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A Novel Coordinated TOPSIS Based on Coefficient of Variation

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Abstract: Coordinated Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a significant improvement of TOPSIS, which take into account the coordination level of attributes in the decision-making or assessment. However, in this study, it is found that the existing coordinated TOPSIS has some limitations and problems, which are listed as follows. (1) It is based on modified TOPSIS, not the original TOPSIS. (2) It is inapplicable when using vector normalization. (3) The calculation formulas of the coordination degree are incorrect. (4) The coordination level of attributes is interrelated with the weights. In this paper, the problems of the existing coordinated TOPSIS are explained and revised, and a novel coordinated TOPSIS based on coefficient of variation is proposed to avoid the limitations. Comparisons of the existing, revised, and proposed coordinated TOPSIS are carried out based on two case studies. The comparison results validate the feasibility of the proposed coordinated TOPSIS.

Keywords: TOPSIS; coordinated TOPSIS; decision-making; assessment; coefficient of variation; information entropy

1. Introduction

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a classical multi-attribute decision-making method, which was first put forward by Hwang and Yoon in 1981 [1]. This method attempts to rank the alternatives by calculating their distances from the ideal solution (IS) and the negative ideal solution (NIS) and selects the optimum one that should simultaneously have the shortest distance from the IS and the farthest distance from the NIS. TOPSIS has been successfully applied in various fields [2–4] such as environmental risk assessment [5], water quality assessment [6], disaster risk management [7,8], supplier selection [9], real estate management [10,11], and sustainability assessment [12] due to the fact that it features a simple principle, easy understanding, and strong capacity to integrate other methods.

Although TOPSIS has many advantages, many scholars have found that it has some limitations for application and put forward some improvement approaches. For example, when alternatives are described by statistically connected criteria, the application of TOPSIS may cause improper ranking results [13]. To avoid this problem, Antuchevičienė et al. (2010) suggested using the Mahalanobis distance instead of Euclidean distance for TOPSIS [13]. Yang and Wu (2019) pointed out that TOPSIS does not consider the data distribution of the degree of dispersion and aggregation when it is compared with the IS and the NIS and proposed a novel TOPSIS based on improved grey relational analysis [14]. Chen's research suggests that when the alternatives are added or reduced, the problem of rank reversal will occur. To void this problem, the absolute IS and the absolute NIS should be used [15]. Considering that TOPSIS lacks evaluation from the perspective of attribute coordination, Yu et al. (2018) proposed coordinated TOPSIS, which takes into account the coordination level of attributes [16].

TOPSIS is a type of multi-attribute decision-making method, in which complementarity exists among attributes. When some attributes are inferior, they can be complemented by the other superior attributes in the decision results [16]. However, in some decision or evaluation problems, the coordination or balance of attributes is very important to be considered, such as evaluation of information system [17], decision of real estate location [18], and evaluation of academic journals [16]. In these cases, the coordination level of attributes should be taken into account when using TOPSIS. Coordinated TOPSIS is a significant improvement of TOPSIS. It is very suitable for the decision or evaluation fields that need to consider the coordination level of attributes [16]. However, according to the principles of coordinated TOPSIS [16], it is found that this method has some limitations and problems that affect its applicability. In this study, the problems of the existing coordinated TOPSIS are explained and revised, and a novel coordinated TOPSIS based on coefficient of variation is proposed to avoid the limitations. The rest of this paper is organized as follows: Section 2 describes the methods; Section 3 gives the results and discussion; Section 4 presents the conclusions.

2. Methods

2.1. The Existing Coordinated TOPSIS

The coordinated TOPSIS proposed by Yu et al. [16] not only takes into account the advantages of TOPSIS, but also can evaluate the coordination level of attributes. However, it should be noted that the TOPSIS adopted in [16] is not the original TOPSIS proposed by Hwang and Yoon in 1981 [1] but modified TOPSIS [19,20]. Therefore, the coordinated TOPSIS proposed by Yu et al. [16] should be called coordinated modified TOPSIS (CM-TOPSIS).

2.1.1. The Principles of CM-TOPSIS

The procedure of CM-TOPSIS consists of the following seven steps [16]:

Step 1: Construct the decision matrix $\mathbf{R} = \{r_{ij}\}$, where r_{ij} is the value of the jth attribute of the ith alternative; $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

Step 2: Normalize the decision matrix $\mathbf{R}$. Two normalization methods are used in CM-TOPSIS [16], not vector normalization (VN) suggested by Hwang and Yoon [1].

For the-bigger-the-better attribute, maximum normalization (MN) is used, which is to divide the values of an attribute by the maximum value of the attribute in all the alternatives. The calculation equation of MN is written as follows:

$$x_{ij} = \frac{r_{ij}}{\max_i r_{ij}}, \tag{1}$$

where x_{ij} is the normalized value of r_{ij}, $\max_i r_{ij}$ is the maximum value of the jth attribute in all the alternatives.

For the-smaller-the-better attribute, min-max normalization (MMN) is used to transform it to be the-bigger-the-better attribute. The calculation equation of MMN is written as follows:

$$x_{ij} = \frac{\max_i r_{ij} - r_{ij}}{\max_i r_{ij} - \min_i r_{ij}}, \tag{2}$$

where $\min_i r_{ij}$ is the minimum value of the jth attribute in all the alternatives. It should be noted that the calculation equation of MMN was written incorrectly in [16].

