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A Hybrid MCDM Model to Evaluate and Classify Outsourcing Providers in Manufacturing

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Abstract: It is a common practice for enterprises to use outsourcing strategies to reduce operating costs and improve product competitiveness. Outsourcing providers or operators need to be aware of environmental protection and make products comply with the restrictions of international environmental regulations. Therefore, this study proposes a set of multiple criteria decision-making (MCDM) approaches for systematic green outsourcing evaluation. First, a team of experts is established to discuss mutually dependent relationships among criteria, and the decision-making trial and evaluation laboratory (DEMATEL) technique is applied to generate subjective influential weights. Then, a large amount of data from outsourcing providers is collected, and the criteria importance through the intercriteria correlation (CRITIC) method is used to obtain the objective influential weights. Finally, a novel classifiable technique for ordering preference based on similarity to ideal solutions (classifiable TOPSIS) is proposed to integrate the performance of green outsourcing providers and classify them into four levels. The classifiable TOPSIS improves the shortcomings of conventional TOPSIS and establishes a visual rating diagram to help decision-makers to distinguish the performance of outsourcing providers more clearly. Taking a Taiwanese multinational machine tool manufacturer as an example, the performance of outsourcing providers related to manufacturing activities was investigated to demonstrate the effectiveness and applicability of this proposed model.

Keywords: multiple criteria decision-making (MCDM); outsourcing provider; DEMATEL; CRITIC; TOPSIS

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1. Introduction

Outsourcing has become one of the most important strategies in business operations. Through outsourcing operations, manpower and equipment investment can be greatly reduced, thereby operating costs can be effectively controlled. The range covered by outsourcing is very wide, including component production, financial planning, accounting, logistics management, legal consulting, marketing, after-sales service, etc. [1]. In 2018, the total amount of global companies signing outsourcing services contracts is estimated to be as high as US $85.6 billion [2]. This phenomenon shows that outsourcing activities have been widespread in all walks of life. An effective outsourcing evaluation system can maximize the benefits of outsourcing activities [3,4]. Improper selection of outsourcing providers can easily lead to the failure of outsourcing strategies, causing a decline in corporate competitiveness, and even financial risks or corporate failures [5,6].

The application of outsourcing strategy brings out diversified decision issues. In general, different business process owners should define not only the most appropriate conditions to gain a full compliance between in-house processes and outsourcing activities, but also require them harmonically converge towards the guidelines at the roots of decision-making [1,3]. However, the rise of environmental awareness has changed the concept of decision-making. It is no longer only cost-effectiveness as the ultimate consideration, but must be incorporated into green criteria to facilitate environmental protection [7,8]. The evaluation and selection of green outsourcing providers is an important task in supply chain management. Especially in the manufacturing industry, for highly complex products such as machine tools or ships, the number of outsourcers they have is very considerable. When an enterprise has many outsourcers, it must have a complete and systematic model to determine the weight of the evaluation criteria and the priority of outsourcing providers, otherwise the management of providers will appear very messy and difficult. [1,3–6].

Many scholars have made significant contributions to the evaluation and selection of outsourcing providers. Some studies have pointed out that the selection of outsourcing providers can be categorized as a multiple criteria decision-making (MCDM) problem [3–5,9–11]. The MCDM method has excellent evaluation performance under many mutually constrained conditions. Its computing concept is different from statistics. MCDM can process expert interview data with a small sample, and can also analyze large sample data from the database. The goal of MCDM is to integrate both objective quantitative data and subjective expert judgment, and provide effective management suggestions to support decision-makers in formulating optimal strategies [12–14]. It is suitable to establish a complete evaluation framework based on the expertise of researchers or experts and the extensive experience of practitioners [15–17]. The evaluation and selection of MCDM projects can usually be divided into three execution stages, namely the identification of evaluation criteria, the calculation of criteria weights, and the performance analysis of alternatives [18].

In the past, research on selecting outsourcing providers has laid the foundation for industry and academia; however, there are still some research gaps and practical application restrictions.

(i) Some evaluation models do not take into account criteria related to environmental protection.

Many manufacturing activities have caused various environmental pollution and destruction. Operators need to be aware of environmental protection and make products comply with the restrictions of international environmental regulations. Therefore, whether outsourcing providers have environmental awareness and green manufacturing capabilities deserves our consideration [7].

