et al.* [8] analyzed urbanization research from 1991 to 2009 with bibliometric analysis, based on the SCI and SSCI databases. They discussed the scientific output, subject categories and major journals and international collaboration and geographic distribution. Gu *et al.* [9] also reviewed the progress of Chinese urbanization research both domestically and internationally. This research was divided into five and three periods, respectively, and focused on the key results of the research on Chinese urbanization and included nine main issues. In this section, a brief review of establishing indices, research perspective and assessment method is given.

To establish an indication system, which can abstract complex object as simple and measurable independent units, is a precondition of appraising the urbanization progress. A wide range of urban development quality indicators are therefore in use across the diversity of different cities and regions [10–12]. Georges *et al.* [13] given a table for summary of the 17 studies and revealed a lack of consensus on the optimal number of indicators. Jochen *et al.* [14] derived 13 suitability criteria for measures of urban sprawl, which can be useful to systematically evaluate the consistency and reliability of metrics of urban development. Moussiopoulos *et al.* proposed a guideline for the systems

development and use for the evaluation of sustainability in urban areas, together with a suggestion for its communication among local stakeholders [15]. Shen *et al.* [16] examined nine different practices use different indicators according to their particular need and proposed a comparative basis. Meanwhile, similar sets of indicators that have been researched by international organizations for developing uniform standards, such as the Organization for Economic Co-operation and Development [17], EU [18], World Health Organization [19]. The above studies contributed greatly to indicator system from diverse perspectives.

Urbanization is a complex giant system affected by diverse social, economic and environmental factors, with many conflicts and interactions among these factors [20], and which has been studied from different perspectives. Most of the research was based on the one aspect of the problems faced in urbanized societies. For example, land use and land cover [21,22], which is considered one of the more disturbing processes in urban development [23]. The transfer of labor from the agricultural sector to the industrial sector was also a popular topic [24–26]. Many papers also looked at urban populations, welfare distribution problems in urban transformation, and the urban transformation modes [27–30]. In comparison with economic and societal research, the ecological and environmental issues in urbanization research have a high priority throughout Wang *et al.* [8]'s paper. About one fifth of papers were in this category and looked at such aspects as the effects of air pollution and the urban thermal environment [31–33], the water environment [34–36] and the soil environment [37,38]. From this review, it could be seen that urbanization research has a wide range of concerns, and is a complicated system made up of many intertwined and interrelated subsystems, such as, housing and infrastructure, social life, regional economies, the ecological environment, and related policies and regulations, which are organized and managed by a meta-synthesis system. Coupling is a useful method and now widely used in studies in this area [39]. There are also many papers which discuss the coupling relationship between urbanization and the environment [39–41], or population development and the economy of the society [42]. Li *et al.* [20] given the full permutation polygon synthetic indicator method to measure sustainable development of Jining City, China.

The most traditional methods of evaluation always compartmentalize the levels of indicators and determine their relative weights artificially [20]. The evaluation criteria are not unified, and thus the methods are not easy to be generalized and applied [43]. In recent years, the methods such as analytic hierarchy process (AHP) [34], principal component analysis (PCA) [44], grey correlation method [45], fuzzy comprehensive evaluation [46] and interpretative structural modeling [47] have been often used for one aspect or comprehensive assessment of urban. Many of those methods ignore the influence of various factors on the collectivity of urbanization. Matter-element theory can be used to solve the incompatibility or contradiction problems by transforming the matter element [48], which has been widely used in circuit board fault diagnosis [49], land suitability evaluation [50], urban network planning risk assessment [51] and supply chain management [52]. AHP, proposed by Saaty [53], is one of the most popular multiple criteria decision making (MCDM) approaches. Fuzzy theory has been shown to be a potentially useful solution [54]. The entropy method (EM) was also used wildly since subjectivity can be avoided [39,55]. AHP and EM have been adequately discussed in the literature.

Previous studies have made significant contributions to the urban development assessment models. A detailed survey of the literature reveals that there appears no consensus concerning the superiority of a

model. As far as evaluating the ESE system is concerned, many indexes and factors must be considered. The matter-element (ME) method (ME), which has the convenient advantage quantifying the qualitative indices, can clearly illustrate the content and the relationship between the quality and the quantity of the comprehensive evaluation. Therefore, the comprehensive evaluation of urbanization is performed based on the ME model. The design of weight is one of the important parts in the synthetic evaluation, as it would have a deep effect on the evaluation results. Using the concept of entropy, the objective attributes have been transformed into integrated importance. In order to do the crosswise comparison among indices, AHP was corporate. It has high reliability, a profound mathematical background and a wide range of applications. AHP-EM combined weight method considered the data and the subjective preferences of decision-makers to achieve unity of subjective and objective and to make the results more realistic and reliable. Because of data shortage, measuring error or the subjectivity of judgement, the fuzzy nature was introduced for addressing uncertainties in ME and AHP. For the purpose of this paper, matter-element theory is used to model the ESE system. Fuzzy AHP (FAHP) and EM as two of the most commonly used models is incorporated to the model to handle the weight of the ESE system .

3. System Description

3.1. ESE Three-Dimensional System

Urbanization is a highly complex system which involves the movement of people from villages to the city, the conversion of the population from agricultural to non-agricultural, the increase in urban spread, the upgrading of industrial structures, and the changes in people's ways of living and seeing themselves in the society, in terms of their sense of place and sense of worth. Comprehensive evaluation is essential not only to understand the complexity but also to illustrate the synergistic evolution. Qiao and Fang [56] concluded that the urbanization process had four courses: the demographic urbanization course, the spatial urbanization course, the economic urbanization course and the social urbanization course. China's urbanization has followed a gradual pattern from 1978 as changes occurred in the general economic framework, such as the household registration system, the development of township and village enterprises, the conceptualization of the small city strategy and the need for coordinated development [57]. In the latest Third Plenary Session of the Eighteenth Central Committee, the urban healthy development mechanism was emphasized. This is usually presented as the intersection between the environment, society and economy to enable sustainable development, and which are thought of as separate but connected entities [58]. Therefore, urban development can be divided into three sub-systems: the economy, society and ecology. Although these all have different functions in the urban system, and each has its own respective structure, function, origin and development laws, coordinated development is the final goal of the ESE system because of the complex interdependency. The conceptual architecture is made up of three functional modules: economic, social and ecological and therefore, when researching urbanization there are three subsystems which need to be consider; the economic subsystem (reflecting the change to the non-agricultural economic structure and the change in the regional landscape), the social subsystem (reflecting the way lives change and urban population centralization) and the ecological subsystem (reflecting the environmental effects caused

by urbanization). The modeling process for the proposed model is clarified in the following with the complete process shown in Figure 1.

Figure 1. Framework for comprehensive urbanization.