Step 3: Determine the IS A^+ and the NIS A^-. As MN and MMN are used in Step 2, all the attributes will change to the-bigger-the-better attributes after normalization and the IS A^+ is

$$A^+ = \left\{ \left(\max_i x_{ij} \middle| j \in J \right) \middle| i = 1,\ 2, \cdots,\ m \right\} = \{1, 1, \cdots, 1\}. \tag{3}$$

To establish a unique coordination reference standard, an absolute NIS is adopted in CM-TOPSIS [16]. The NIS A^- is

$$A^- = \{0, 0, \cdots, 0\}. \tag{4}$$

Step 4: Calculate the weighted Euclidean distance of each alternative from the IS and the NIS by the following equations:

$$S_i^+ = \sqrt{\sum_{j=1}^{n} w_j \left(x_{ij} - 1\right)^2}, \tag{5}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n} w_j \left(x_{ij} - 0\right)^2}, \tag{6}$$

where w_j is the weight of the jth attribute.

Step 5: Calculate the relative closeness (RC) to the IS for each alternative by the following equation:

$$C_i = \frac{S_i^-}{S_i^+ + S_i^-}. \tag{7}$$

Step 6: Calculate the coordination degree (CD) of attributes by the following equations:

For unweighted modified TOPSIS:

$$\cos(\theta_i) = \frac{\sum_{j=1}^{n} x_{ij}}{n\sqrt{\sum_{j=1}^{n} x_{ij}^2}}, \tag{8}$$

$$p_i = \frac{45^\circ - \theta_i}{45^\circ}, \tag{9}$$

where θ_i is the angle between the line from the origin to a point (represents an alternative) and the line from the origin to the IS; p_i is the CD of attributes.

For weighted modified TOPSIS:

$$\cos(\theta_i) = \frac{\sum_{j=1}^{n} w_j x_{ij}}{n\sqrt{\sum_{j=1}^{n} w_j x_{ij}^2}}, \tag{10}$$

$$p_i = \frac{90^\circ - \theta_i}{90^\circ}. \tag{11}$$

Step 7: Calculate the comprehensive evaluation value by the following equation:

$$T_i = (1 - v)\frac{C_i}{\max(C_i)} + v\frac{p_i}{\max(p_i)}, \tag{12}$$

where v is the weight of the CD. If the decision or assessment is to encourage the coordinated development of the attributes, v must be greater than or equal to 0.5 [16].

Then, the alternatives can be ranked with respect to their comprehensive evaluation values. A larger comprehensive evaluation value of an alternative indicates that the alternative is relatively better.

2.1.2. The Limitations and Problems of CM-TOPSIS

Although CM-TOPSIS takes into account the coordination level of attributes, which is a significant improvement of TOPSIS, it still has some limitations and problems.

(1) CM-TOPSIS is not based on the original TOPSIS.

The TOPSIS adopted in [16] is not the original TOPSIS proposed by Hwang and Yoon in 1981 [1], but modified TOPSIS [19,20]. In the original TOPSIS, the attribute weights are used to weight the normalization value x_{ij}. In this case, Equations (5) and (6) should be written as follows.

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(w_j x_{ij} - w_j\right)^2}, \tag{13}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(w_j x_{ij} - 0\right)^2}. \tag{14}$$

Deng et al. [19] used the weighted Euclidean distances instead of the Euclidean distances that are calculated based on the weighted decision matrix. Equations (5) and (6) are the weighted Euclidean distances. The TOPSIS using weighted Euclidean distances is called modified TOPSIS [19,20]. Compared with modified TOPSIS, the original TOPSIS is more frequently used for decision-making and assessment. Therefore, it is significant to establish a coordinated TOPSIS based on the original TOPSIS.

(2) CM-TOPSIS is inapplicable when using VN.

When TOPSIS was proposed, VN was suggested as the normalization method [1], which is frequently used for TOPSIS [21–23]. However, in some studies, VN was replaced by other normalization methods when using TOPSIS, such as MMN [24–26].

An important prerequisite for the application of CM-TOPSIS is that the IS is {1, 1, . . . , 1} and the NIS is {0, 0, . . . , 0}. If MMN is used for CM-TOPSIS, this prerequisite can be satisfied. However, if VN is used, the IS is not always $\{1, 1, \cdots, 1\}$, and the NIS is not always $\{0, 0, \cdots, 0\}$. In this case, the prerequisite of CM-TOPSIS cannot be satisfied and the calculate formulas of the CD are inapplicable. Since VN is the most frequently used normalization method for TOPSIS, it should be taken into account in establishing coordinated TOPSIS.

(3) The calculation formulas of the CD are incorrect.

For unweighted modified TOPSIS, taking two-dimensional space as an example, the CD is illustrated in Figure 1. In Figure 1, point N represents an alternative that is described by two attributes. The values of the two attributes are X_N and Y_N, respectively. Point A (1, 1) represents the IS and origin O (0, 0) represents the NIS. OA is the 45° line (coordination line). A point located on the 45° line means that the attributes represented by the point are completely coordinated. The size of ∠NOA indicates the coordination level of attributes. Assuming that point N is located on the 45° line, it can be easily obtained that $X_N = Y_N$. Plugging $X_N = Y_N$ into Equation (8) gives

$$\cos(\theta) = \frac{2X_N}{2\sqrt{2X_N^2}} = \frac{\sqrt{2}}{2}, \tag{15}$$

$$\angle \mathrm{NOA} = \theta = 45°. \tag{16}$$

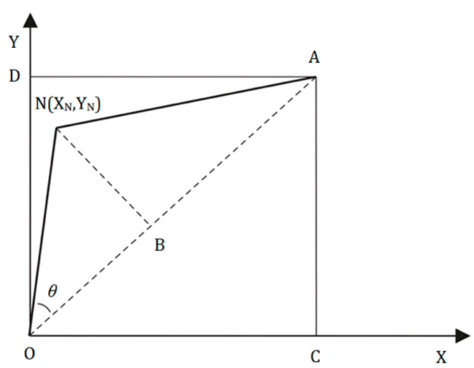

Figure 1. Calculation of the coordination degree (CD) [16].