(ii) Many weight-setting methods assume that the criteria are independent.

Past studies on outsourcing provider selection have often overlooked the mutually dependent relationships among criteria. For example, the analytic hierarchy process (AHP) and the best-worst method (BWM) are used to obtain criteria weights. In fact, the root causes of problems are composed of many interrelated factors [19–21]. The decision-making trial and evaluation laboratory (DEMATEL) can overcome the assumption of independence of the criteria and determine the interdependence among the criteria [6,9].

(iii) Few studies consider both subjectivity and objectivity.

The methods of determining the importance of the criteria can be divided into two categories. Experts conduct pairwise comparisons of the criteria to evaluate their importance and call them subjective weights. Common methods are AHP, BWM, analytic network process (ANP), and DEMATEL. The other type is based on a large amount of data to estimate a set of criteria weights, called objective weights. Entropy and criteria importance through intercriteria correlation (CRITIC) belong to this type of method. If both perspectives can be included in the evaluation model, the results will be comprehensive and complete [22].

(iv) When an enterprise has a large number of outsourcing providers, the ranking of outsourcing providers can no longer meet the needs of decision-makers.

For industries with a wide variety and a small amount of production (such as machinery), there would be a lot of outsourcing providers needed. However, even though the ranking of outsourcing providers is determined, it is impossible to give each outsourcing provider practical suggestions for improvement. If all outsourcing providers can be classified into different levels and given appropriate management suggestions for each level, the management efficiency of the managers can be improved. It is a good practice to classify outsourcing providers through the closeness coefficient of technique for ordering preference based on similarity to ideal solutions (TOPSIS) [8].

Therefore, in order to tackle the aforementioned problems, this study proposes a MCDM model with a systematic green outsourcing evaluation. First, based on the existing evaluation criteria of the case company and the documentation, a complete evaluation framework for green outsourcing providers was established. The proposed framework can be divided into four main dimensions: capacity of operation, capacity of professional skills, capacity of service, and environment management. These dimensions can be divided into 15 evaluation criteria. Here, the dimension of environmental management was added to conform to the development trend of environmental awareness. Next, the DEMATEL technique was used to explore the mutually dependent relationship among the criteria, and a set of subjective weights was obtained. The DEMATEL questionnaires were obtained by interviewing eight senior managers of the case company. Furthermore, the external auditors surveyed the performance data of 165 outsourcing providers, and applied CRITIC's algorithm to generate a set of objective weights. The proposed DEMATEL–CRITIC method can reflect the importance of mutually dependent relationships among the criteria. Finally, this study develops a classifiable TOPSIS technique, which not only introduces the concept of aspiration level, but also divides the performance of outsourcing providers into four levels. Appropriate management suggestions are given for the four levels to support outsourcing providers in formulating improvement strategies to enhance their business performance. The DEMATEL, CRITIC, and TOPSIS used in this model are all breakthrough improvements, which make the analysis ability improved and more in line with the actual needs of the industry.

To demonstrate the effectiveness of the proposed model, a Taiwanese multinational machine tool manufacturer is used as an example. Sensitivity analysis and model comparisons are also conducted in this study to demonstrate the robustness of this methodology. The proposed hybrid model is not limited to the amount of data in use. The data can be a small sample or a big data. In addition, when new outsourcing providers join, their performance levels can be quickly classified. Based on the results obtained, the decision-makers can decide whether to cooperate with a new outsourcing provider or not. In summary, the advantages and contribution of our study are described below.

(i) Integrating environmental protection criteria in the framework of green outsourcing providers.
(ii) Using the DEMATEL–CRITIC method which considers both subjectivity and objectivity. And, this method can identify the mutual influence of the criteria.
(iii) Proposing a classifiable TOPSIS to classify a large number of green outsourcing providers, and give appropriate suggestions for improvement according to their levels.
(iv) The effective and robustness of the proposed model being confirmed through the model comparisons and sensitivity analysis.