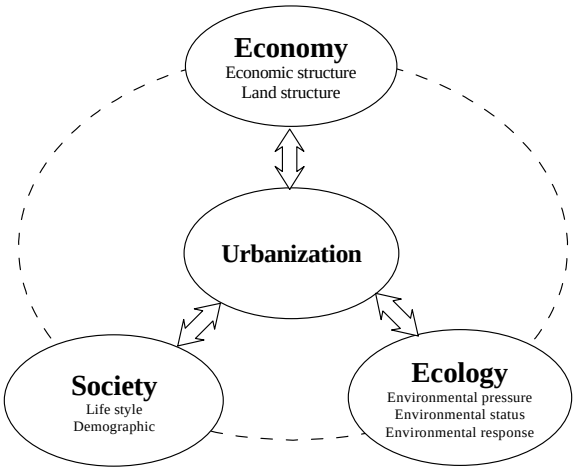
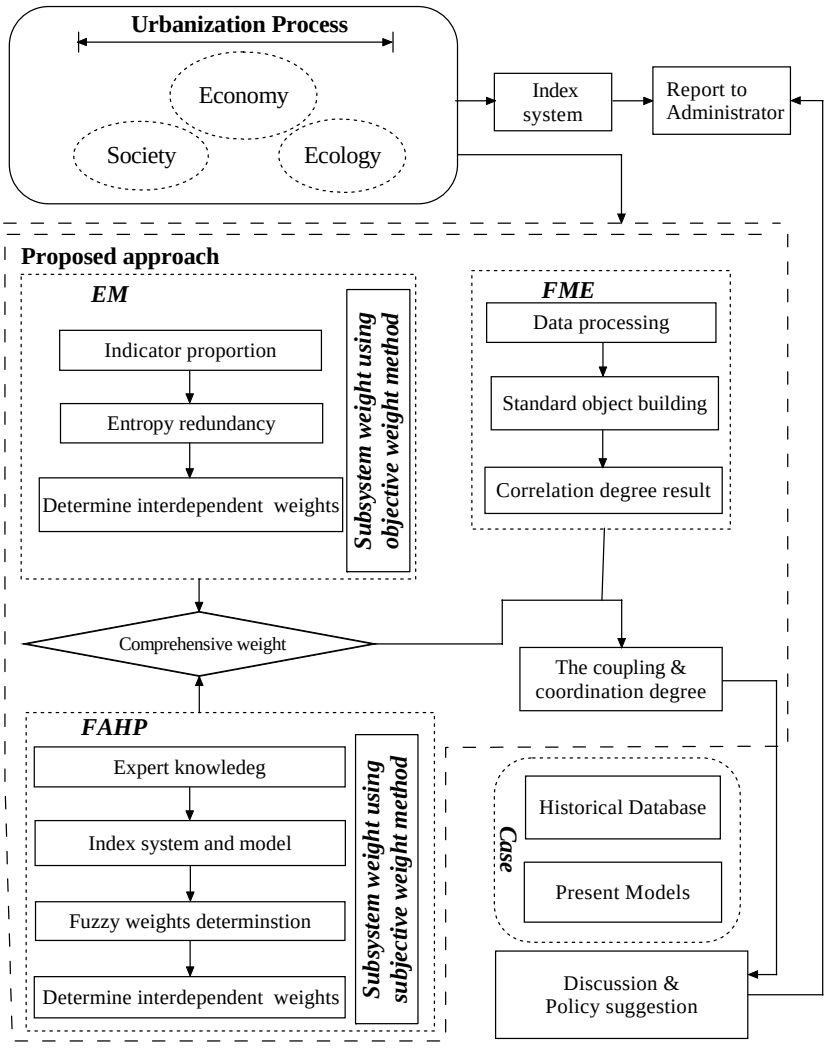


Figure 2. Proposed ESE-oriented model.



3.2. Proposed Research Framework

New methods for system matter-element analysis have been developed and adapted to suit systems theory applications, which have been successfully applied to handle complex system evaluation problems in many areas [50]. Condition weights can be calculated using the FAHP and EM. Based on actual investigations and theoretical analysis from the above discussion and the ESE three-dimensional subsystem given in Figure 1, the research framework is constructed as shown in Figure 2.

The ESE oriented model includes: (1) An urbanization system division: the economy, society and ecology (ESE); (2) analysis tools: FME, EM and FAHP; (3) planning objectives: the healthy development of urbanization (comprehensive level and coupling coordination degree); (4) Discussion and policy suggestions: analysis of urbanization level and harmonious degree; giving some guidance to decision makers.

4. Model Building

4.1. The Outside Representation and Indices for Evaluation of ESE

From the above definition, urbanization would be expected to be a compound ESE process. From previous studies [37,39,59] and following the principle of systematicness, completeness, effectiveness and operability, the indices were further selected through a comparison of the correlation coefficients and significance levels, as well as a qualitative analysis to place all the potential indices in economic, social and ecological categories. The following general selection criteria was adopted: (1) choose the most cited indicators; (2) cover the components of the ESE subsystem and the pertinent predetermined categories. The detailed index system is shown in Table 2.

Table 1. Index system used for measurement of urbanization.

Sub-system		**Index&Direction**
The integration value of Economic (E)	Economic structure	Per capita GDP (Yuan) +
		Per capita industrial output value (Yuan) +
		The proportion of output value between secondary industry and tertiary industry (%) +
		The proportion of GDP density between secondary industry and tertiary industry(%) +
	Land structure	Total urban area (Km^2) +
		Urban population density (persons/sq · km) -
The integration value of Society (S)	Life style	Number of doctors per 10,000 people +
		The per household electricity consumption (○/person) -
		People with college degrees (per 10,000 people) +
		Per capita area of roads (m^2/person) +
	Demographic	The nonagricultural population (million persons) +
		Percentage of nonagricultural population(%) +
		The proportion of the third industry practitioners(%) +

Table 1. *Cont.*

Sub-system		Index&Direction
The integration value of Ecology (E)	Environmental pressure	Discharge of industrial waste water (tons/capita) -
		Volume of sulfur dioxide emission by industry (t) -
		The per unit area industrial waste water emissions (t/km^2) -
	Environmental status	Cultivated area per capita (hm^2 /capita) +
		Land use per capita (sq.m/capita) +
		Water supply per capita (tons/capita) +
		Green area per capita (sq.m) +
	Environmental response	Ratio of industrial waste water meeting discharge standards (%) +
		Ratio of Industrial solid waste comprehensive utilization (%) +
		Total investment in the treatment of
		Environmental pollution as percent of GDP (Yuan) +

4.2. ESE Evaluation Based on the ME Theory and EM

4.2.1. The FME and Complex FME

4.2.1.1. FME

ME theory was first introduced by [60,61] for solving incompatibility problems. New methods of system matter-element analysis were created and adapted to suit its applications in system theory [50]. Systems can be divided to a set of matter-elements, with each element consisting of objects, characteristics and values which can be represented by the orderly ternary group $R = (M, c, v)$ [43]. If the value v is fuzzy, then the element is called fuzzy element. The object M, which is called an n-dimensional fuzzy matter-element, has n characteristics $(c_1, c_2, \ldots, c_n)$ and the corresponding fuzzy value $(v_1, v_2, \ldots, v_n)$. The n-dimensional m objects can be expressed as in the following matrix:

$$R_{mn} = (M, c, v) = \begin{bmatrix} M & c_1 & v_1 \\ & c_2 & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} = \begin{bmatrix} & M_1 & M_2 & \ldots & M_j & \ldots & M_m \\ c_1 & x_{11} & x_{21} & \ldots & x_{j1} & \ldots & x_{m1} \\ c_2 & x_{12} & x_{22} & \ldots & x_{j2} & \ldots & x_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_n & x_{1n} & x_{2n} & \ldots & x_{jn} & \ldots & x_{mn} \end{bmatrix} \quad (1)$$

where R_{mn} is an n-dimensional fuzzy matter-element, M_i is the ith matter ($i = 1, 2, \ldots, m$), c_j is the jth characteristic of the matter-element ($j = 1, 2, \ldots, n$) and x_{ij} is the fuzzy value of the characteristic in ith element. In this paper, C_i represents every factor (indices), M_i is every year from 2003 to 2012 and x_{ij} is the index value in ith year.

4.2.1.2. Preferred Membership in FME

The degree of correlation between each characteristic and each class was calculated using the following functions:

Positive indicators were used (larger value of parameter help)

$$u_{ij} = \frac{x_{ij}}{max\{x_j\}} \tag{2}$$

Negative indicators were used (smaller value of parameter help)

$$u_{ij} = \frac{x_{ij}}{min\{x_j\}} \tag{3}$$

where u_{ij} represents the value of preferred membership, and $max\{x_j\}$ and $min\{x_j\}$ indicate the minimum and maximum value of every evaluation indicator, respectively. The preferred membership fuzzy matter-elements can be built as follow matrix:

$$\widetilde{R}_{mn} = \begin{bmatrix} & M_1 & M_2 & \dots & M_j & \dots & M_m \\ c_1 & \mu_{11} & \mu_{21} & \dots & \mu_{j1} & \dots & \mu_{m1} \\ c_2 & \mu_{12} & \mu_{22} & \dots & \mu_{j2} & \dots & \mu_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_n & \mu_{1n} & \mu_{2n} & \dots & \mu_{jn} & \dots & \mu_{mn} \end{bmatrix} \tag{4}$$

The data were also standardized using formulas 2 and 3 for eliminating the influence of dimension, magnitude, and positive and negative orientation.

