Research on Sustainable Development Level Evaluation of Resource-based Cities Based on Shapely Entropy and Choquet Integral

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Abstract: In order to evaluate sustainable development level of resource-based cities, an evaluation method with Shapely entropy and Choquet integral is proposed. First of all, a systematic index system is constructed, the importance of each attribute is calculated based on the maximum Shapely entropy principle, and then the Choquet integral is introduced to calculate the comprehensive evaluation value of each city from the bottom up, finally apply this method to 10 typical resource-based cities in China. The empirical results show that the evaluation method is scientific and reasonable, which provides theoretical support for the sustainable development path and reform direction of resource-based cities.

1. Introduction

Resource-based cities mean that the cities are dominated by the mining and processing of natural resources such as minerals and forests in its region. Since the founding of new China, China’s resource-based cities are numerous and widely distributed. They have made indelible historical contributions to China’s industrial development and economic upgrading. However, due to the scarcity and non-renewable nature of many resources, some resource-based cities encounter the problem of resource depletion. Maintaining the sustainable development of resource-based cities and transforming resource-exhausted cities has been put on the agenda. In 2017, “Transformation of Resource-based Cities in China” reported by Peking University pointed out that China’s resource-based cities have entered a new phase of transition and sustainable development. Therefore, the sustainable development level evaluation of resource-based cities has a very important practical significance.

For the research on the sustainable development level evaluation of resource-based cities, both domestic and foreign scholars have conducted corresponding research and analysis. On foreign aspects, such as: Nourry [1] for some cities in France, the status of sustainable development conducted a detailed study and put forward the corresponding development proposals; Kondyli [2] conducted a field survey on the North Aegean Island region, pointed out the main impact indicators in the process of sustainable development. Klein J A, Yeh E and Bump J [3] point out the transition from a management perspective to a governance perspective of resource-based cities in terms of climate and ecological environment. Esanov A [4] pointed out the problems in transformation process of resource-exhausted cities, indicating relative policy support that the country should give. Domestic aspects, such as Yang Xianming, Jiaohuafu and Xu Jili [5] compared and analyzed the urban spatial expansion, characteristics and influencing factors of different stages of resource-based cities in Huainan and Huaibei. Wang Keliang, Yan Huibin and Meng Xiangrui [6] combined the factor analysis with the entropy method to construct a measure model. Guo Cunzhi, Luo Linlin and Ye Ming [7] used factor analysis to establish a data panel model, analyze the influencing factors of sustainable development of resource-based cities from different aspects. Song Yuchen, He Wei, Zhang Pu and Han Yan [8] constructed BP neural network
model to analyze and predict the index of resource-based city’s sustainable development level. Zhao Dandan and Gao Shikui [9] build a resource-based city’s sustainable development level evaluation system based on AHP. Most of existing researches stay at the theoretical level. Although many scholars have set up impact index system for them, the qualitative systematic evaluation is not perfect enough. Based on the impact index system constructed by scholars, this paper uses the maximum Shapely entropy principle to weight the attributes so as to eliminate the complexity of the correlation between attribute indices. Then, the Choquet integral is used to establish a level-by-level assessment model to make a reasonable assessment of resource-based city’s development status, thus responding to the transformation of resource-based cities in our country.

2. The sustainable development level evaluation index system of resource-based city
Since the establishment of sustainable development index system firstly proposed at the World and Environment Development Conference in 1992, the research on indicators of sustainable development has gradually become a hot issue in the field of sustainable development research, then building a reasonable and scientific indicator system of sustainable development plays a crucial role in implementing the sustainable development strategy. The scholars in different countries have built a rich and perfect index system of sustainable development. However, as a special kind of city classification, resource-based cities not only share common characteristics with ordinary cities, but also have their own unique characteristics and development paths. Therefore, establishing a scientific and reasonable sustainable development level evaluation index system of resource-based cities can’t be completely generalized and completely follows the existing research results. It needs a comprehensive analysis based on its urban characteristics.