The rest of the paper is organized as follows. Section 2 reviews the research on using MCDM to evaluate outsourcing providers. Section 3 introduces the proposed novel model. Moreover, we improved the DEMATEL, CRITIC, and TOPSIS methods and introduced the calculation process and execution steps in detail. Section 4 uses a real case to demonstrate the applicability of the proposed model. Section 5 discusses management implication issues, sensitivity analysis and model comparisons. Finally, conclusions and future research directions are given in Section 6.

2. A Brief Review of the Evaluation of Applying MCDM to Outsourcing Providers

At present, compared with the articles of suppliers, there are relatively few studies on evaluation and selection of outsourcing providers. With the rapid development of outsourcing strategies, the issue of evaluation of outsourcing providers has become increasingly important [3,4]. When enterprises face shortages of technology and manpower, they often increase their operational capabilities through outsourcing. From the process of finding outsourced objects to the willingness of cooperation between both parties, many details need to be coordinated and improved.

The success of the outsourcing strategies will create a lot of added values, including saving setup costs, reducing operational risks, and focusing more on core business. However, outsourcing activities will produce a certain degree of two-way information exchange and communication, and the success or failure of cooperation will involve many complicated factors [23]. Therefore, the evaluation of outsourcing providers is a difficult and complex MCDM problem. Previous studies have used various MCDM methods to explore this issue. Research based on linear programming, for example, Li and Wan [24] developed a method of fuzzy linear programming to address the issue of outsourcing provider selection. This method is implemented in the largest light-emitting diode (LED) production company in China. The results show that both positive and negative ideal solutions should be considered when evaluating outsourcing providers, to overcome the shortcoming that the linear programming technique for multidimensional analysis of preference (LINMAP) can only obtain local optimal solutions. In the same year, Li and Wan [25] extended Li and Wan [24] research and applied to a well-known information technology company in Jiangxi, China. The study shows that it is feasible to determine the weights of attributes through linear programming. In order to consider the importance of experts, Wan et al. [8] optimized the linear programming method of Li and Wan [25], combined with intuitionistic fuzzy preference relations (IFPRs) to determine the weights of experts to effectively integrate the group decision-making judgment.

In addition, Ji et al. [3] proposed a comprehensive MCDM framework to solve the problem of non-compensatory criteria. The modified multi-attributive border approximation area comparison (MABAC) method is a novel weight determination method, which can explore the non-compensatory structure of the criteria. Next, the elimination et choice translating reality (ELECTRE) technique was used to rank the outsourcing providers. The study used data from Li and Wan [24] to analyze and compare TOPSIS, weighted bonferrroni mean, and traditional MABAC methods, to explain the advantages of the proposed method. In recent years, several novel MCDM models have extended the research on outsourcing providers evaluation. Zarbakhshnia et al. [26] combined fuzzy AHP (FAHP) and gray multi-objective optimization by ratio analysis (MOORA-G) methods to select the third-party reverse logistics providers for a car parts manufacturing company. Their research shows that the combined model can effectively deal with uncertain qualitative data. A hybrid framework was proposed by Prajapati et al. [27], who integrated fuzzy Delphi, FAHP, and fuzzy additive ratio assessment (F-ARAS) methods to prioritize alternative outsourcing providers in energy industry. However, these studies all consider the criteria to be independent, which violates the situation in which the existing social factors depend on one another.

Taking into account factor-dependent research, for example, Liou and Chuang [9] proposed a hybrid MCDM model to evaluate more than 50 outsourcing providers of Taiwan Airlines. The study used DEMATEL and ANP to discuss the influential relationships and influential weights of the criteria, and applied the visekriterijumska optimizacija i kompromisno resenje (VIKOR) to obtain the gap between each alternative and the ideal level. Hsu et al. [6] improved the methodology of Liou and Chuang [9] and integrated DEMATEL-based ANP (DANP) and modified grey relation analysis (GRA), where the DANP method puts the output values of DEMATEL into ANP to generate a set of dependent weight values. Next, modified GRA is used to determine and rank the grey correlation coefficient of each outsourcing provider. Uygun et al. [11] combined fuzzy theory with the ANP method to evaluate the competitiveness of a Turkish communications company's outsourcing providers. Their research focuses on the processing of uncertain information.

Table 1 summarizes the existing studies applying MCDM model to evaluate and select outsourcing providers. The studies mentioned above have made significant contributions to this topic. Unfortunately, no research has simultaneously discussed and solved the four research gaps mentioned in Section 1.