4.2.1.3. Classical Domain and Segmented Domain of ME

If a thing has m levels with $N_{01}, N_{02}, \dots$ and N_{0m}, the matter-element (R_{0j}) is

$$R_{0j} = (N_{0j}, c_i, X_{0ji}) = \begin{bmatrix} N_{0j} & c_1 & X_{0j1} \\ & c_2 & X_{0j2} \\ & \vdots & \vdots \\ & c_n & X_{0jn} \end{bmatrix} = \begin{bmatrix} N_{0j} & c_1 & < a_{01}, b_{01} > \\ & c_2 & < a_{02}, b_{02} > \\ & \vdots & \vdots \\ & c_n & < a_{0n}, b_{0n} > \end{bmatrix} \tag{5}$$

where N_{0j} is the jth evaluation level ($j = 1, 2, , m$); X_{0ji} is the jth-level value range of c_i, that is the classical domain. The range of X_{0ji} is an interval $< a_{0ji}, b_{0ji} >$, $i = 1, 2, , n$.

4.2.1.4. Correlation Degree Between Each ME Object and Standard Object

The standard fuzzy matter-element is constituted by the max or min index value of the preferred membership fuzzy matter-element $\widetilde{R}_{mn}$. The correlation degree matrix between each matter-element object and a standard object is expressed as follows:

$$R_{0n} = \begin{bmatrix} & M_0 \\ c_1 & u_{01} \\ c_2 & u_{02} \\ \vdots & \vdots \\ c_n & u_{0n} \end{bmatrix} \qquad \widetilde{R}_{\triangle} = \begin{bmatrix} & M_1 & M_2 & \dots & M_j & \dots & M_m \\ c_1 & \triangle_{11} & \triangle_{21} & \dots & \triangle_{j1} & \dots & \triangle_{m1} \\ c_2 & \triangle_{12} & \triangle_{22} & \dots & \triangle_{j2} & \dots & \triangle_{m2} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ c_n & \triangle_{1n} & \triangle_{2n} & \dots & \triangle_{jn} & \dots & \triangle_{mn} \end{bmatrix} \tag{6}$$

4.2.2. The Weight Determination Using the Hybrid Algorithm Along with EM and FAHP

There are two methods to compute weight, which are the subjective and objective weighting methods, such as AHP [62], Delphi [63], PCA [64] and the EM [65]. Athawale *et al.* [66] gave an extensive list of different MCDM methods and weighting techniques as employed by past researchers for material selection. Most of these weighting techniques were based on the judgment of the designer over the entire decision making process. The objective weighting methods determine the weight according to the relationship between the original data rather than subjective judgments. These methods do not increase the decision analysis burden and give the results a strong theoretical mathematical basis. For the objective weighting method, the EM is far more widely used than any of the other techniques.

4.2.2.1. EM

The weight of each indicator is calculated according to information entropy and variations in the indicators. The steps are as follows.

The proportion of the indicator:

$$s_{ij} = \frac{1 + u_{ij}}{\sum_{i=1}^{n}(1 + u_{ij})} \tag{7}$$

According to the definition of entropy, m elements with n indicators, the information entropy of the indicator can be computed as in the following equation.

$$e_j = -\frac{1}{lnm}\sum_{i=1}^{m} s_{ij} ln s_{ij} \qquad (0 \le e_j \le 1) \tag{8}$$

Entropy redundancy:

$$d_j = 1 - e_j \tag{9}$$

Weight of the indicator:

$$w_j = \frac{1 - d_j}{m - \sum_{j=1}^{n} d_j} \tag{10}$$

4.2.2.2. FAHP Method

From the entropy principle, the entropy weight indicates the variation degree of the index rather than the real importance. FAHP can deal with such ambiguous situations using membership functions and allows for multi-criteria and simultaneous evaluation. It has been successfully applied in the handling of complex but vague decision making problems in health management areas [67]. Therefore, the FAHP method, the details of which can be seen Xu and Xu [68], was used to amend the weight. λ'_j was assumed to be the weight computed using the FAHP method.

4.2.2.3. Blend Weights

The weights are determined by EM according to the variance degree of the indicators' value rather than the actual importance. Therefore, the weights computed using the entropy method are chosen when

the same sorting results are drawn between the EM and the FAHP. Otherwise, the weight is determined using the FAHP-EM integrated algorithm using the geometric method. The blended weights can be determined as in the following formula.

$$\begin{cases} w'_j = w_j, & \text{the same sorting results between ME and FAHP} \\ w'_j = \frac{\lambda_j w_j}{\sum\limits_{j=1}^{n} \lambda_j w_j}, & \text{otherwise} \end{cases} \tag{11}$$

Comprehensive level in year i:

$$S_i = \sum_{j=1}^{n} (w'_j \Delta_{ij}) \tag{12}$$

where n is the number of indicators, and m is the number of years.

4.3. The Coupling Coordination Degree Model of ESE

The concept of coupling, which means that two or more systems interact, is from physics [69]. The coupling degree is the measuring standard of this influence, which determines the way that the system goes when it reaches a critical value. The ESE coupling degree refers to the mutual actions, influences and relationships between economic, social and ecological urbanization. This can be computed using the following formula.

$$C_n = \frac{(\prod_{i=j}^{k} S_i)^{\frac{1}{n}}}{\prod \sum\limits_{i=j}^{k} S_i} \tag{13}$$

where, $k = 2, 3; i, j = 1, 2, 3; i \neq j$, $C_n (0 \leq C_n \leq 1)$ denotes the coupling degree. The economy, ecology and society reach a good coupling and move toward an ordered structure as the value of C_n increases.

Although the coupling degree of the economy, ecology and society can be derived, the real status cannot be fully reflected. For example, the developmental levels of all three are roughly equal but a lot of low level development would result in a high coupling degree. Then, the mathematical models for the quantitative characterization for all three can be established as in the following equations.

$$D = (C \times T)^{\frac{1}{2}} \tag{14}$$

$$T = \alpha S_1 + \beta S_2 + \gamma S_3 \tag{15}$$

where, D is the degree of coupling coordination and T reflects the overall effect on each other. A similar equation was adopted by [39] to test the level of urbanization and the environment. α, β and γ represent the contribution of the economy, society and ecology, respectively. In this paper, the importance of all three is considered equal. Therefore, to investigate these three sub-systems, the contribution value should be 1/3; for two of the three, the value should be 1/2 with the other being zero.

5. Case Study

5.1. Study Area

In this section, Chengdu, the first city that has claimed to be a modern world garden city in China, is chosen as an application to verify the approach outlined in the previous section. We apply the data and parameter values from Chengdu into the above model. Chengdu, formerly transliterated Chengdu, is the capital of Sichuan province in Southwest China (Figure 3) and holds a sub-provincial administrative status. The urban area houses 14,047,625 inhabitants: 7,123,697 within the municipality's nine districts and 6,730,749 in the surrounding region. Chengdu is one of the most important economic, transportation, and communication centers in Western China. According to the 2007 Public Appraisal for the Best Chinese Cities for Investment, Chengdu was chosen as one of the top ten cities to invest in out of a total of 280 urban centers in China. In late 2009, the city committee and government made the development of a world modern garden city its historic positioning and long-term target based on in-depth research, sufficient analysis and extensive public participation in the notion. It presents an attempt to capitalize on the historic opportunities generated by the prosperity of China to further the urban-rural integration, and push along the strategic transformation of growth models so that the city can better contribute to the new round of opening-up and development activities in western China, and to the provinces strategic move to become the top driving force in the development of western China [70].