As a kind of city that undertakes special economic functions, resource-based cities show their unique characteristics in the economic and social development: Highly dependent resources, single economic structure, cyclical, environmental governance is under tremendous pressure, and presents Northam S-curve theory. Based on the perfect sustainable development index system, consider resource-based city’s characteristics and their development characteristics, this paper starts from the four dimensions of economic subsystem, social subsystem and resources and environment subsystem under the complex system of resource-based cities, to build the sustainable development level evaluation index system in line with resource-based city(Table 1).

| Sustainable development level of resource-based city(V) | GDP                                                                 |
|--------------------------------------------------------|----------------------------------------------------------------------|
|                                                      | The proportion of Tertiary Industry in GDP                           |
|                                                      | Investment in fixed assets                                           |
| Economy subsystem(V1)                                 |                                                                       |
|                                                      | Education Resources                                                 |
|                                                      | Social Security                                                     |
| Social subsystem(V2)                                  |                                                                       |
|                                                      | Natural population growth rate                                       |
| Resource subsystem(V3)                                |                                                                       |
|                                                      | Resource development and utilization rate                            |
|                                                      | Resource year extraction                                            |
|                                                      | Energy Survival Elasticity Coefficient                              |
| Environment Subsystem(V4)                             |                                                                       |
|                                                      | Green coverage                                                      |
|                                                      | Environmental carrying capacity                                     |
|                                                      | Ecological governance investment in GDP ratio                       |

3. Sustainable development level evaluation of resource-based city based on Shapely entropy and Choquet integral
As can be seen from Table 1, the resource-based city is a complex system composed of four subsystems: economic subsystem, social subsystem, resource and environment subsystem, we need to make a
scientific, reasonable and objective assessment of resource-based city’s sustainable development level to maintain the composite system in a relatively balanced state. In the process of evaluating the index construction, Shapely function is introduced to calculate the importance of attribute and attribute set, then use the Choquet integral calculate program evaluation value to solve the problem of lack of relevance information, which is conducive to making a comprehensive and objective assessment of resource-based city’s sustainable development level.

3.1 Basic theory

3.1.1 Shapely entropy. The Shapely method is a kind of interactive influence thought proposed by Shapely L.S. [10] in solving multi-person cooperative game. The Shapely value is mainly an indicator of the important contribution of participants in the cooperation process. After that, Yager [11] defined the entropy based on discrete fuzzy measure - Shapely entropy according to the Shapely value, which is used to describe the uncertainty of information based on fuzzy measure and ensure the objectivity of weighting.

Definition 1 Let \( X = \{x_1, x_2, \ldots, x_n\} \) be a finite set, \( W(X) \) is the power set of \( X \). Let \( \vartheta \) be the fuzzy measure of \( W(X) \), \( \forall x_i \in X \). Shapely value can be defined as:

\[
I(x_i) = \sum_{k=0}^{n-1} \delta_k \sum_{T \in X/x_i} [\vartheta(T \cup x_i) - \vartheta(T)]
\]

Where \( \delta_k = (n - k - 1)! / n! \), \( |T| \) is the potential or element number of the set \( T \). \( I(x_i) \) is the contribution of the uncertain variable \( x_i \) to the set \( X \), and \( I(x_i) \in [0, 1] \), \( \sum_{i=1}^{n} I(x_i) = 1 \).

Definition 2 Let \( X = \{x_1, x_2, \ldots, x_n\} \) be a finite set, \( W(X) \) is the power set of \( X \). Let \( \vartheta \) be the fuzzy measure of \( W(X) \), Shapely entropy \( H \) is the uncertainty measure of \( \vartheta \):

\[
H[\vartheta(x_i) | x_i \in X] = -\sum_{i=1}^{n} I(x_i) \ln I(x_i) \quad \text{where:} \quad I(x_i) = \sum_{k=0}^{n-1} \delta_k \sum_{T \notin X/x_i} [\vartheta(T \cup x_i) - \vartheta(T)]
\]

3.1.2 Fuzzy measure and Choquet integral. Sugeno [12] proposed the concept of fuzzy measure, which can not only represent the weight of a single attribute index, but also calculate the weight of the attribute index set based on the degree of association between the attributes. Then use Choquet integral to make a comprehensive evaluation of the aggregation.