According to the calculated result of Equation (16), point N should be located on the X or Y axis, which is contradictory to the assumption (N is located on the 45° line). Thus, Equation (8) is incorrect. According to the calculation formula of the angle between two vectors in Euclidean space, the correct calculation formula of $\cos(\theta_i)$ is

$$\cos(\theta_i) = \frac{\sum_{j=1}^{n} x_{ij}}{\sqrt{n}\sqrt{\sum_{j=1}^{n} x_{ij}^2}}. \tag{17}$$

Yu et al. (2018) used $p_i = (45° - \theta_i)/45°$ to indicate the coordination level of attributes [16]. In two-dimensional space, the maximum θ_i is 45°, however, in multi-dimensional space, the maximum θ_i is larger than 45°. In this case, p_i is less than zero, which is irrational. Thus, Equation (9) is incorrect. Equation (11) can be used to replace Equation (9).

For weighted modified TOPSIS, the calculation formula of $\cos(\theta_i)$ is interrelated with the attribute weights, as shown in Equation (10). Assuming that the normalization values of all the attributes are equal for an alternative, Equation (10) can be written as

$$\cos(\theta_i) = \frac{x_{ij}\sum_{j=1}^{n} w_j}{n\sqrt{x_{ij}^2\sum_{j=1}^{n} w_j}} = \frac{1}{n} \neq 1, n \geq 2. \tag{18}$$

Equation (18) indicates that even if the normalization values of all the attributes are equal, the attributes are not coordinated. This means that the attributes of the alternative represented by the IS {1, 1, . . . , 1} are also not coordinated. For example, a student gets full marks in both Chinese and mathematics. Only considering these two courses, no matter what weight is, it can be obtained that $\cos(\theta) = 1/2$, $\theta = 60°$ and $p_i = 0.333 < 1$. This indicates that the student's learning is very unbalanced in Chinese and mathematics, which is inconsistent with the actual scores. Therefore, the calculation formula of $\cos(\theta_i)$ for weighted modified TOPSIS is incorrect.

Equations (5) and (6) can be written as

$$S_i^+ = \sqrt{\sum_{j=1}^{n}\left(\sqrt{w_j}x_{ij} - \sqrt{w_j}\right)^2}, \tag{19}$$

$$S_i^- = \sqrt{\sum_{j=1}^{n}\left(\sqrt{w_j}x_{ij} - 0\right)^2}. \tag{20}$$

In this case, an equivalent IS is $\left\{\sqrt{w_1}, \sqrt{w_2}, \cdots, \sqrt{w_n}\right\}$, an equivalent NIS is {0, 0, . . . , 0}, and an equivalent point that represents an alternative is $\left\{\sqrt{w_1}x_{i1}, \sqrt{w_2}x_{i2}, \cdots, \sqrt{w_n}x_{in}\right\}$. Obviously, if an equivalent point is located on the line from the equivalent NIS to equivalent IS, the attributes of the alternative represented by the point are completely coordinated. According to the calculation formula of the angle between two vectors in Euclidean space, $\cos(\theta_i)$ can be calculated by the following equation:

$$\cos(\theta_i) = \frac{\sum_{j=1}^{n} w_j x_{ij}}{\sqrt{\sum_{j=1}^{n} w_j}\sqrt{\sum_{j=1}^{n} w_j x_{ij}^2}} = \frac{\sum_{j=1}^{n} w_j x_{ij}}{\sqrt{\sum_{j=1}^{n} w_j x_{ij}^2}}. \tag{21}$$

Assuming that the normalization values of all the attributes are equal for an alternative, Equation (21) can be written as

$$\cos(\theta_i) = \frac{x_{ij}\sum_{j=1}^{n} w_j}{\sqrt{x_{ij}^2\sum_{j=1}^{n} w_j}} = 1, n \geq 2. \tag{22}$$

Equation (22) indicates that if the normalization values of all the attributes are equal, the attributes are completely coordinated. Thus, Equation (10) should be replaced by Equation (21) when using weighted modified TOPSIS.

If the original TOPSIS is adopted to establish coordinated TOPSIS, Equation (21) should be written as

$$\cos(\theta_i) = \frac{\sum_{j=1}^{n} w_j^2 x_{ij}}{\sqrt{\sum_{j=1}^{n} w_j^2}\sqrt{\sum_{j=1}^{n} w_j^2 x_{ij}^2}}. \tag{23}$$

(4) The coordination level of attributes should be independent of weight.

The weight of an attribute represents the importance of the attribute in decision-making or assessment, but not the importance in the evaluation of coordination level. The coordination level of attributes should be independent of weight, and be evaluated based on the values of attributes. However, Equations (10), (21), and (23) all indicate that the coordination level of attributes is interrelated with the weights, which may cause an irrational result. For example, a student's learning performance is always evaluated based on the scores in the exam, experiment and class discussion. Assuming that there are three students for evaluation, the scores of the three students are listed in Table 1. The weights of the exam, experiment, and class discussion are 0.6, 0.3, and 0.1. An absolute NIS is adopted, which is $\{0, 0, \cdots, 0\}$. Equations (11) and (23) are adopted to calculate the CD. The coefficients of variation (CV) are also calculated for comparison. In terms of the scores, it can be easily judged that the coordination level of Zhang in the three aspects is higher than that of Wang. The CV for the scores of Zhang is 0.088, which is much smaller than that of Wang. However, from Table 1, the CD for the scores of Wang is 0.947, which is larger than that of Zhang. This means that the coordination level of Wang in the three aspects is higher than that of Zhang. A student with a high coordination level of learning should not have a bad performance in class discussion. The contradictory results are caused by the attribute weight. The small weight of 0.1 results in that the score of class discussion has little effect on the coordination level. Even if the score of class discussion is small, a high coordination level can be also obtained. Therefore, the coordination level of attributes should be independent of weight. If the decision-maker believes that the importance of attributes in the evaluation of coordination level is the same as that in decision-making or assessment, the weight should be taken into account in the coordination level. In this case, Equations (21) and (23) can be used.