Figure 3. Location of Chengdu, Sichuan, China.

5.2. Simulation

For this paper, data was collected from 2003–2012. The reasons why those data were chosen were as follows: One of the main reasons is that the time span of government planning was usually five years. Therefore, two recent spans were investigated (The data in 2013 couldn't be obtained due to the delay of statistics). The other reason is that the benefit of the policy usually comes up late in the city regions. The start year is chosen from 2003 instead of 2000 although the start year of the government's tenth national five-year plan is 2000. In addition, the world garden city strategy was presented in 2009.

The effect can also be viewed from data before and after policy adjusting. To apply the proposed assessment and coordination model, the required data were collected from the Statistical Yearbook of Chengdu (2003–2012) and an expert team consisting of 15 experts from ESE sectors (from academic, research and urban planing) was consulted. The modeling steps together with the results are explained as follows.

Step 1: To measure the weight, the index system was first established as shown in Table 2. The FAHP hierarchal model structure was based on the index system as shown in Figure 4. The model is composed of four levels. At the top level of the hierarchy, the weight assessment goal for the ESE is located. The related criteria are located on the second level and the corresponding sub-criteria are located on the third level. On the fourth level, there are fuzzy scalars which are used in the evaluation of the sub-criteria condition weights. As in the algorithm in Xu and Xu [68], the index weights were calculated and are shown in Table 3.

Step 2: From the index in Table 2, the EM was used. The original data (2003–2012) describing the 24 indicators for Chengdu were processed using Equations (7)–(12). The weights for the urbanization process sub-system indicators are shown in Table 3.

Step 3: In a traditional ME method, the classical domain and the section domain need to be established. The interval size for the classical domain and the section domain is one subjective option, which introduces other sources of error. Therefore, in this paper, the idea of TOPSIS [71] was adopted. The ideal solutions (the max and min value of original data (2003–2012) in each of the indicators) are used to determine the classical domain interval.

$$M^{+} = (max(u_{ij})|i \in I), (min(u_{ij})|i \in I') = \{x_1^{+}, x_2^{+}, \ldots, x_n^{+}\} \qquad j = 1, \ldots, m \tag{16}$$

$$M^{-} = (min(u_{ij})|i \in I), (max(u_{ij})|i \in I') = \{x_1^{-}, x_2^{-}, \ldots, x_n^{-}\} \qquad j = 1, \ldots, m \tag{17}$$

where, I is the positive indicator set, and I' is the negative indicator set. Then, the correlation degree between each factor and the evaluation was calculated using the following functions:

$$u_{ij}^{+} = 1 - |u_{ij} - x_i^{+}|, \qquad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{18}$$

$$u_{ij}^{-} = 1 - |u_{ij} - x_i^{-}|, \qquad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{19}$$

$$\triangle_{ij} = \frac{u_{ij}^{+}}{u_{ij}^{+} + u_{ij}^{-}}, \qquad (i = 1, 2, \ldots, n; j = 1, 2, \ldots, m) \tag{20}$$

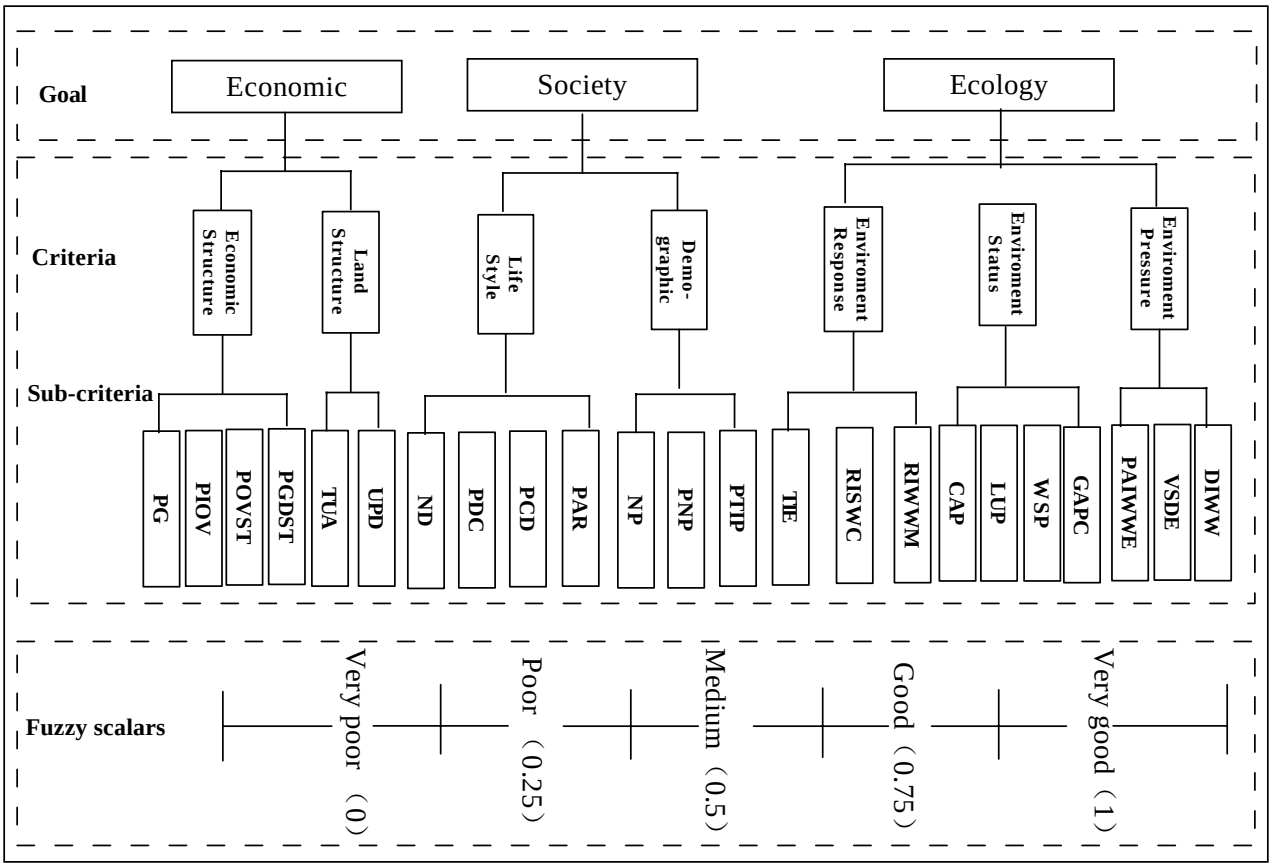
Taking a single index (PG) as an example, the original data for the PG was taken from 2003 to 2012 as follows (14,632, 17,158, 19,670, 22,445, 26,849, 31,203, 35,215, 41,253, 48,794, 57,841 (yuan)). Considering the Equation (2), the data should be (0.24, 0.30, 0.34, 0.39, 0.46, 0.54, 0.61, 0.71, 0.84, 1.00). The corresponding correlation degree between this indicator and relevant ideal grade is as follows: ($\triangle_{11} = 0.20, \triangle_{12} = 0.24, \triangle_{13} = 0.27, \triangle_{14} = 0.31, \triangle_{15} = 0.37, \triangle_{16} = 0.43, \triangle_{17} = 0.49, \triangle_{18} = 0.57, \triangle_{19} = 0.68, \triangle_{10} = 0.80$). The corresponding correlation degree of the other indicators and each ideal level can be obtained using the same method.

Step 4: The sub-criteria global weights can be determined using Equation (11), which is shown in Table 3. Correspond- ingly, the comprehensive level for the economy, society and ecology in every year can be determined using Equation (12).

Table 2. Weights of ESE indicators.

