Evaluating Low-Carbon Development of Smart City Based on I-COPRAS: An Application for Jiangsu Province

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Abstract. More than 60% of China's population is currently live in cities. The trend of urbanization highlights the importance of city low-carbon development. While the construction of smart city effectively improves the efficiency of urban low-carbon development management. To achieve the goal of urban low-carbon development, it's essential to evaluate the urban low-carbon development by considering diverse performance criteria. As the evaluation of low-carbon development usually involves many criteria and exists interaction between criteria, this paper improves complex proportional assessment (COPRAS) considering interacting criteria with λ fuzzy measure. To demonstrates the feasibility and applicability of I-COPRAS, this paper includes an empirical study on the low-carbon development performance evaluation of smart city pilots in Jiangsu Province, urban data analysis and comparison with the COPRAS method without considering interaction.

Keywords: smart city · low-carbon development · interacting criteria · complex proportional assessment (COPRAS) · λ fuzzy measure

1 Introduction

Adhering to low-carbon development of smart city is an important way to actively respond to climate change and achieve carbon neutrality [11]. Research on urban low-carbon development evaluation has been attracting much attention, constructing the index system and establishing evaluation methods for it are used to evaluate urban low-carbon development. The evaluation of urban low-carbon development involves a large number of criteria [5], which is suitable for its evaluation by constructing an integrated evaluation index. And the construction of an aggregated evaluation index requires the use of a suitable evaluation method.

The commonly used multi-criteria evaluation methods are Weight Average (WA) [6], DEA [9] and TOPSIS [10] in the research of urban low-carbon development evaluation. However, Complex proportional assessment (COPRAS) [12] calculates the sum of benefit-based criteria and cost-based criteria separately, derives the evaluation results through a linear relationship, and ranks each solution by its high utility degree, which

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can indicate the gap between other cities and the optimal city in the evaluation of urban low-carbon development. Currently, the COPRAS method has been applied to supplier selection problems [7], renewable energy evaluation [1], risk assessment problems [8], etc. At the same time, the evaluation of urban low-carbon development involves several statistical criteria of economy, environment and society, and there may be interactions among these criteria. To solve the problem of multiple criteria considering interacting among criteria, [4] proposed to replace the additive set function with a weaker monotonicity and continuity and called it a fuzzy measure. The λ fuzzy measure is more convenient to calculate and is widely used. In order to evaluate the performance of low-carbon development of cities by considering the interaction among criteria comprehensively, the concept of fuzzy measure is introduced to measure and model the interaction among performance criteria. To obtain the urban low-carbon development (ULCD) performance of each city based on interacting criteria, the λ fuzzy measure is combined with the COPRAS method. The rest of the paper is organized as follows: in the second part, we introduce I-COPRAS, a new model for evaluating urban low-carbon development. In the third part, we apply I-COPRAS to solve a real city evaluation problem in Jiangsu Province, China. Finally, we conclude with a discussion in Sect. 4.

2 Evalaution Approach for City Low-Corbon Development

Let us introduce the notion of the alternatives set is $a = \{a_1, a_2, \ldots, a_n\}$ and the evaluation criteria set is $c = \{c_1, c_2, \ldots, c_m\}$, We consider a decision model where in n alternatives $a_1, a_2, \ldots, a_n$ act as cities. To assess sustainable development, m facets $c_1, c_2, \ldots, c_m$ of the city should be considered. Then construct the initial evaluation matrix $X = (x_{ij})_{n\times m}$ to describe the score of a_i on criteria c_j.

2.1 λ Fuzzy Measure calculation

Let us further associate with each criteria c_j $(j = 1, 2, \ldots, m)$ and their coalitions, a non-negative number denote its importance in evaluation. Let $P(C)$ denote the importance set of C, the definition of λ fuzzy measure is then given as follows.

Definition 1 (Sugeno et al., 1995). λ fuzzy measure on the set C of criteria is a set function g_λ: $P(C) \to [0,1]$ satisfying the following properties:

(2) $g_\lambda(C) = 1$;
(2) $\forall M, N \in P(C), M \bigcap N = \varnothing$, then

$$g_\lambda\left(M \bigcup N\right) = g_\lambda(M) + g_\lambda(N) + \lambda g_\lambda(M) g_\lambda(N) \quad (1)$$

(3) g_λ is continuous.