Table 1. The scores of the three students and calculated results of the CD and coefficients of variation (CV).

Student	Exam Score	Experiment Score	Class Discussion Score	CD	CV
Wang	80	80	35	0.947	0.326
Zhang	70	85	85	0.946	0.088
Li	100	100	100	1.000	0.000

2.2. A Novel Coordinated TOPSIS

In this study, the calculate formulas of the CD for CM-TOPSIS are revised. However, the application of the revised formulas has the same prerequisite as that of the original formulas, which is the IS is $\{1, 1, \ldots, 1\}$ and the NIS is $\{0, 0, \ldots, 0\}$. To avoid this prerequisite and the limitations of CM-TOPSIS, a novel coordinated TOPSIS is proposed in this study.

2.2.1. Original TOPSIS

In this study, the original TOPSIS is adopted to establish the coordinated TOPSIS. The procedure of the original TOPSIS consists of the following six steps [1]:

Step 1: Construct the decision matrix $\mathbf{R} = \{r_{ij}\}$, where r_{ij} is the value of the jth attribute of the ith alternative; $i = 1, 2, \ldots, m$; $j = 1, 2, \ldots, n$.

Step 2: Normalize the decision matrix $\mathbf{R}$ using vector normalization. Other normalization methods can also be used as needed.

Step 3: Calculate the weighted normalized decision matrix $\mathbf{V} = \{v_{ij}\}$ by the following equation:

$$v_{ij} = w_j x_{ij}, \tag{24}$$

where w_j is the weight of the jth attribute; x_{ij} is the normalized value of r_{ij}.

Step 4: Determine the IS A^+ and the NIS A^-:

$$A^+ = \left\{\left(\max_i v_{ij} \middle| j \in J\right), \left(\min_i v_{ij} \middle| j \in J'\right) | i = 1,\ 2, \cdots,\ m\right\} = \left\{v_1^+, v_2^+, \cdots, v_n^+\right\}, \tag{25}$$

$$A^- = \left\{\left(\min_i v_{ij} \middle| j \in J\right), \left(\max_i v_{ij} \middle| j \in J'\right) | i = 1,\ 2, \cdots,\ m\right\} = \left\{v_1^-, v_2^-, \cdots, v_n^-\right\}, \tag{26}$$

where $J = \{j = 1,\ 2,\ \cdots, n | j$ associated with the – bigger – the – better attribute$\}$, $J' = \{j = 1,\ 2,\ \cdots, n | j$ associated with the – smaller – the – better attribute$\}$.

Step 5: Calculate the Euclidean distance of each alternative from the IS and the NIS by the following equations:

$$S_i^+ = \sqrt{\sum\nolimits_{j=1}^{n} \left(v_{ij} - v_j^+\right)^2}, \tag{27}$$

$$S_i^- = \sqrt{\sum\nolimits_{j=1}^{n} \left(v_{ij} - v_j^-\right)^2}. \tag{28}$$

Step 6: Calculate the RC to the IS for each alternative using Equation (7).

2.2.2. Evaluation of the Coordination Level of Attributes

Obviously, if a point is located on the line from the NIS to the IS, the attributes of the alternative represented by the point are completely coordinated. In this case, the following equation can be obtained.

$$\frac{v_{i1} - v_1^-}{v_1^+ - v_1^-} = \frac{v_{i2} - v_2^-}{v_2^+ - v_2^-} = \cdots = \frac{v_{in} - v_n^-}{v_n^+ - v_n^-}. \tag{29}$$

Plugging Equation (24) into Equation (29) gives

$$\frac{x_{i1} - x_1^-}{x_1^+ - x_1^-} = \frac{x_{i2} - x_2^-}{x_2^+ - x_2^-} = \cdots = \frac{x_{in} - x_n^-}{x_n^+ - x_n^-}, \tag{30}$$

where $\left\{x_1^+, x_2^+, \cdots, x_n^+\right\}$ and $\left\{x_1^-, x_2^-, \cdots, x_n^-\right\}$ are the IS and the NIS without the attribute weights, respectively.

Supposing that $z_{ij} = \frac{x_{ij} - x_j^-}{x_j^+ - x_j^-}$, Equation (30) can be written as

$$z_{i1} = z_{i2} = \cdots = z_{in}. \tag{31}$$

If $x_j^+ = 1$ and $x_j^- = 0$, Equation (31) can be written as

$$x_{i1} = x_{i2} = \cdots = x_{in}. \tag{32}$$

If Equation (31) holds true, the attributes are completely coordinated. Obviously, a large difference among $\mathbf{Z} = \{z_{i1}, z_{i2}, \cdots, z_{in}\}$ means a low coordination level of attributes. Therefore, in this study, the diversity of $\mathbf{Z}$ is used to indicate the coordination level of attributes, which is independent of weight.

The CV and information entropy (IE) are the two frequently used indicators to measure the diversity of data [27]. In this study, the CV is used to evaluate the coordination level of attributes. The CV can be calculated by the following equation [28]:

$$V_i = \frac{\sigma_i}{\mu_i} = \frac{\sqrt{\frac{1}{n}\sum_{j=1}^{n}\left(z_{ij} - \mu_i\right)^2}}{\mu_i}, \tag{33}$$

where σ_j is the standard deviation of $\mathbf{Z}$; μ_j is the mean value of $\mathbf{Z}$.

The minimum value of the CV is 0, which indicates that the attributes are completely coordinated. The smaller the CV is, the more coordinated the attributes are.

As a comparison, the IE is also used to evaluate the coordination level of attributes. The calculation steps of the IE are described as follows:

Step 1: Normalize $\mathbf{Z}$ by the following equation:

$$F_{ij} = z_{ij} / \sum_{j=1}^{n} z_{ij}. \tag{34}$$

Step 2: Calculate the IE of $\mathbf{Z}$ by the following equation:

$$E_i = -K \sum_{j=1}^{n} F_{ij} lnF_{ij}. \tag{35}$$

where $K = 1/\ln n$. In particular, when $F_{ij} = 0$, let $lnF_{ij} = 0$ [29].