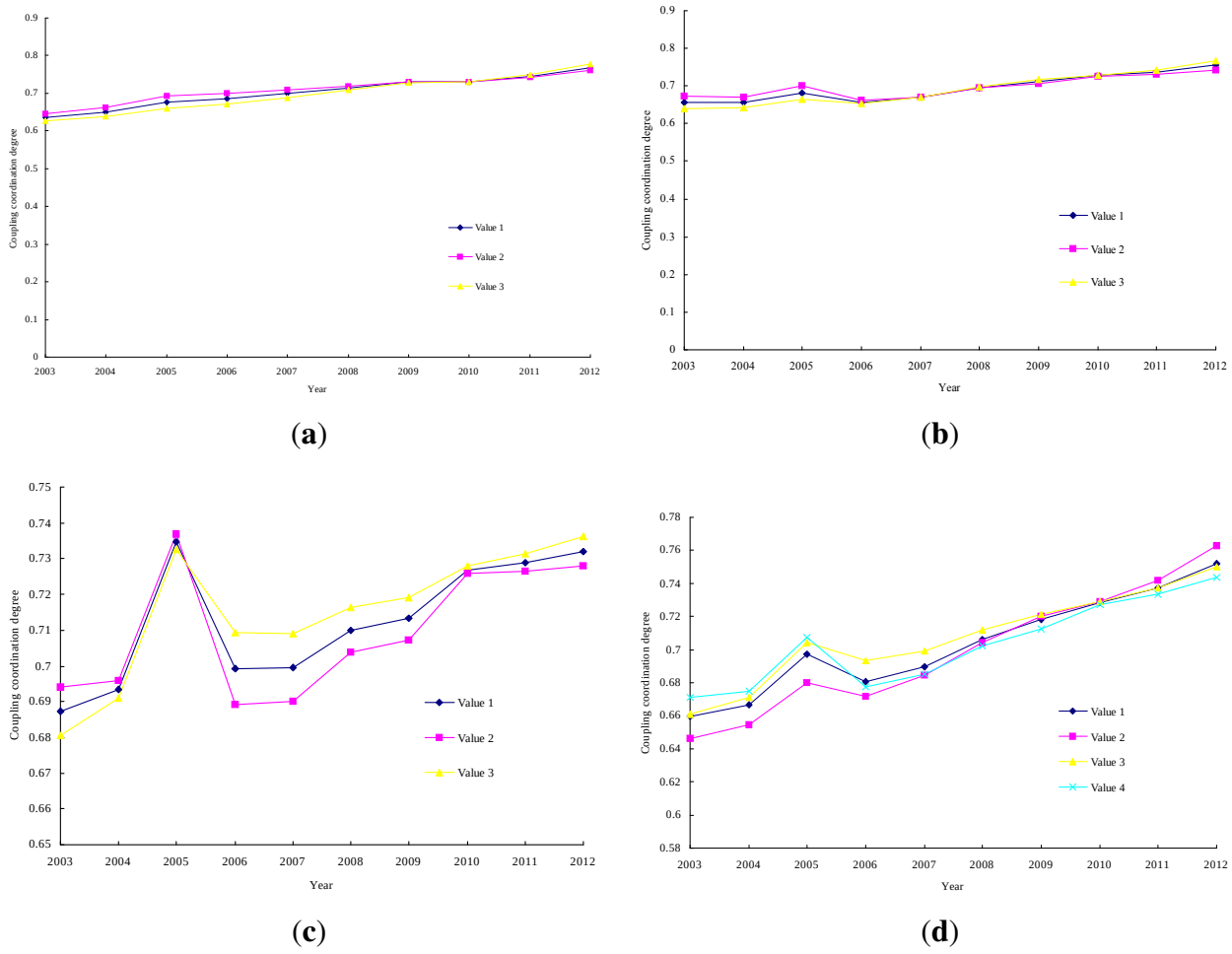
Goal	Criteria	Sub-criteria	Local weights by FAHP	Local weights by ME	Comprehensive local weights	Comprehensive global weights
Economic subsystem	Economic structure	PG	0.1916	0.2270	0.3254	0.1081
		PIOV	0.1389	0.2564	0.2664	0.0885
		POVST	0.1556	0.1364	0.1588	0.0527
		PGDST	0.1830	0.1822	0.2494	0.0828
	Land Structure	TUA	0.1178	0.1700	0.6079	0.0497
		UPD	0.0802	0.1610	0.3921	0.0321
Society subsystem	Life style	ND	0.1614	0.0595	0.1139	0.0239
		PDC	0.1534	0.2305	0.4205	0.0881
		PCD	0.1046	0.2255	0.2798	0.0586
		PAR	0.1854	0.0845	0.1858	0.0389
	Demographic	NP	0.1512	0.1305	0.3762	0.0490
		PNP	0.1289	0.1275	0.3133	0.0408
		PTIP	0.1151	0.1415	0.3105	0.0405
Environment subsystem	Environmental pressure	DIWW	0.0993	0.0860	0.3190	0.0212
		VSDE	0.1317	0.0678	0.3334	0.0222
		PAIWWE	0.1023	0.0909	0.3476	0.0231
	Environmental status	CAP	0.0413	0.1058	0.0995	0.0109
		LUP	0.0740	0.0678	0.1142	0.0125
		WSP	0.0910	0.1950	0.4040	0.0441
		GAPC	0.1270	0.1322	0.3823	0.0417
	Environmental response	RIWWM	0.1227	0.1091	0.4719	0.0333
		RISWC	0.1140	0.0529	0.2126	0.0150
		TIE	0.0967	0.0926	0.3155	0.0222

Figure 4. FAHP hierarchy model of weight assessment for comprehensively urbanization. Note: The related indexes can be referenced in Table 1 PG: Per capita GDP; PIOV: Per capita industrial output value; POVST: The proportion of output value between secondary industry and tertiary industry; PGDST: The proportion of GDP density between secondary industry and tertiary industry; TUA: Total urban area; UPD:Urban population density; ND: Number of doctors per 10,000 people; PDC: The per household electricity consumption; PCD:People with college degrees (per 10,000 people); PAR: Per capita area of roads; NP: The nonagricultural population; PNP: Percentage of nonagricultural population; PTIP: The proportion of the third industry practitioners; DIWW: Discharge of industrial waste water; VSDE: Volume of sulfur dioxide emission by industry; PAIWWE: The per unit area industrial waste water emissions; CAPC: Cultivated area per capita; LUP: Land use per capita; WSP: Water supply per capita; GAPC: Green area per capita; RIWWM: Ratio of industrial waste water meeting discharge standards; RISWC: Ratio of Industrial solid waste comprehensive utilization; TIE: Total investment in the treatment of Environmental pollution as percent of GDP.



Step 5: With the results of each subsystem above, using the Equations (14) and (15), the coupling and coordination degrees from 2003 to 2012 for the economy, society and ecology subsystems can be determined as shown in Figure 5.

Figure 5. The trends of the coordinated coupling degree. (**a**) Trends of the ES coordinated coupling degree; (**b**) Trends of the EE coordinated coupling degree; (**c**) Trends of the SE coordinated coupling degree; (**d**) Trends of the ESE coordinated coupling degree.



5.3. Results and Discussion

Based on the statistical data from 2003–2012, we simulated the development of Chengdu from three perspectives as described in Figures 6–8: the ESE subsystem comprehensive level trends. We then synthesized the results to provide a single coupling coordination indicator for the ESE system.

5.3.1. Comprehensive Trend Analysis

From Figure 6, it can be seen that the comprehensive level of the economic subsystem increased over the past 10 years. A 0.37 level in 2003 had reached 0.63 by 2012, representing a 70% increase. Obviously, from this it can be surmised that Chengdus economy maintained a rapid growth trend. From 2003 to 2009, the degree for the economic subsystem rose rapidly (about two or four points) and then stabilized, slowing in 2009 and 2010 (about 0.5 points). The main reason for this may be an after effect of the Wenchuan earthquake. An similar inference was also be drawn by previous study [72]. After 2010, the growth trend gradually accelerated at a similar rate to the pre-earthquake rate.