In this definition, $g_\lambda(M)$ represents the weight of the set of criteria M $(\in P(C))$. For a pair of criteria $M, N \in P(C)(M \bigcap N = \varnothing)$, the difference $d(M,N) = g_\lambda(M,N) - g_\lambda(M) - g_\lambda(N)$ reflects the degree of interaction between M and N. If $d(M, N)$ is equal to zero, M and N are independent. If $d(M, N)$ is positive, a synergy effect exits between M and N. If $d(M, N)$ is negative, a redundancy effect exits between M and N.

With interaction being identified between the criteria, the contribution of a criterion c_j ($\in C$) is to be assessed by considering the weight of c_j and the weight of all criteria sets of interrelated criteria involving c_j. To model the contribution of a criterion alone in all criteria sets, the concept of Shapley value is often utilized. With the use of λ fuzzy measure, the contribution of a criterion c_j can be modelled by a Shapley value w.r.t. λ fuzzy measure [3].

Definition 2 (Grabisch, 2016). If λ fuzzy measure on the set C of criteria is a set function g_λ, the Shapley value w.r.t. λ fuzzy measure for criterion can be defined as:

$$I(c_j) = \sum_{T \subseteq C \backslash c_j} \frac{(m-k-1)!k!}{m!} (g_\lambda \left(T \bigcup c_j\right) - g_\lambda(T)) \tag{2}$$

where $I(c_j)$ can be used to measure the contribution of c_j in the criteria set C. $g_\lambda(c_j) = I(c_j)$ when there is no interaction between c_j and other criteria in set C. The Shapley values can be interpreted as an average value of the contribution of a criterion.

In order to utilize the maximum information in the evaluation scores, the optimization model is developed to maximize the Marichal entropy for objectively determining the criteria weights $g_\lambda(c_j)$ by considering their interactive relationships. The optimization model (Xu, Zhang, Yeh, & Liu, 2018) is given as:

$$maxH_M(g_\lambda) = \sum_{j=1}^{m} \sum_{S \subseteq C \backslash c_j} \gamma_S(m) \cdot h[g_\lambda\left(S \bigcup c_j\right) - g_\lambda(S)] \tag{3}$$

$$\begin{cases} I_j = \sum_{k=0}^{m-1} \frac{(m-k-1)!k!}{m!} \sum_{\substack{T \subseteq C \backslash c_j \\ |T| = k}} g_\lambda\left(T \bigcup \mathrm{c_j}\right) - g_\lambda(T) \\ g_\lambda(C) = 1 \\ g_\lambda\left(c_j\right) \in [0, 1], j = 1, 2, \ldots, m \\ -1 < \lambda < +\infty \end{cases} \tag{4}$$

where

$h(x) = \begin{cases} -xlnx, x > 0 \\ 0, x < 0 \end{cases}$, $\gamma_S[m] = \frac{(n-|S|-1)!|S|!}{m!}$, |S|is the potential of criteria.

2.2 I-COPRAS Model

With the concept of λ fuzzy measure, the I-COPRAS evaluation method for ULCD is developed and presented in the following steps, as shown in Fig. 1.

Step1: Criteria system construction and analysis. Determine the evaluation criteria system and analyse the interactions between the criteria.

Step2: Criteria value determination and standardization processing. Assuming that the alternatives set is $a = \{a_1, a_2, \ldots, a_n\}$, the evaluation criteria set is $c = \{c_1, c_2, \ldots, c_m\}$,

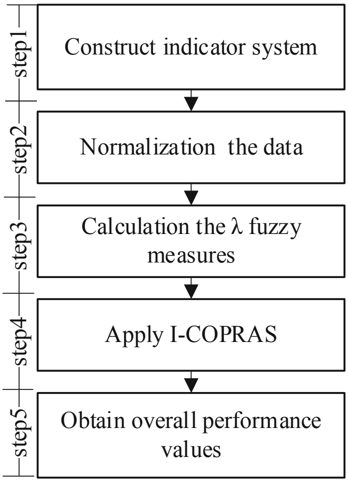

Fig. 1. The evaluation method for I-COPRAS

the initial evaluation matrix $X = (x_{ij})_{n\times m}$ is constructed; the initial matrix is based on the formula (5) to get the normalized decision matrix $Y = (y_{ij})_{n\times m}$.

$$y_{ij} = \frac{x_{ij}}{\sum_{i=1}^{m} x_{ij}}, i = 1, 2, \ldots, nj = 1, 2, \ldots, m \tag{5}$$

Step3: Criteria (set) λ fuzzy measure calculation. According to formula (3)–(4) and combined with formula (1) in Definition 1, the fuzzy measure of the criteria (set) can be obtained.