Table 1. Literature review of the evaluation of applying multiple criteria decision-making (MCDM) to outsourcing providers.

Author	Research Methodology	Application Field	Green Criteria Included	Consideration of Criteria Dependence
Li and Wan [24]	Fuzzy inhomogenous multi-attribute group decision making approach	Light-emitting diode (LED) production company	No	No
Li and Wan [25]	Fuzzy heterogeneous multi-attribute decision making method	Information technology company	No	No
Wan et al. [10]	An intuitionistic fuzzy linear programming method	Logistics industry	No	No
Ji et al. [3]	Combined MABAC and ELECTRE techniques.	Information technology company	No	No
Zarbakhshnia et al. [26]	Combined FAHP and MOORA-G methods.	Car parts manufacturing company	Yes	No
Prajapati et al. [27]	Integrated fuzzy Delphi, FAHP, and F-ARAS methods.	Energy industry	No	No
Liou and Chuang [9]	Integrated DEMATEL, ANP, and VIKOR methods.	Airlines	No	Yes
Hsu et al. [6]	Integrated DANP and modified GRA approaches.	Airlines	No	Yes
Uygun et al. [11]	Combined DEMATEL and fuzzy ANP methods.	GSM (global system for mobile) communication company	No	Yes

DEMATEL, decision-making trial and evaluation laboratory; MABAC, multi-attributive border approximation area comparison; AHP, analytic hierarchy process; MOORA-G, multi-objective optimization by ratio analysis; F-ARAS, fuzzy additive ratio assessment; ANP, analytic network process; VIKOR, visekriterijumska optimizacija i kompromisno resenje; DANP, DEMATEL-based ANP; GRA, grey relation analysis.

3. The Proposed Classifiable MCDM Model

This section introduces the proposed classifiable MCDM model. First, the influential weights of the criteria for evaluating outsourcing providers are obtained through the DEMATEL–CRITIC model. Next, these weights are used by the classifiable TOPSIS algorithm to evaluate the performance of outsourcing providers. The proposed model converts the performance of each outsourcing provider into a score between 0 to 1, which is further divided into four levels. Appropriate suggestions for improvement strategies for outsourcing providers in each level are given. Past research has focused on the selection of outsourcing providers, often only able to determine the ranking of outsourcing providers. However, in the face of a large number of outsourcing providers, ranking can no longer meet the requirement of the enterprise. Figure 1 presents the analysis flow of this study. The detailed implementation steps of this study are described below.