Figure 6. Trends of the urbanization and every subsystem.

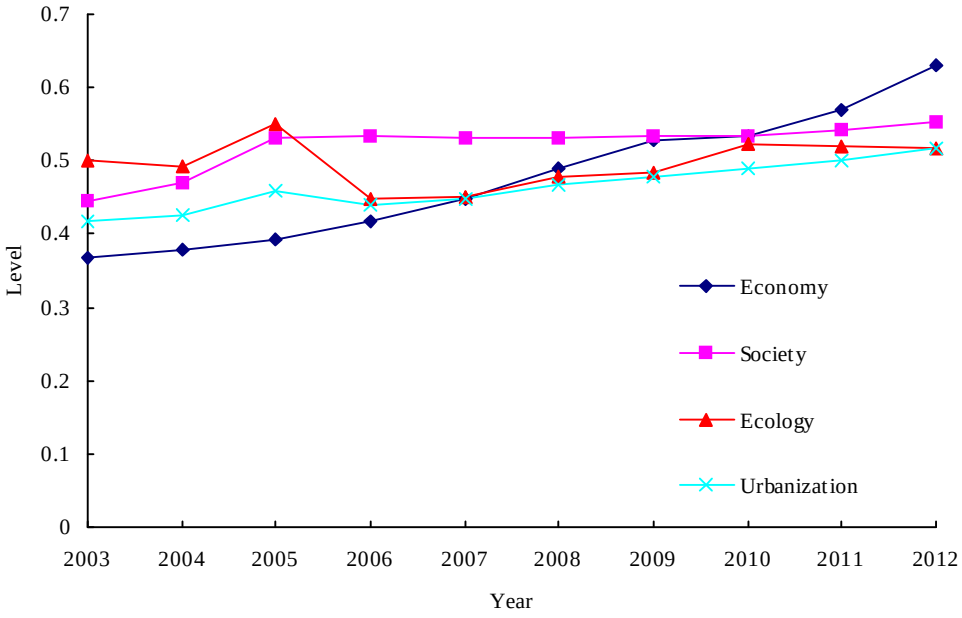
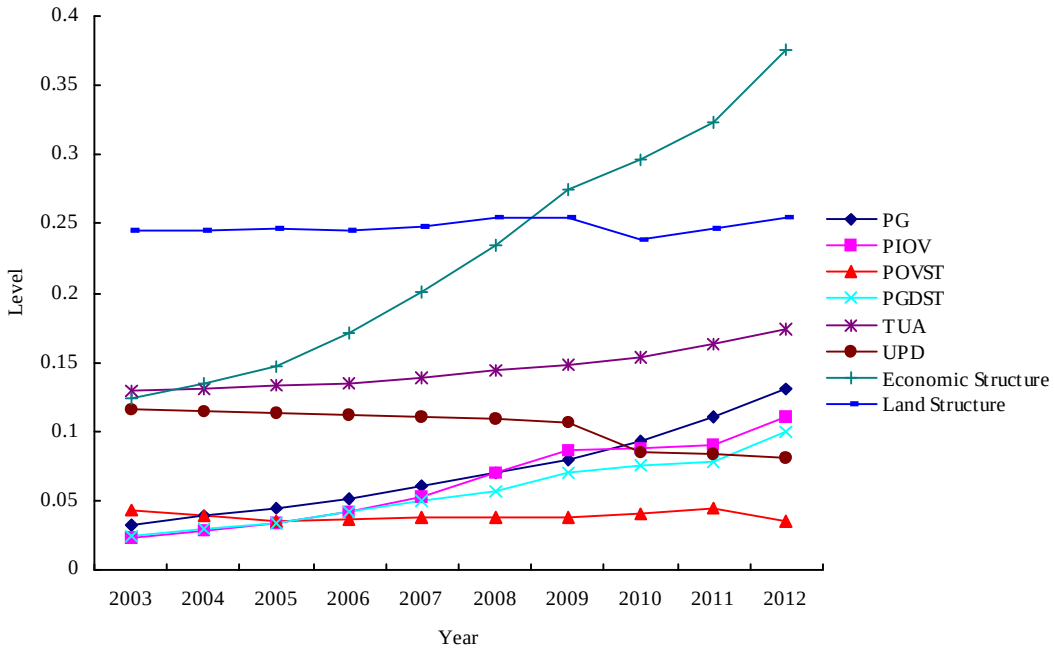


Figure 7. Trends of comprehensive levels in the economy subsystem.

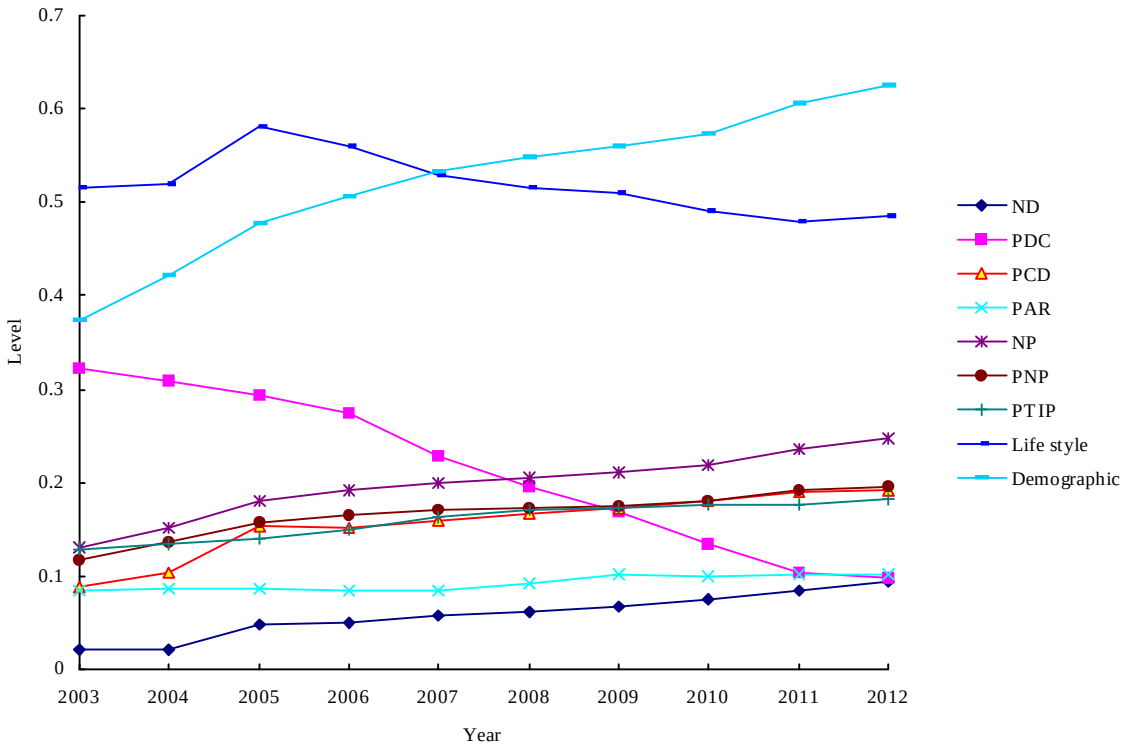


The overall level of the social subsystem showed an increasing trend from 2003 to 2012 in Chengdu, but had a weak effect after 2005. A 0.44 level in the 2003 reached 0.55 at 2012, a 25% increase. However, there was only 5% growth from 2005.