Step4: Use the formula (6) to calculate the sum of benefit-type and cost-type criteria separately.

Benefit/Cost -type:

$$S(\pm, i) = \sum_{j=1}^{n} y^{\pm}_{i(j)}\left[g_\lambda\left(C_{(j)}\right) - g_\lambda\left(C_{(j+1)}\right)\right], j = 1, 2, \ldots, n \tag{6}$$

where (j) represents the vector transformation of $y_{i(j)}$, make $0 \le y_{i(1)} \le y_{i(2)} \le \ldots \le y_{i(m)}$,$C_{(j)} = \{c_{(j)},c_{(j+1)},\ldots,c_{(n)}\}$,

and $g_\lambda(C_{(j+1)}) = 0$; $y^{\pm}_{i(j)}$ represents the benefit/cost criteria after normalization.

Step5: Calculate the performance of each alternative by formula (7) and the relative importance of each plan by utility degree of the alternatives by formula (8). Rank cities based on utility degree.

$$F_i = S(+, i) + \frac{\sum_{i=1}^{m} S(-, i)}{S(-, i) \times \sum_{i=1}^{m} \frac{1}{S(-,i)}}, i = 1, 2, \ldots, m \tag{7}$$

$$U_i = \frac{F_i}{F_{max}} \times 100\% \tag{8}$$

Among them, $F_{\max} = max(F_i)(i = 1,2,\ldots,m)$. The utility of the alternative is between 0% and 100%, which makes it easier for decision makers to compare the degree of differences among alternatives.

3 Evaluation of Urban Low-Carbon Development of Smart City in Jiangsu Province

3.1 The Application of Smart City in Jiangsu Province Based on I-COPRAS

As economic, political and culture of cities are interdependent and interrelated with economic, social and environmental factors. Considering that the essence of low-carbon development of smart city is to maximize energy efficiency and reduce greenhouse gas emissions, the evaluation of urban low-carbon development needs to take into account the energy pattern.

Therefore, comprehensively analysing and considering these aspects, draw on the evaluation criteria recognized by most scholars [2, 6] in the evaluation of urban low-carbon development, and establish the following criteria system. As shown in Table 1, the four urban low-carbon development dimensions $d_k(k = 1, 2, 3, 4)$ are identified together with 12 associated low-carbon development criteria c_{kj} $(j = 1, 2, \ldots, 12)$ for evaluating the low-carbon development performance of 13 Jiangsu cities $a_i(i = 1, 2, \ldots, 13)$. It is worth noting that these criteria are not all independent of each other. Their relationship may influence each other. The data is based on the Statistical Yearbook of Jiangsu Province in 2020 government department data.

According to the calculation step 3 of the I-COPRAS model, the λ fuzzy value of the low-carbon development criteria (set) of Jiangsu Province can be obtained. As shown in Table 2, there are redundant interaction among the criteria in the d_1 (low-carbon economy) dimension, and there are complementary interaction among the criteria in the d_2 (low-carbon society), d_3 (low-carbon environment), and d_4 (energy pattern) dimensions.

Using the calculation steps 4–5 of the I-COPRAS model, the values of low carbon development level in Jiangsu province under each dimension can be obtained, as shown in Fig. 2. In the low-carbon economy dimension and low-carbon society dimension, only benefit-based criteria are considered, i.e., the higher the benefit-based criteria are, the better.

For example, in the low-carbon economy dimension, Nanjing has the highest evaluation value, and the leading sectors of low-carbon development are still the tertiary industry and high-tech industry. Nanjing has the highest ratio of tertiary industry (c_{12}) in Jiangsu Province, and Nanjing has dense universities and research institutes all over the city, and its proportion of R&D expenditure to GDP (c_{11}) is also high, thus Nanjing is in the leading position in the evaluation value of the low-carbon economy dimension. The low-carbon environment and energy pattern dimensions contain both benefit and cost criteria, which need to be considered together, i.e., the larger the benefit criterion and the smaller the cost criterion, the higher the city's evaluation value in these two dimensions.