Definition 3 Let \( X = \{x_1, x_2, \ldots, x_n\} \) be a non-empty finite set, \( W(X) \) is the power set of \( X \). We can define \( \mu: W(X) \to [0, 1] \) as the fuzzy measure of \( X \), which can satisfy:

1) \( \mu(\emptyset) = 0 \), \( \mu(X) = 1 \);
2) \( \forall M, N \in W(X) \), if \( M \subseteq N \), then \( \mu(M) \leq \mu(N) \);
3) \( \forall P_i \in W(X) \), and \( \{P_i\}_{i=1}^{m} \) is monotonous, then \( \lim_{l \to m} \mu(P_l) = g \left( \lim_{l \to m} P_l \right) \).

Definition 4 Let \( X = \{x_1, x_2, \ldots, x_n\} \) be a non-empty finite set, \( W(X) \) is the power set of \( X \). Let \( \mu: W(X) \to [0, 1] \) be the fuzzy measure of \( X \), \( f(x) \) is a non-negative real value on \( X \), the Choquet integral of function \( f \) to \( \mu \) can be defined as:

\[
\mathcal{C}_\mu(f) = \sum_{i=1}^{n} [f(x_{(i)}) - f(x_{(i-1)})] \mu(B_{(i)})
\]

where, \( (i) \) is a substitution for the element subscript in \( X \), satisfies \( f(x_{(i)}) \leq f(x_{(i+1)}) \leq \cdots \leq f(x_{(n)}) \), and \( B_{(i)} = \{x_{(i)}, x_{(i+1)}, \ldots, x_{(n)}\} \), \( B_{(n+1)} = \emptyset \).

3.2 Specific steps of resource-based cities sustainable development level evaluation based on Shapely entropy and Choquet integral

1) Establish a hierarchy of evaluation goals: Constructing a sustainable development level evaluation
index system of resource-based cities based on the idea that layer by layer decomposition, which includes target level, standard level and indicator level, and evaluation value of parent attribute should be calculated from the Choquet integral of the child attribute.

2) Construct Shapely value pairwise judgment matrix: Based on the relative importance scale of the nine-point scale in the AHP of the general evaluation method, a scale of pairwise comparison between Shapely values of the same level of indicators is set to construct Shapely value judgment matrix.

3) The Shapely value of each indicator property is calculated by the above judgment matrix: Reference to the calculation of attribute weights in the general evaluation method AHP, firstly, solve the eigenvalue and eigenvector of the judgment matrix, then conduct a consistency test, finally use the square root method or sum of the product to calculate the Shapely value.

4) Construct the maximum Shapely entropy optimization model: Consider the Shapely entropy eigenvector as the attribute weight to construct the maximum Shapely entropy optimization model. Firstly, solve the optimization model based on Shapely entropy and choose the maximum Shapely entropy eigenvector as the attribute weight. Finally, use the square root method or sum of the product to calculate the Shapely value.

5) Solve the comprehensive evaluation results: Use Choquet integral to solve the comprehensive evaluation results from the lowest evaluation matrix level by level.

4. An application example

This paper selects 10 typical resource-based cities in China as an example, including: 2 coal cities Datong, Yangquan, 2 nonferrous metallurgy cities Huludao, Jinchang, 2 black metallurgy cities Ma’anshan, Panzhuhua, 2 forest city Songyuan, Yichun and 2 oil cities Daqing, Dongying, according to the evaluation index constructed above, we use the optimization model based on Shapely entropy and Choquet integral to evaluate their future sustainable development level.

1) Establish hierarchy index system: According to the evaluation index system shown in Table 1, the target level development level of resource-based cities (V), the guidelines are four subsystems: economic subsystem (V₁), social subsystem (V₂), resource (V₃) and environment subsystem (V₄).