The maximum value of the IE is 1, which indicates that the attributes are completely coordinated. The larger the IE is, the more coordinated the attributes are.

In order to combine the RC and CV, the CV needs to be normalized. As the CV is the-smaller-the-better indicator, the following equation is proposed to calculate the comprehensive evaluation value.

$$T_i = (1 - v)\frac{C_i}{\max(C_i)} + v\left(1 - \frac{V_i}{\max(V_i)} + \frac{\min(V_i)}{\max(V_i)}\right). \tag{36}$$

If the IE is used, the comprehensive evaluation value can be calculated by the following equation:

$$T_i = (1 - v)\frac{C_i}{\max(C_i)} + v\frac{E_i}{\max(E_i)}. \tag{37}$$

Then, the alternatives can be ranked or selected with respect to their comprehensive evaluation values. In this study, the coordinated TOPSIS based on the CV is abbreviated as C-TOPSIS-CV, and the coordinated TOPSIS based on the IE is abbreviated as C-TOPSIS-IE.

Since the coordination level of attributes is independent of weight, Equations (36) and (37) can be also used for modified TOPSIS [19,20] to establish coordinated modified TOPSIS. In this study, the coordinated modified TOPSIS based on the CV is abbreviated as CM-TOPSIS-CV, and the coordinated modified TOPSIS based on the IE is abbreviated as CM-TOPSIS-IE.

3. Results and Discussions

3.1. Case 1: Evaluation of Journals

To illustrate the problem of CM-TOPSIS and compare the CV and IE in evaluating the coordinated level of attributes, the evaluation of JCR2016 robotics journal in [16] is taken as an example. In [16], CM-TOPSIS is used to evaluate the journals. Therefore, in this study, CM-TOPSIS-CV and CM-TOPSIS-IE are adopted to evaluate the journals for comparison. The same indicators, weights, and normalization methods as in [16] are adopted when using CM-TOPSIS-CV and CM-TOPSIS-IE.

The absolute NIS is also used, which is $\{0, 0, \cdots, 0\}$. The weight of the CV is set to 0.5, and the weight of the CD or CV or IE is also 0.5. As Equation (10) is incorrect, Equation (21) is also used to calculate the CD. The CM-TOPSIS using the revised calculation formula (Equation (21)) is called revised CM-TOPSIS. The evaluation results of the several methods are listed in Tables 2 and 3. In [16], all the attributes are set to the same weight ($w_j = 1/n$). In this case, Equation (21) can be transformed to Equation (17), which means that the coordinated level determined by revised CM-TOPSIS is independent of weight. Therefore, for this example, the coordinated level determined by revised CM-TOPSIS can be compared with that determined by CM-TOPSIS-CV and CM-TOPSIS-IE.

From Table 2, the calculated results of θ_i and CD have great difference between CM-TOPSIS and revised CM-TOPSIS. For CM-TOPSIS, the CD varies in a narrow domain [0.107, 0.212], which indicates that the coordination level of attributes is low and the difference among the journals is small. However, for revised CM-TOPSIS, the CD varies in a wide domain [0.334, 0.872], which indicates that the difference of the coordination level among the journals is large, and some journals have high coordination level of attributes. Taking the CV as a reference, from Table 3, the CV also has a wide domain [0.203, 1.752], and the largest CV is more than nine times as much as the smallest CV, which also indicates that the difference of the coordination level among the journals is large. Therefore, the calculated results of CM-TOPSIS [16] are irrational, and the revised CM-TOPSIS can be used to replace it.

When the attributes have the same weight or no weight, the CD is independent of weight. Thus, the normalized values of the CD, CV, and IE can be compared. From Tables 2 and 3, the normalized values of the three indicators are different, which may result in different rankings. Figure 2 illustrates the statistical relationships among the normalized CV, normalized IE, and normalized CD. In Figure 2, the 45° line is given. All points on the 45° line have the same values of each component.

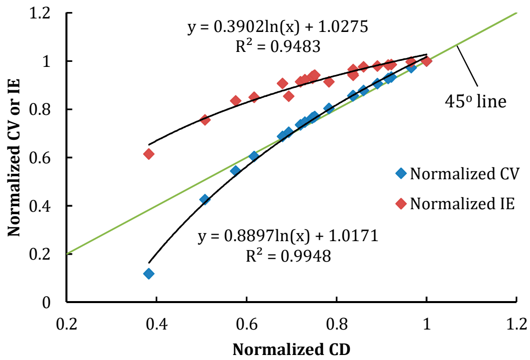

Figure 2. Variation of the normalized CV and information entropy (IE) vs. the normalized CD.

Table 2. Evaluation results of modified Technique for Order Preference by Similarity to Ideal Solution (TOPSIS), coordinated modified (CM)-TOPSIS, and revised CM-TOPSIS.