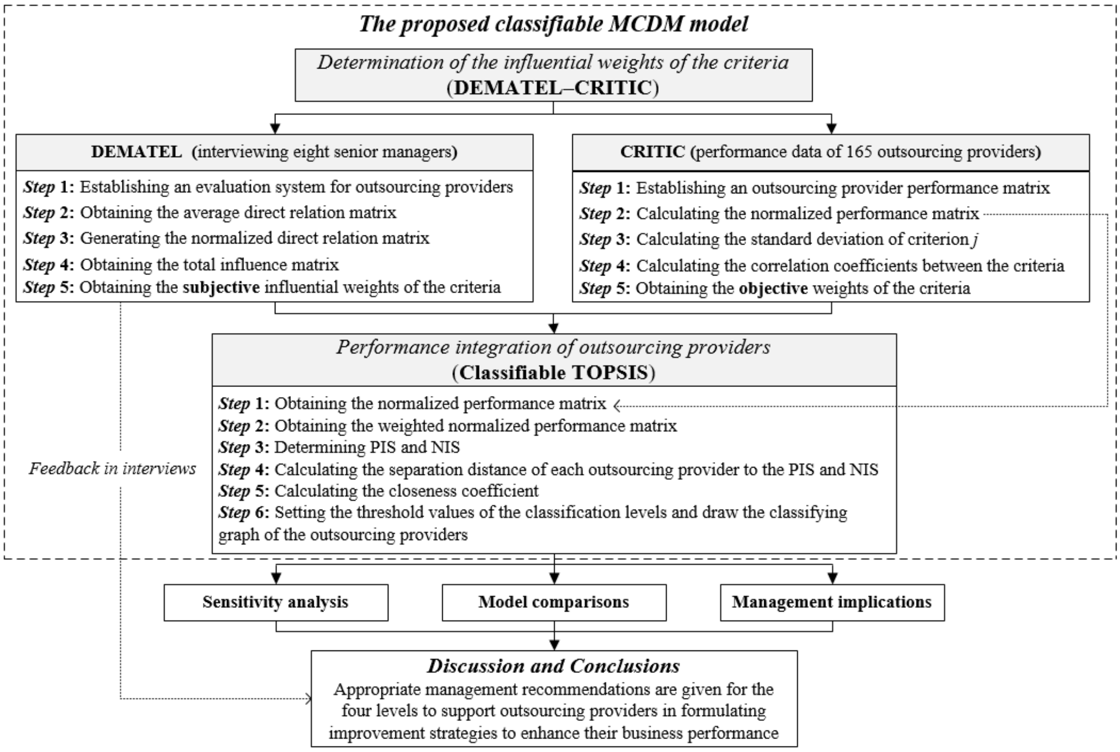

Figure 1. The analysis flow of this study. CRITIC, criteria importance through intercriteria correlation; TOPSIS, technique for ordering preference based on similarity to ideal solutions.

3.1. Determination of the Influential Weights of the Criteria (DEMATEL–CRITIC)

In the past, most academic articles used a single MCDM method to obtain the subjective weights of criteria (e.g., AHP, ANP, BWM, DEMATEL, and DANP). Unfortunately, few studies have discussed the subjective and objective weights of criteria at the same time. This study proposes the DEMATEL–CRITIC method to construct a reliable set of criteria weights and takes into account the dependency of the criteria. This method can quickly process the big data of multiple criteria, construct the dependency relationships of the criteria through correlation coefficients and standard deviations, and extract the information on the influence degrees of the criteria in the complex systems.

3.1.1. DEMATEL (Subjective Weights)

DEMATEL is a technique that effectively explores the mutual influence among criteria. This technique can identify the influential relationships and strength among the criteria, and then help decision-makers to find the key causes in a complex evaluation system. DEMATEL is widely used in various industries, including disaster prevention science [20], e-commerce [28], advertising design [29], transportation [19], and green building [30]. The issue of evaluation of outsourcing providers involves factors such as government regulations, company policies, and process requirements. How to generate a reasonable set of weights from these factors is the purpose of DEMATEL. DEMATEL conducts interviews through experts or inspectors to give back quantifiable linguistics to reflect their true feelings. The calculation steps of the DEMATEL technique are described below.

Step 1. Establishing an evaluation system for outsourcing providers

In reality, every company has an evaluation system for outsourcing providers. The evaluation period of outsourcing providers may last half a year or once a year. We define the evaluation criterion as $c_i,\ i = 1,\ 2, \ldots,\ n$.

Step 2. Obtaining the average direct relation matrix $\boldsymbol{A}$

Experts are required to evaluate the mutual influence of n criteria. Each expert evaluates the direct influence of criterion i on criterion j through linguistic variables (Table 2) to obtain the direct relation matrix.

Table 2. Linguistic variables for the influence evaluation.

Linguistic Variable (Code)	Crisp
No influence (N)	0
Low influence (L)	1
Medium influence (M)	2
High influence (H)	3
Very high influence (VH)	4

In this study, the arithmetic mean is used to integrate the opinions of multiple experts, and an average direct relation matrix $\boldsymbol{A}$ is formed, as shown in Equation (1).

$$\boldsymbol{A} = \left[a_{ij}\right]_{n\times n} = \begin{bmatrix} 0 & a_{12} & \cdots & a_{1j} & \cdots & a_{1n} \\ a_{21} & 0 & \cdots & a_{2j} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{i1} & a_{i2} & \cdots & 0 & \cdots & a_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nj} & \cdots & 0 \end{bmatrix}_{n\times n},\ i,j = 1,\ 2, \ldots,\ n. \tag{1}$$

In the operation rules of DEMATEL, the criteria have no self-influential relationship, indicating that the diagonal elements in the matrix are 0, i.e., $a_{ii} = 0,\ i = 1,\ 2, \ldots,\ n$.