The level of the comprehensive ecological subsystem increased from 2003–2012, but with a weak effect. A 0.50 level in the 2003 reached 0.52 in 2012, a 4% increase. In 2006, the values of the ecological sub-system has a suddenly decline. Conversely, the status curve showed an increasing trend (with an 35.7% increase) over the 10 years as the city rapidly urbanized. This indicates that the ecological

strategy which commenced from 2007 is effective. However, there was a significant decline in recent two years, which indicated that the ecological environment should be noticed in rapid urbanization process.

Figure 8. Trends of comprehensive levels in the society subsystem.



The comprehensive urbanization level shown a obvious phase characters. From 2003 to 2006, the urbanization level was higher than economy and lower than society and ecology level. With the inflection point occurring in 2006, it lagged behind economy and society, ahead of ecology. From 2007–2012. The trend was along with the society development curve (The Pearson correlation coefficient was 0.96 between urbanization and society, and 0.79 between economy and urbanization, 0.42 between ecology and urbanization, respectively), which indicated society aspects had the greatest effect on the urbanization level. Therefor, social issues is highly important in the determining urban policies and planning guidelines for urbanization policy makers. The conclusion corroborates the results of previous studies in Chinas other regions [39].

5.3.2. The Each Subsystem Development Level Analysis

5.3.2.1. Economic Subsystem

The economic structure trend was fairly consistent with the comprehensive economy level, which presented phased development characteristics (Figure 7). That is to say that economic structure aspects had global weights shown in Table 3. The PG (0.1081) had the maximum weight and PIOV (0.0885) came in second, which suggested that the rapid industrialization was the main determiner in the evolution of economical urbanization. This was followed by PGDST, POVST. Conversely, the impact indicators that had the smallest effect were the POVST (0.1364 was shown in local weights by ME, primarily

because the smaller the difference between these numbers, the lower the entropy weight). In fact, the POVST even has a tiny decline from 0.0437 in 2003 to 0.0351 in 2012, and the growth rate is extremely unchanged in all stages. The main reason for these results is that rural over-industrialization caused the development of the service sector to be very weak. This corroborates the results of previous studies [7].

The land curve shown that there was almost unchanged (from 0.24 in 2003 to 0.25 in 2012). The variable land structure has an positive relationship with TUA and negative correlation with UPD. It can be conclude that the effect of urban encroachment was offset by the population density.

5.3.2.2. Society Subsystem

To investigate the specific indicators (local weights by ME in Table 3 with the same reason as in the above case), the PDC and PCD had the maximum weight, which indicates that electricity consumption and college students were important development indices. The main reason about PCD was the policy of expanding enrollment in higher education adopt by China since 1999. The variable PCD has a positive relationship with social urbanization, which means that as the more high quality characterized population, the greater the level of social urbanization will be. However, a surge in electricity consumption (PDC) meant that the corresponding electricity services were required to grow as urbanization increased. The impact indicators that had the smallest effect were the ND (0.0595) and the PAR (0.0845), which indicates that the urbanization process was highly uneven. These results shows that the social urbanization process is extremely unbalanced and that health and urban transport conditions should be urgently improved.

From the demographic aspect, all three variables had almost the same weights and a fast growth rate (Figure 8). The conclusion on PTIP was different from the Chen *et al.*'s research (The labor force trend in secondary and tertiary industries only had a small growth in their research) [7]. The main reason for this difference is that population urbanization and industrialization would increase the labor opportunity cost in recent 10 years. The peasant worker shortage has become a common phenomenon in most Chinese cities [73].

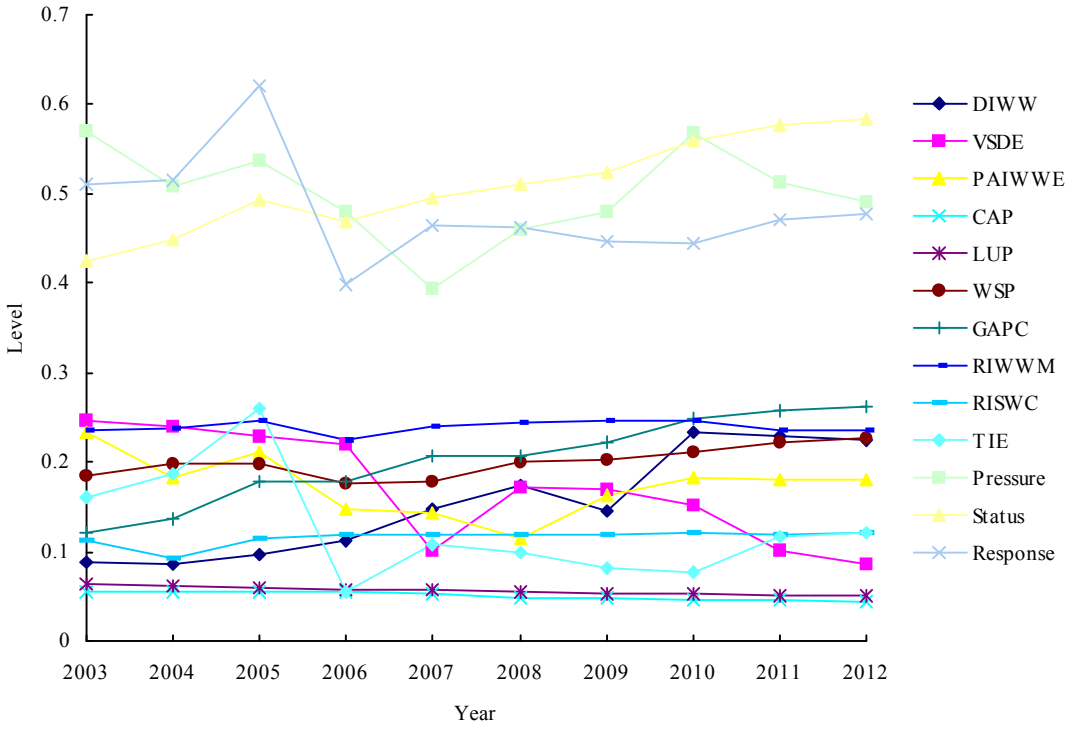
5.3.2.3. Ecological Subsystem

The ecology aspect was investigated from Press-State-Response (PSR) framework [74]. Actually, the response as the driving force was to promote the ecology subsystem development. Relatively speaking, the status and pressure factor were passive and was stimulated by response index. The environmental response trend from 2003–2006 was fairly consistent with the comprehensive ecological level, while from 2007–2012 the environmental status and the environmental pressure was consistent with it (The Pearson correlation coefficients between comprehensive level and pressure, status and response, respectively, in two period as follows: The first period (2003–2006): 0.6494, 0.3322, 0.9909; The second period (2007–2012): 0.9102, 0.9475, 0.7980). The same conclusion was drawn by previous research [39], which indicated that policy makers had made a certain amount of the work on ecological improvement.

There was a obvious turning point in 2006 about all four curves because the three indices values simultaneously decreased. From 2006, the status curve showed an increasing trend (with an 35.7%

increase) over the 6 years as the city rapidly urbanized (Figure 9). This indicates that the ecological strategy which commenced in 2007 has a certain effect .

Figure 9. Trends of comprehensive levels in the ecology subsystem.



From the weights of each indicator (Table 2), WSP (0.1950) and GAPC (0.1322) had the greatest impact on the ecological subsystem. This indicates that the water supply and green areas, which are considered to be the most vulnerable indices on status, were more significant change than other factors and should be deserved more protection. A conclusion can be also drawn similar to that in Li *et al.* [39] for Lianyungang city in China.