JCR Abbreviated Title	Modified TOPSIS		CM-TOPSIS [16]				Revised CM-TOPSIS				
	RC	Ranking	θ_i	CD	T_i	Ranking	θ_i	CD	Normalized CD	T_i	Ranking
INT J ROBOT RES	0.610	2	71.479	0.206	0.967	1	17.643	0.804	0.922	0.943	1
SOFT ROBOT	0.633	1	72.970	0.189	0.947	2	28.523	0.683	0.783	0.892	2
IEEE ROBOT AUTOM MAG	0.507	4	72.314	0.197	0.864	3	24.303	0.730	0.837	0.819	3
J FIELD ROBOT	0.426	5	71.539	0.205	0.821	5	18.197	0.798	0.915	0.794	4
BIOINSPIR BIOMIM	0.415	6	71.751	0.203	0.806	6	20.040	0.777	0.891	0.773	5
AUTON ROBOT	0.346	8	70.934	0.212	0.773	8	11.489	0.872	1.000	0.773	6
IEEE T ROBOT	0.515	3	73.132	0.187	0.849	4	35.491	0.606	0.694	0.754	7
ROBOT CIM-INT MANUF	0.401	7	72.060	0.199	0.787	7	22.473	0.750	0.860	0.747	8
ROBOT AUTON SYST	0.302	13	71.140	0.210	0.733	9	14.129	0.843	0.966	0.722	9
SWARM INTELL-US	0.322	12	72.320	0.196	0.718	10	24.344	0.730	0.836	0.672	10
J BIONIC ENG	0.333	9	73.465	0.184	0.696	11	31.371	0.651	0.747	0.636	11
J MECH ROBOT	0.328	11	73.416	0.184	0.694	12	31.103	0.654	0.750	0.634	12
INT J SOC ROBOT	0.329	10	73.853	0.179	0.683	13	33.457	0.628	0.720	0.620	13
J INTELL ROBOT SYST	0.278	15	73.478	0.184	0.652	14	31.444	0.651	0.746	0.593	14
ROBOTICA	0.167	20	72.311	0.197	0.596	15	24.278	0.730	0.837	0.550	15
ADV ROBOTICS	0.193	18	73.395	0.185	0.588	17	30.981	0.656	0.752	0.528	16
INT J ADV ROBOT SYST	0.296	14	76.305	0.152	0.593	16	44.745	0.503	0.576	0.522	17
INT J HUM ROBOT	0.162	21	73.707	0.181	0.555	18	32.685	0.637	0.730	0.493	18
IND ROBOT	0.171	19	74.480	0.172	0.542	19	36.611	0.593	0.680	0.475	19
APPL BIONICS BIOMECH	0.159	22	75.557	0.160	0.504	20	41.560	0.538	0.617	0.434	20
INT J ROBOT AUTOM	0.203	16	77.649	0.137	0.484	21	50.083	0.444	0.508	0.415	21
REV IBEROAM AUTOM IN	0.195	17	80.377	0.107	0.407	22	59.903	0.334	0.383	0.346	22

Table 3. Evaluation results of CM-TOPSIS-IE and CM-TOPSIS-CV.

JCR Abbreviated Title	CM-TOPSIS-IE				CM-TOPSIS-CV			
	IE	Normalized IE	T_i	Ranking	CV	Normalized CV	T_i	Ranking
INT J ROBOT RES	0.975	0.985	0.974	1	0.318	0.933	0.949	1
SOFT ROBOT	0.905	0.914	0.957	2	0.543	0.803	0.901	2
IEEE ROBOT AUTOM MAG	0.955	0.965	0.883	3	0.452	0.856	0.829	3
J FIELD ROBOT	0.974	0.983	0.828	5	0.329	0.927	0.800	4
BIOINSPIR BIOMIM	0.970	0.979	0.817	6	0.365	0.906	0.781	5
AUTON ROBOT	0.990	1.000	0.773	8	0.203	1.000	0.773	6
IEEE T ROBOT	0.846	0.854	0.834	4	0.713	0.705	0.759	7
ROBOT CIM-INT MANUF	0.966	0.976	0.805	7	0.414	0.878	0.756	8
ROBOT AUTON SYST	0.986	0.996	0.737	9	0.252	0.972	0.724	9
SWARM INTELL-US	0.937	0.946	0.728	11	0.452	0.856	0.682	10
J BIONIC ENG	0.919	0.928	0.727	12	0.610	0.764	0.645	11
J MECH ROBOT	0.931	0.940	0.729	10	0.603	0.768	0.643	12
INT J SOC ROBOT	0.905	0.914	0.717	13	0.661	0.735	0.627	13
J INTELL ROBOT SYST	0.926	0.935	0.687	14	0.611	0.763	0.601	14
ROBOTICA	0.931	0.940	0.602	17	0.451	0.856	0.560	15
ADV ROBOTICS	0.932	0.942	0.623	16	0.600	0.770	0.537	16
INT J ADV ROBOT SYST	0.827	0.835	0.651	15	0.991	0.543	0.505	17
INT J HUM ROBOT	0.913	0.922	0.589	18	0.642	0.746	0.501	18
IND ROBOT	0.899	0.907	0.589	19	0.743	0.687	0.479	19
APPL BIONICS BIOMECH	0.842	0.850	0.550	20	0.887	0.604	0.428	20
INT J ROBOT AUTOM	0.748	0.756	0.538	21	1.195	0.425	0.373	21
REV IBEROAM AUTOM IN	0.608	0.614	0.461	22	1.725	0.118	0.213	22

A significant logarithmic function relationship is observed between the normalized IE and normalized CD, and the fitting formula is y = 0.3902ln(x) + 1.0275, the R^2 of which is 0.9483. All the red points are located above the 45° line except point (1, 1), which indicates that the normalized IE is always larger than the normalized CD except the largest value of 1, and the dipartite degree of the normalized IE is lower than that of the normalized CD.

A significant logarithmic function relationship is also observed between the normalized CV and normalized CD, and the fitting formula is y = 0.8897ln(x) + 1.0171, the R^2 of which is 0.9948. Most of the blue points are located close to the 45° line, which indicates that the difference between the normalized CV and normalized CD is small. As shown in Tables 2 and 3, the ranking results determined by CM-TOPSIS and CM-TOPSIS-CV are the same. The blue points located below the 45° line indicates that the normalized CV has a higher dipartite degree when the coordination level of attributes is low.