Step 3. Generating the normalized direct relation matrix $\boldsymbol{X}$

The normalization formulas (Equations (2) and (3)) are used to convert the range of elements in the matrix to be between 0 and 1.

$$\boldsymbol{X} = \left[x_{ij}\right]_{n\times n} = \begin{bmatrix} 0 & \varepsilon\cdot a_{12} & \cdots & \varepsilon\cdot a_{1j} & \cdots & \varepsilon\cdot a_{1n} \\ \varepsilon\cdot a_{21} & 0 & \cdots & \varepsilon\cdot a_{2j} & \cdots & \varepsilon\cdot a_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \varepsilon\cdot a_{i1} & \varepsilon\cdot a_{i2} & \cdots & 0 & \cdots & \varepsilon\cdot a_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ \varepsilon\cdot a_{n1} & \varepsilon\cdot a_{n2} & \cdots & \varepsilon\cdot a_{nj} & \cdots & 0 \end{bmatrix}_{n\times n},\ i,j = 1,\ 2, \ldots,\ n. \tag{2}$$

$$\varepsilon = \min\left\{\frac{1}{\max_i \sum_{j=1}^{n} a_{ij}},\ \frac{1}{\max_j \sum_{i=1}^{n} a_{ij}}\right\} \tag{3}$$

Step 4. Obtaining the total influence matrix $\boldsymbol{T}$

Here, the total direct and indirect influential relationships of all the criteria are considered. Therefore, the total influence matrix $\boldsymbol{T}$ is obtained by summing up all the powers of the matrix $\boldsymbol{X}$, such as Equation (4). Equation (4) can be converted to Equation (5), to simplify the calculation of the total influence matrix $\boldsymbol{T}$.

$$\boldsymbol{T} = \boldsymbol{X} + \boldsymbol{X}^2 + \cdots + \boldsymbol{X}^{\infty} \tag{4}$$

$$\begin{aligned} \boldsymbol{T} &= \boldsymbol{X} + \boldsymbol{X}^2 + \cdots + \boldsymbol{X}^{\infty} = \boldsymbol{X}\left(I + \boldsymbol{X} + \boldsymbol{X}^2 + \cdots + \boldsymbol{X}^{\infty-1}\right) \\ &= \boldsymbol{X}(I - \boldsymbol{X}^{\infty})(I - \boldsymbol{X})^{-1} = \boldsymbol{X}(I - \boldsymbol{X})^{-1} \end{aligned} \tag{5}$$

where $\boldsymbol{X}^{\infty} = [0]_{n \times n}$, $\boldsymbol{I}$ is the identity matrix, and the superscript symbol "−1" indicates the inverse matrix.

$$\boldsymbol{T} = \left[t_{ij}\right]_{n \times n} = \begin{bmatrix} t_{11} & t_{12} & \cdots & t_{1j} & \cdots & t_{1n} \\ t_{21} & t_{22} & \cdots & t_{2j} & \cdots & t_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{i1} & t_{i2} & \cdots & t_{ij} & \cdots & t_{in} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ t_{n1} & t_{n2} & \cdots & t_{nj} & \cdots & t_{nn} \end{bmatrix}_{n \times n}, i, j = 1, 2, \ldots, n. \tag{6}$$

Step 5. Obtaining the subjective influential weights of the criteria

The elements of the total influence matrix are summed horizontally to obtain a vector $\boldsymbol{r}$, such as Equation (7). Similarly, using Equation (8), the elements of the matrix $\boldsymbol{T}$ are summed vertically to obtain the vector $\boldsymbol{s}$.

$$\boldsymbol{r} = (r_1, r_2, \ldots, r_i, \ldots, r_n) \tag{7}$$

$$\boldsymbol{s} = \left(s_1, s_2, \ldots, s_j, \ldots, s_n\right) \tag{8}$$

where $r_i = \sum_{j=1}^{n} t_{ij}$ and $s_j = \sum_{i=1}^{n} t_{ij}$, $i, j = 1, 2, \ldots, n$.