5.3.3. The Coupling Coordination Degree Evaluation and Analysis

The coordinated degree of coupling is the most important indicator we want to check. Here the parameter of different values of abc that influence the result are examined. Different α, β and γ (Value 1: α=β=γ=$\frac{1}{3}$; Value 2: α=β=$\frac{1}{4}$ and γ=$\frac{1}{2}$; Value 3: α=γ=$\frac{1}{4}$ and β=$\frac{1}{2}$; Value 4: β=γ=$\frac{1}{4}$ and α=$\frac{1}{2}$.) were used respectively for three subsystem. Different α, β (Value 1: α=β=$\frac{1}{2}$; Value 2: α=$\frac{1}{3}$ and β=$\frac{2}{3}$; Value 3: α=$\frac{2}{3}$ and β=$\frac{1}{3}$) were also used respectively for two of the three. Every coupling coordination curve with different weight values shown a consistent overall trends, only slightly difference, which meant the coordinated coupling degree was not sensitivity to the weight of three subsystem. The previous research also comes to the same conclusion [39].

5.3.3.1. Economy-Society (ES) Analysis

The value of ES increased over 10 years, which means the coupling coordination is in continuous refinement phase between economy and society subsystem. Investigating the specific process, the value

during 2003–2009 kept stable increasing, but a a short pause at 2009–2010, then increasing again using former rate. In connection with Figure 5a, the value trend was fairly consistent with the economy subsystem, which suggested that the economy development had the greatest effect on the ES value. The main reason for this result is that the development of economy will has positive effects on social aspects in initial stage, such as social mobilization, literacy, education, income, and health [75,76]. However, there was a slight decline trend in recent two year, which also suggested that the two had adverse effects on each other.

5.3.3.2. Economy-Ecology (EE) Analysis

The value for the EE increased almost from 0.45 to 0.55 over the 10 years, indicating an increase in the balance between the two (Figure 5b). There was an obvious decrease from 2005–2006, the main reason of which could be deduced that the rapid economic development was beyond the capacity of the ecology (with Figure 6). The cumulative effect can be seen in Figure that there was a apparent decline in 2006. The slow rise from 2003–2005 illustrates there was an ecological residual relative to the economy. Since 2006, which was the start year of Chinas 11th-plan, the ecological Sichuan strategy was launched. From then on, the world garden cityplan for Chengdu was laid out with a commencement in 2009. Establishing a ecological city became a primary policy for urbanization. The coupling level increased in recent 6 years by policy effect. However, the rate of increase was becoming more slower, which suggested that the rate of the economic development in terms of the ecological environment was greater than the sound rate.

5.3.3.3. Society-Ecology (SE) Analysis

From Figure 5, an overall increasing trend (almost from 0.48 to 0.53 over 10 years) appeared to occur from 2003–2012, resulting in the society and the ecology becoming better coordinated. Similar to the EE trend, there was also an obvious decrease from 2005–2006, with the main causes being in the ecological development. At the early stage (from 2003–2005), the ecological residual brought improvements in social welfare [39]. In 2006, the accumulative effect of the ecological overuse began to appear and caused the turnaround. After 2006, the ecological sub-system was steadily improving because of the active policy mentioned above and the urban area expansion, which resulted in a slower increase in the coordination degree.

5.3.3.4. Economy-Society-Ecology (ESE) Analysis

The value of the ESE increased roughly from 0.42 to 0.52 over the 10 years, which indicates that the coordination in the ESE was in a promotional process. The ESE aspects showed a more similar trend to the SE and EE curves (The Pearson correlation coefficients between ESE and ES, EE and SE was roughly 0.8447, 0.9816 and 0.9697, respectively), which indicates that ecological aspects (because it is a common factor) had the greatest effect on the ESE coordination. Through an analysis of the ES, EE and SE above, the economic development rate was greater than that of either the society or the ecology. This rapid urbanization had a very strong effect on resources, energy and the environment. Policy makers

need to pay more attention to ecological issues and, in particular, the ecological construction of cities should become a focal point, and be considered a vitally important measure in solving city problems.

5.3.4. Policy Suggestion

The purpose of the coordination degree analysis of the economy, society and ecology is to guide urban planning. From this analysis , it can be seen that the Chengdu's overall urbanization level shows a better coordination effect. Specifically, some policy implications were proposed for potential future policy decisions.

- Through this study, the proportion of GDP between secondary industry and tertiary industry change in Chengdu was small, which indicated that Chengdu's economic growth is mainly driven by secondary industry and the increase of material resources consumption. Therefore, we need to strengthen the industrial structure adjustment to reduce investments in resources, and improve the efficiency of the economic development [58]. Moreover, the economy is developing too fast compared with society and ecology; the combination of a reasonable velocity and the quality and quantity development for the economy should be considered.
- In the society aspect, the household's welfare level (*i.e.*, number of doctors) and urban soft environmental construction (*i.e.*, urban transportation and public utilities) should be improved. The investment proportion for production and social infrastructure should be increased, which could assist urban residents to fully appreciate the benefits of economic growth [77].
- Through the above analysis, ecological construction appears to be a key factor in the determination of the coordination degree of the EE, ES and ESE in Chengdu's study. In our study, the change value of per unit area industrial water water in pressure was biggest, and the ratio of industrial solid waste comprehensive utilization was smallest, which suggested that there needs to be an increase in such guidance through the development of policies for economic investment, market mechanism stimulation and public awareness raising, to respond to potential ecological problem.

6. Conclusions

The urban sustainable development dominance is more tightly locked to the planet than ever. Measuring cities' comprehensive carrying capacity is a fundamental problem. Urbanization development represented different degrees due to different economic, social, and environmental development processes. The paper integrated both the ESE factors to evaluate the comprehensive status, named the coupling coordination degree. Therefore, urbanization sustainability was analyzed by systemic analysis and dynamic modeling. Three subsystems–economy, society and ecology aspects–were considered in this paper. The improved fuzzy matter-element method hybrid with TOPSIS idea that was used to solve the interval decision difficulty, was conducted to evaluate the development level of the economy, society and ecology, which was able to compartmentalize the specific types and effectively evaluate each level objectively and scientifically. The subjective (FAHP) and objective (ME) hybrid algorithms were used to choose index weights. Then, a coupling coordination degree model was developed instead of relying on the traditional coupling degree model. Chengdu, China was used as an example, to simulate the results from 2003 to 2012. According to the results, the economic development speed was higher than

social and ecological sector. The comprehensive urbanization development level shown a obvious phase characters which can be divided two period as that the first: 2003–2006 and the second: 2007–2012. To investigate every subsystem, per capita GDP and per capita industrial output value for economy subsystem, per household electricity consumption and people with college degree for society subsystem and water supply per capita and green area per capita were the fastest-changing indicators, which made greater contributions to urbanization level. Conversely, the proportion of output value between second industry and tertiary industry, number of doctors per 10,000 people and cultivated area per capita has the smallest weights in their subsystem, which meant the slow-growing indicator should be more attention. To adjust and upgrade industrial structure, improve medical conditions and create a livable region should be considered a priority. To identify a sustainable urbanization coordination degree, a sensitivity analysis on every subsystem weights was designed to compare the suitability, which indicated that the parameters had little effect on it. These findings from coordination degree evaluation indicated economic growth was developing too fast relative to the society and ecology in Chengdu and the ecological aspects had the greatest effect on the ESE coordination. This research suggests that the ecological subsystem would be the limiting aspect for urbanization development and should be considered more.

This paper also presented an integrated approach to modelling the ESE System in urbanization process. The results provided an alternative approach for measuring comprehensive development quality of urban and can be used to help policy makers to check whether an ongoing process of every aspect in urbanization was in reasonable speed and structure consistent with the sustainable principles. Because various practices of urbanization exist due to different backgrounds [76], the proposed model also could be applied in various urbanization processes by changing details (*i.e.*, index system). Moreover, the improvement index system, qualitative index processing and the details of the urbanization coordination mechanism and the countermeasures should be considered explicitly in future analysis.

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Author contributions

In this paper, Yunqiang Liu and Jiuping Xu developed the research ideas and global design; Yunqiang Liu also collected the data and completed empirical analysis; Huawei Luo carried out the research about discussions and completed the writing work of corresponding parts with Yunqiang Liu.

Conflicts of Interest

The authors declare no conflicts of interest.

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