The Spearman's rank correlation coefficients (SRCC) between the normalized RC and the three normalized indicators are calculated respectively. The calculated results as well as the range of each normalized indicator are listed in Table 4. As shown in Table 4, the range of the normalized IE is 0.386, which is much smaller than that of the normalized CD and normalized CV. This means that the dipartite degree of the normalized IE is lower than that of the normalized CD and normalized CV. Due to the lowest dipartite degree, the SRCC of the normalized IE is the largest, which is 0.935. Since the difference between the normalized CV and normalized CD is small, the SRCCs of the two indicators are the same, and smaller than that of the normalized IE. From Table 3, 77% of the journals have a normalized IE larger than 0.9, which also indicates that the dipartite degree of the normalized IE is low. Therefore, if the decision-maker expects a good dipartite degree of the coordination level, the CD and CV should be used to evaluate the coordination level of attributes. Since the application of the CD has some prerequisites, the CV is recommended.

Table 4. The Spearman's rank correlation coefficients (SRCC) and range of each indicator.

Normalized Indicator	Normalized CD	Normalized IE	Normalized CV
SRCC	0.909	0.935	0.909
Range	0.617	0.386	0.882

3.2. Case 2: Decision-Making for Real Estate Location

Location selection of a real estate project is influenced by many factors. The developers are always concerned about the costs and benefits such as land price and the future development of project. However, for the consumers, they will consider various factors of the real estate project when purchasing a house, such as house prices, traffic conditions, surroundings, and infrastructure. Any drawback of the project may affect the consumers' purchasing desire. Therefore, the coordination level of factors should be taken into account in decision-making for real estate location [18]. To compare C-TOPSIS-IE and C-TOPSIS-CV, and analyze the effect of weight on the coordination level of factors, the decision-making for real estate location [18] is taken as an example. Five factors for decision-making are "educational and medical conditions," "business environment," "land price," "transportation conditions," and "surroundings." The details of each proposed location are listed in Table 5. The 100-point system is used to determine the scores of factors for the five locations [18], as shown in Table 6. The weights of the factors are 0.1, 0.2, 0.3, 0.3, and 0.1, respectively [18].

Table 5. Details of each proposed location [18].

Location	Educational and Medical Conditions	Business Environment	Land Price	Transportation Conditions	Surroundings
Location 1	15 schools and six hospitals nearby. The nearest hospital is 1.6 km away.	One Shopping Mall nearby; six supermarkets within 3km	3.94 million yuan/mu; 1655 yuan/m^2	Within the Third Ring Road area; 11 bus lines; Zaoyuan Station of Metro Line 1	Two parks nearby, about 1.5 km away
Location 2	25 schools and eight hospitals nearby. The nearest hospital is 1.9 km away.	Four Shopping Malls nearby; eight supermarkets within 3 km	4.10 million yuan/mu; 1759 yuan/m^2	Within the Third Ring Road area; three bus lines; 0.66 km from Baihuacun Station of Metro Line 4 and 2.80 km from Fengcheng Station of Metro Line 2	One park nearby, 3.2 km away
Location 3	23 schools and five hospitals nearby. The nearest hospital is 0.5 km away.	Eight supermarkets within 3 km	4.21 million yuan/mu; 1610 yuan/m^2	Within the Second Ring Road area; 18 bus lines; 0.1 km from Xinjiamiao Station of Metro Line 3	Two parks nearby, about 3.2 km away
Location 4	29 schools and five hospitals nearby. The nearest hospital is 1.4 km away.	Two Shopping Malls nearby; 10 supermarkets within 3 km	5.50 million yuan/mu; 1992 yuan/m^2	Within the Third Ring Road area; eight bus lines; Jinye Road Station of Metro Line 6 (expected to be completed in 2020)	Five parks nearby; the nearest one is 1.6 km away
Location 5	18 schools and six hospitals nearby. The nearest hospital 2.5 km away.	Central Cultural Business District nearby; five supermarkets within 3 km	3.12 million yuan/mu; 1508 yuan/m^2	Outside the Third Ring Road area; five bus lines; Jinsituo Station of Metro Line 4	Four parks nearby; the nearest one is 0.9 km away

Table 6. Scores of the factors for the proposed locations [18].

Factor	Location 1	Location 2	Location 3	Location 4	Location 5
Educational and medical conditions	65	90	90	88	80
Business environment	75	90	75	90	82
Land price	80	85	84	75	95
Transportation conditions	75	65	95	85	80
Surroundings	90	65	85	95	92

In this study, C-TOPSIS-IE and C-TOPSIS-CV are used to determine the optimum location. Since the 100-point system is used, normalization is not required. Absolute IS and NIS are adopted, which are {0, 0, . . . , 0} and {100, 100, . . . , 100} respectively. In this case, Equation (23) can be used to evaluate the coordinated level of factors. Although the NIS is {100, 100, . . . , 100} not {1, 1, . . . , 1}, it does not affect the calculation results. The coordinated TOPSIS based on the original TOPSIS and Equation (23) is abbreviated as C-TOPSIS-CD in this paper. The decision results of the several methods are listed in Tables 7 and 8.

Table 7. Decision results of TOPSIS and coordinated (C)-TOPSIS-IE.

Location	TOPSIS		C-TOPSIS-IE		
	RC	Ranking	Normalized IE	T_i	Ranking
Location 1	0.7646	5	0.9983	0.9495	4
Location 2	0.7649	4	0.9949	0.9479	5
Location 3	0.8489	1	0.9998	0.9999	1
Location 4	0.8325	3	0.9998	0.9902	3
Location 5	0.8485	2	1.0000	0.9998	2

Table 8. Decision results of C-TOPSIS-CV and C-TOPSIS-CD.