2) Construct Shapely value judgment matrix: Combined with experts scoring based on the 1-9 scale, Shapely value judgment matrix is obtained as follows

|   | Sᵥ₁ | Sᵥ₂ | Sᵥ₃ | Sᵥ₄ |
|---|-----|-----|-----|-----|
| 1 | 1/2 | 1/2 | 3   | 1/5 |
| 1 | 3   | 1/2 | 5   | 3   |

3) Calculate the Shapely value of each property: It can be seen from the test that all of the above judgment matrices satisfy the consistency requirements, and the Shapely values of each layer attribute are obtained by using the square root method:

Iᵥ = [0.427 0.303 0.175 0.095]  Iᵥ₁ = [0.300 0.531 0.169]
\[I_V = [0.174 \ 0.285 \ 0.541] \quad I_V = [0.500 \ 0.357 \ 0.143] \quad I_V = [0.236 \ 0.139 \ 0.625]\]

4) Calculate the fuzzy measure based on the maximum Shapely entropy optimization model: Using Matlab program to solve the optimization model to get the fuzzy measure of each attribute set, as shown in Table 2 and Table 3:

### Table 2 Fuzzy measure of first-level indicators and indicators sets of resource-based city’s sustainable development evaluation level

| Index | Fuzzy measure |
|-------|---------------|
| \(V_1\) | 0.153 |
| \(V_1, V_2\) | 0.423 |
| \(V_2, V_3\) | 0.097 |
| \(V_3\) | 0.305 |

### Table 3 Fuzzy measure of first-level indicators and indicators sets of resource-based city’s sustainable development evaluation level

| Index | Fuzzy measure |
|-------|---------------|
| \(V_1\) | 0.100 |
| \(V_1, V_2\) | 0.178 |
| \(V_2, V_3\) | 0.297 |
| \(V_3\) | 0.250 |
| \(V_1, V_2, V_3\) | 0.801 |
| \(V_1, V_2, V_3\) | 0.783 |
| \(V_1, V_2, V_3\) | 1.000 |

5) Calculate the composite score step by step using Choquet points: The Choquet integral is used to calculate the fuzzy integral of each resource-based city’s sustainable development level (Table 4). As can be seen from the table, the sustainable development level of Dongying and Daqing is relatively high, several other cities have lower levels of sustainable development. So these cities should consider whether to carry out the transition problem, or draw lessons from the development experience of higher level cities, to create modern resource-based cities.

### Table 4 The evaluation results of sustainable development level of resource-based cities

| City | Economic subsystem | Social subsystem | Resource subsystem | Environment subsystem | Total score | Sequence |
|------|--------------------|-----------------|-------------------|----------------------|-------------|---------|
| Datong | 0.248 | 0.263 | 0.275 | 0.215 | 0.251 | 6 |
| Yangquan | 0.201 | 0.196 | 0.303 | 0.097 | 0.162 | 10 |
| Huludao | 0.199 | 0.201 | 0.296 | 0.108 | 0.197 | 8 |
| Jinchang | 0.215 | 0.207 | 0.352 | 0.201 | 0.236 | 7 |
| Ma’anshan | 0.582 | 0.462 | 0.497 | 0.297 | 0.431 | 3 |
| Panzhihua | 0.316 | 0.357 | 0.493 | 0.263 | 0.304 | 5 |
| Songyuan | 0.359 | 0.297 | 0.426 | 0.301 | 0.332 | 4 |
| Yichun | 0.178 | 0.201 | 0.195 | 0.132 | 0.185 | 9 |
| Daqing | 0.701 | 0.257 | 0.631 | 0.528 | 0.525 | 2 |
| Dongying | 0.871 | 0.792 | 0.809 | 0.307 | 0.601 | 1 |

5. Conclusion
Integrate with the previous studies, the research on the sustainable development level evaluation of
resource-based cities based on the Shapely entropy and Choquet integral mainly solves the following two problems:

1) Integrity. This paper sets out the index system from the four subsystems, which guarantee the integrity of the index system; And the introduction of Shapely entropy and Choquet integral model, fully taking into account the issue of the relevance between the attribute indicators, make sure that the evaluation results are more objective and perfect.

2) Practicality. The empirical results obtained by using this model are basically in line with the facts.

The realization of “integrity” and “practicability” makes the resource-based city’s sustainable development level evaluation system based on Shapely entropy and Choquet integral more scientific and reasonable, and provides a scientific basis for the future planning of resource-based cities.

Acknowledgements
This work was supported in part by National Natural Science Foundation of China (number 71471094).

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