Table 1. ULCD evaluation system for smart cities

Dimensions	Criteria	Criteria type
Low-carbon economy d_1	Per capita GDP c_{11}	Benefit
	Proportion of tertiary industry to GDPc_{12}	Benefit
	Proportion of R&D expenditure to GDP c_{13}	Benefit
Low-carbon society d_2	Green coverage rate in built-up area c_{21}	Benefit
	Public transportation vehicles per 10,000 people (standard station) c_{22}	Benefit
	Park green area per capita (m^2/person) c_{23}	Benefit
Low-carbon environment d_3	Industrial wastewater discharge (10,000 tons) c_{31}	Cost
	Industrial waste gas emissions (100 million standard cubic meters) c_{32}	Cost
	Comprehensive utilization rate of industrial waste (%)c_{32}	Benefit
Energy pattern d_4	Energy intensity (ton of standard coal/10,000 yuan) c_{41}	Cost
	Natural gas consumption (ten thousand cubic meters) c_{42}	Benefit
	Coal consumption (tons of standard coal) c_{43}	Cost

Table 2. λ fuzzy measure of dimensions and associated criteria

dimensions	λ fuzzy value	Criteria	λ fuzzy value
d_1	-0.125	$g_\lambda(c_{11}, \varnothing)$	0.338
		$g_\lambda(c_{12}, \varnothing)$	0.074
		$g_\lambda(c_{13}, \varnothing)$	0.380
d_2	0.807	$g_\lambda(c_{21}, \varnothing)$	0.030
		$g_\lambda(c_{22}, \varnothing)$	0.452
		$g_\lambda(c_{23}, \varnothing)$	0.241
d_3	0.735	$g_\lambda(c_{31}, \varnothing)$	0.367
		$g_\lambda(c_{32}, \varnothing)$	0.335
		$g_\lambda(c_{33}, \varnothing)$	0.010
d_4	1.044	$g_\lambda(c_{41}, \varnothing)$	0.220
		$g_\lambda(c_{42}, \varnothing)$	0.264
		$g_\lambda(c_{43}, \varnothing)$	0.174

From Figure, we can learn that Yangzhou has the highest evaluation value in the low carbon environment dimension. As we can see in the Table 3, although the sum of benefit criteria $S(+, i)$ (0.0091) is not the highest, the sum of cost criteria $S(-, i)$ (0.0028) is the smallest in 13 cities. Yangzhou is one of the first national historical and cultural cities and a scenic tourist city with traditional characteristics, mainly developing tourism and less industrial pollution than other urban areas, and the cost-based criteria of industrial wastewater emissions (c_{31}) and industrial emissions (c_{32}) are at a lower

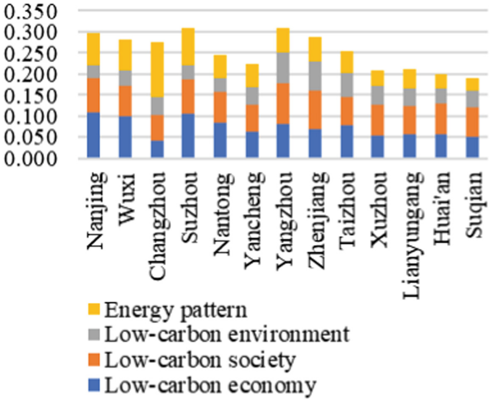

Fig. 2. ULCD performance values of each city under dimension

Table 3. The sum of benefit criteria and cost criteria of each city in low-carbon environment dimension

Cities	*S*(+,*i*)	*S*(-,*i*)
Nanjing	0.0089	0.0816
Wuxi	0.0094	0.0640
Changzhou	0.0097	0.0553
Suzhou	0.0094	0.1969
Nantong	0.0094	0.0739
Yancheng	0.0090	0.0482
Yangzhou	0.0091	0.0280
Zhenjiang	0.0092	0.0286
Taizhou	0.0095	0.0364
Xuzhou	0.0097	0.0470
Lianyungang	0.0086	0.0539
Huai'an	0.0091	0.0610
Suqian	0.0091	0.0528

level in Jiangsu province, thus affecting the final value of Yangzhou in the low-carbon environment dimension.

Similarly, the Shapley value is obtained by calculating the coefficient of variation using ULCD value of each dimension, and the fuzzy measure of each dimension and the λ value are obtained, and finally the benefit value is the comprehensive evaluation value of each dimension by passing steps 3–5 on each dimension, and the overall ULCD value of each city in Jiangsu province is obtained.