Location	C-TOPSIS-CV			C-TOPSIS-CD		
	Normalized CV	T_i	Ranking	Normalized CD	T_i	Ranking
Location 1	0.7890	0.8448	4	1.0000	0.9503	4
Location 2	0.5091	0.7050	5	0.9449	0.9230	5
Location 3	0.9781	0.9891	2	0.9823	0.9911	2
Location 4	0.9849	0.9828	3	0.9861	0.9834	3
Location 5	1.0000	0.9998	1	0.9834	0.9914	1

From Table 7, the RCs have little difference between Location 3 and Location 5. Thus, the coordinated level of factors will be an important element affecting the decision result. Due to the low dipartite degree of the IE, the ranking determined by C-TOPSIS-IE is the same as that determined by TOPSIS, and the comprehensive evaluation value have little difference between Location 3 and Location 5. As for C-TOPSIS-CV, the comprehensive evaluation value has a significant difference between Location 3 and Location 5. Location 5 is determined as the best choice, which is the same as that determined by the multi-attribute decision-making method based on balance expectations [18]. From the sales, Location 5 is more popular with consumers [18], which is consistent with the decision result. This validates the feasibility of C-TOPSIS-CV.

The ranking determined by C-TOPSIS-CD is the same as that determined by C-TOPSIS-CV, but the normalized CD is much different from the normalized CV. For example, Location 1 has the largest normalized CD but a normalized CV of 0.7890 that is much smaller than 1.000. This is because that the normalized CD is interrelated with the weights. The three factors of "business environment," "land price," and "transportation conditions" have a total weight of 0.8. If the weight is taken into account, the coordination level will mainly depend on the three factors. As shown in Table 6, the scores of the three factors for Location 1 are 75, 80, and 75, the diversity of which is low. The CV of the three factors for Location 1 is 0.031, which is the smallest among the five Locations. As a result, Location 1 has the largest normalized CD. However, the score of "educational and medical conditions" for Location 1 is just 65, which may severely affect the consumers' purchasing desire. Therefore, the coordination level of factors should be independent of weight so as to obtain a reliable result.

3.3. Discussion

In this study, it was pointed out that the calculation formulas of the CD for CM-TOPSIS are incorrect, and revised calculation formulas of the CD were proposed for CM-TOPSIS. Meanwhile, the calculation formula of the CD for the original TOPSIS was also proposed. However, if the attributes are weighted, these calculation formulas of the CD are interrelated with the weights, which may be result in an irrational result. Therefore, the CV and IE that are independent of the weight were adopted to evaluate the coordination level of attributes. The comparison results show that the dipartite degree of the IE is lower than that of the CV. Therefore, if the decision-maker expects a good dipartite degree of the coordination level, the CV is recommended. The application of the CV has no prerequisite, and it is available for any normalization method. However, the application of the CD has an important prerequisite, which is that the IS is {1, 1, . . . , 1} and the NIS is {0, 0, . . . , 0}. If the prerequisite is satisfied or MMN is used, the CD can be used to evaluate the coordination level of attributes.

The CD, IE, and CV are all available for the original TOPSIS and modified TOPSIS to establish coordinated TOPSIS. The calculation formulas of the CD for the two methods are different, while that of the CV or IE is the same for the two methods. However, only when the weights of attributes are equal, the coordination level determined by the CD is independent of weight, and can be compared with that determined by the CV and IE. In this study, it is suggested that the coordination level of attributes should be independent of weight. Therefore, another prerequisite is needed for the application of the CD, which is that the weights of attributes are equal or there is no weight. If the decision-maker believes that the importance of attributes in the evaluation of coordination level is the same as that in decision-making or assessment, the weight should be taken into account in the coordination level. In this case, a weighted CV determined by the following equation can be used.

$$V_i = \frac{\sigma_i^w}{\mu_i} = \frac{\sqrt{\sum_{j=1}^{n} w_j \left(z_{ij} - \mu_i\right)^2}}{\mu_i}. \tag{38}$$

If the weights of attributes are equal, Equation (38) can be transformed to Equation (33). The larger the weight of an attribute is, the greater the influence of the attribute on the coordinated level is.

4. Conclusions

CM-TOPSIS is a significant improvement of TOPSIS, which takes into account the coordination level of attributes in the decision-making or assessment. However, CM-TOPSIS has some limitations and problems listed as follows.

(1) CM-TOPSIS is not based on the original TOPSIS, which is frequently used for decision-making and assessment.
(2) CM-TOPSIS has an important prerequisite, which is that the IS is {1, 1, . . . , 1} and the NIS is {0, 0, . . . , 0}. Thus, it is inapplicable when using VN.
(3) The calculation formulas of the CD for CM-TOPSIS are incorrect.
(4) If the attributes are weighted, the coordination level of attributes is interrelated with the weights when using the CD.

In this study, the calculation formulas of the CD for CM-TOPSIS were revised, and that for the original TOPSIS was proposed. The evaluation results of JCR2016 robotics journal indicated that the revision of the calculation formulas of the CD was successful. However, the application of the CD has an important prerequisite, which is that the IS is {1, 1, . . . , 1} and the NIS is {0, 0, . . . , 0}. If the prerequisite is satisfied or MMN is used, the CD can be used to evaluate the coordination level of attributes. As the CD is interrelated with the weights, another prerequisite is needed for the application of the CD, which is that the weights of attributes are equal or there is no weight.

To avoid the limitations of CM-TOPSIS, the CV and IE that are independent of the weight were adopted to evaluate the coordination level of attributes. Combining the IE or CV and the original TOPSIS, two types of coordinated TOPSIS called C-TOPSIS-IE and C-TOPSIS-CV were proposed in this study. Two case studies were conducted to compare the IE and CV in evaluating the coordination level of attributes. The comparison results indicate that the dipartite degree of the IE is lower than that of the CV. Therefore, if the decision-maker expects a good dipartite degree of the coordination level, the CV is recommended. Moreover, the CV has no requirement for the normalization method, and is available for the original TOPSIS and modified TOPSIS. It is suggested to use C-TOPSIS-CV or CM-TOPSIS-CV as coordinated TOPSIS, the feasibility of which was validated by the case studies.

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