r_i represents the extent of criterion i affecting other criteria, and s_i represents the extent of criterion i affected by other criteria. Therefore, we can define $r_i + s_i$ as the total influence and $r_i - s_i$ as the net influence for each criterion i. If $r_i - s_i$ is positive, it means that the effect of criterion i affecting other criteria is more significant, which is called a causal factor; otherwise, if $r_i - s_i$ is negative, it means that criterion i is greatly affected by other criteria, which is called an affected factor. Moreover, according to the study of Lo et al. [21], $r_i + s_i$ can reflect the total influence of criterion i on the overall evaluation system. Therefore, Equation (9) can generate the subjective influential weight of criterion i, namely $w_i^{subjective}$, $i = 1, 2, \ldots, n$. It can be seen that $w_i^{subjective} \geq 0$ and $\sum_{i=1}^{n} w_i^{subjective} = 1$.

$$w_i^{subjective} = \frac{r_i + s_i}{\sum_{i=1}^{n} (r_i + s_i)} \tag{9}$$

3.1.2. CRITIC (Objective Weights)

CRITIC is a type of objective weights based on performance data (the performance scores of all outsourcing providers under each criterion). This method is measured by the linear correlation coefficient among the criteria, so it contains information about the degree of correlation. CRITIC mainly constructs the dependent weights of the criteria from the "standard deviation of the criteria" and the "correlation coefficient among the criteria". The conflict among criteria is measured through the relevance of criteria to echo the core concepts of MCDM. The detailed steps of the CRITIC method are as follows:

Step 1. Establishing an outsourcing provider performance matrix $\boldsymbol{D}$

There are m outsourcing providers $A_h,\ h = 1,\ 2, \ldots,\ m$ and n criteria $c_j,\ j = 1,\ 2, \ldots,\ n$. In the construction of the performance matrix, the rows of the matrix correspond to the outsourcing providers and the columns of the matrix correspond to the criteria. The element d_{hj} of matrix $\boldsymbol{D}$ represents the evaluation performance of outsourcing provider h under criterion j, as shown in Equation (10).

$$\boldsymbol{D} = \left[d_{hj}\right]_{m\times n} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1j} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2j} & \cdots & d_{2n} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{h1} & d_{h2} & \cdots & d_{hj} & \cdots & d_{hn} \\ \vdots & \vdots & \ddots & \vdots & \ddots & \vdots \\ d_{m1} & t_{m2} & \cdots & d_{mj} & \cdots & d_{mn} \end{bmatrix}_{m\times n}, \quad (10)$$
$$h = 1,\ 2, \ldots,\ m; j = 1,\ 2, \ldots,\ n.$$

where the rating score d_{hj}, ranging from 0 to 100, is developed by the case company's rating system.

Step 2. Calculating the normalized performance matrix $\boldsymbol{D}^*$

The matrix $\boldsymbol{D}^*$ can be obtained through normalization (Equation (11)). The conventional normalization method is to take the best performance of the alternatives under each criterion as the denominator, which will result in the situation of "pick the best apple from a bucket of rotten apples". Therefore, this article introduces the concept of aspiration level to modify the normalization scheme, such as Equation (12).

$$\boldsymbol{D}^* = \left[d^*_{hj}\right]_{m\times n} \quad (11)$$

where

$$d^*_{hj} = \frac{d_{hj}}{\max\limits_{1\le i\le n} d_{ij}}.$$
$$d^*_{hj} = \frac{d_{hj}}{d_j^{aspire}} \quad (12)$$

where d_j^{aspire} represents the highest rating score (the aspiration level is 100) of criterion j.

Step 3. Calculating the standard deviation of criterion j

Matrix $\boldsymbol{D}^*$ presents the performance of each outsourcing provider under various criteria. Through the standard deviation σ_j, the degree of variation of outsourcing providers under criterion j can be known.

$$\sigma_j = \sqrt{\frac{\sum_{h=1}^{m}\left(d_{hj} - \overline{d}_j\right)^2}{m-1}} \quad (13)$$

where $\overline{d}_j = \frac{\sum_{h=1}^{m} d_{hj}}{m}$.