Table 4. Overall ULCD performance, utility degree and rankings of 13 cities

Cites	F_i	U_i	Ranking
Suzhou	0.0734	100.0%	1
Yangzhou	0.0706	96.15%	2
Nanjing	0.0682	92.97%	3
Zhenjiang	0.0669	91.16%	4
Wuxi	0.0664	90.43%	5
Taizhou	0.0607	82.74%	6
Changzhou	0.0595	81.08%	7
Nnatong	0.0561	76.49%	8
Xuzhou	0.0530	72.28%	9
Yancheng	0.0529	72.15%	10
Lianyungang	0.0512	69.80%	11
Huai'an	0.0456	62.13%	12
Suqian	0.0442	60.26%	13

It can be seen from Table 4 that the relative importance (F_i) of low-carbon development in Suzhou is the highest at 0.0734, while the relative importance of low-carbon development in Suqian is the lowest at 0.0442. U_i can clearly indicates the degree of divergence of low-carbon development performance among cities. For example, the low-carbon development level of Suzhou is 100%, and the low-carbon development level of Yangzhou is 96.15%, that is, the level of low-carbon development unity of Yangzhou is only 96.15% of Suzhou. The utility of Suqian low-carbon city development performance is 60.26%, which can indicate that the low-carbon development level of Suqian is nearly 40% different from that of Suzhou.

3.2 Comparison with the COPRAS Method Without Considering Interaction

In order to illustrate the effectiveness of the proposed method, this method is compared with the COPRAS method which does not consider the correlation between criteria. If the correlation between criteria is not considered and the criteria are assumed to be independent of each other, the Shapley value of the criteria is the importance of the criteria, and the weighted average is used to calculate the low carbon development evaluation value of each city, and the evaluation results are shown in Fig. 3. By comparing the results with those of the I-COPRAS evaluation method, we can find that the ranking of Suzhou and Yangzhou does not change when the correlation between criteria is not considered, while the ranking of Taizhou increases and that of Nantong decreases, and the ranking of the last city changes significantly. The analysis of the fuzzy measures among the criteria in Table 2 shows that due to the redundancy/complementary relationships among the criteria in each dimension, the idea of the I-COPRAS evaluation method is to use fuzzy measures to describe the importance of the criteria set, and the process of

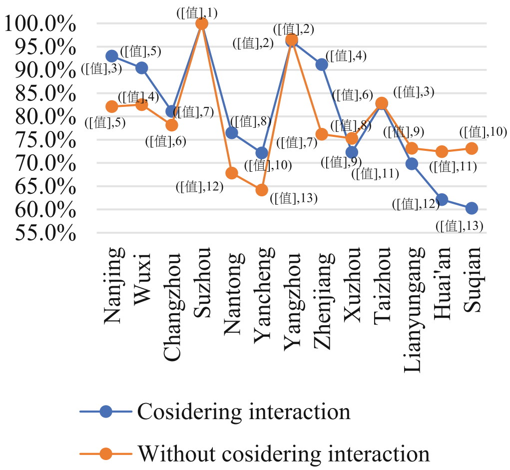

Fig. 3. Comparison of results with and without considering interaction

data assembly portrays the influence of the criteria through the difference between the fuzzy measures of the criteria set and the fuzzy measures of the individual criterion, which finally avoids the abnormal results of the calculations because of the interaction between criteria.

4 Conclusions

Based on the characteristics that the evaluation of low carbon development of smart city has a large number of criteria and the correlation between criteria, this paper combines fuzzy measurement and COPRAS method, considers the correlation between criteria, and applies the I-COPRAS evaluation method to evaluate the level of urban low carbon development. Through the application study of low carbon development in Jiangsu cities, the COPRAS method considering the interaction between criteria can measure the actual low carbon development in Jiangsu province more accurately, which is in line with the actual development of Jiangsu province, and measure the differences between cities through the utility degree.

In addition, through the theoretical study and application results of the I-COPRAS method, the following conclusions can be drawn: the I-COPRAS method uses fuzzy measures instead of probability measures to measure the weights of criteria (sets), which is suitable for multi-criteria evaluation problems with interaction effects among criteria, and constructs an extended COPRAS method system, which provides a new way of thinking for solving evaluation problems with interaction effects among criteria. What's more, the I-COPRAS method extends the solution method in urban low-carbon development of smart city and enhances the integration between multi-criteria evaluation theory and practical problems.

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