Step 4. Calculating the correlation coefficients between the criteria

Considering the correlation among the criteria, a linear correlation coefficient is used to measure the correlation between every two criteria, such as Equation (14). These coefficients are used to construct the correlation matrix $\boldsymbol{R}$ of the criteria, such as Equation (15).

$$r_{jj'} = \frac{\sum_{h=1}^{m}\left(d_{hj} - \overline{d}_j\right)\left(d_{hj'} - \overline{d}_{j'}\right)}{\sqrt{\sum_{h=1}^{m}\left(d_{hj} - \overline{d}_j\right)^2} \cdot \sqrt{\sum_{h=1}^{m}\left(d_{hj'} - \overline{d}_{j'}\right)^2}} \quad (14)$$

$$\boldsymbol{R} = \left[r_{jj'}\right]_{n\times n} = \begin{bmatrix} 1 & r_{12} & \cdots & r_{1n} \\ r_{12} & 1 & \cdots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{1n} & r_{2n} & \cdots & 1 \end{bmatrix}_{n\times n}, \ j, j' = 1, 2, \ldots, n \quad (15)$$

Step 5. Obtaining the objective weights of the criteria

Through Equation (16), the "standard deviation" and "correlation coefficient between every two criteria" are integrated to generate an overall evaluation value. Next, the objective weights of the criteria are computed through normalization (Equation (17)). Thus, the sum of the weights is 1, and all the weights are greater than or equal to 0.

$$\varphi_j = \sigma_j \sum_{j'=1}^{n} \left(1 - r_{jj'}\right) \quad (16)$$

$$w_j^{objective} = \frac{\varphi_j}{\sum_{i=1}^{n} \varphi_i} \quad (17)$$

3.2. Performance Integration of Outsourcing Providers (Classifiable TOPSIS)

TOPSIS technique is one of the effective MCDM methods for integrating performance values. This method determines the relative position of each outsourcing provider by calculating the distance between each outsourcing provider and the positive and negative ideal solutions (PIS and NIS). The best outsourcing provider is the one closest to the positive ideal solution and farthest from the negative ideal solution. The solution time and quality of TOPSIS will not be affected by the numbers of outsourcing providers or criteria. By improving the conventional TOPSIS, this study proposes a classifiable TOPSIS technique which can generate more reliable performance scores. In this technique, all outsourcing providers are classified into four levels. When a new outsourcing provider is included, this technique can be used to quickly classify it. The detailed steps of the classifiable TOPSIS technique are explained as follows:

Step 1. Obtaining the normalized performance matrix $\boldsymbol{D}^*$

The input data of TOPSIS and CRITIC are the same. Therefore, the normalized performance matrix $\boldsymbol{D}^*$ can be obtained through Steps 1 and 2 of the CRITIC.

Step 2. Obtaining the weighted normalized performance matrix $\boldsymbol{D}^{**}$

We consider the importance of the criteria to be different and multiply the weights obtained by DEMATEL and CRITIC with the normalized performance matrix to obtain a weighted normalized performance matrix, such as Equation (18). Since both subjective (DEMATEL) and objective (CRITIC) influential weights are considered, here, parameter α is used to express preference between subjective and objective weights, and the final weights are shown as in Equation (19).

$$\boldsymbol{D}^{**} = \left[d_{hj}^{**}\right]_{m\times n} \quad (18)$$

where $d_{hj}^{**} = w_j^* \cdot d_{hj}^*$.

$$w_j^* = \alpha w_j^{subjective} + (1-\alpha) w_j^{objective} \quad (19)$$

where $w_j^{subjective}$ is the subjective weight of criterion j generated by DEMATEL (Equation (9)), and $w_j^{objective}$ is the objective weight of criterion j obtained by CRITIC (Equation (17)).

Step 3. Determining PIS and NIS

After normalization, the value of aspiration (positive) and worst (negative) level should be 1 and 0, respectively. Therefore, after considering the criteria weights, the PIS (z_j^+) and NIS (z_j^-) of the system can be obtained, as shown in Equations (20) and (21).

$$\text{PIS} = \left(z_1^+,\ z_2^+, \ldots,\ z_j^+, \ldots,\ z_n^+\right) = \left(1 \cdot w_1^*,\ 1 \cdot w_2^*, \ldots,\ 1 \cdot w_j^*, \ldots,\ 1 \cdot w_n^*\right) \quad (20)$$

$$\text{NIS} = \left(z_1^-,\ z_2^-, \ldots,\ z_j^-, \ldots,\ z_n^-\right) = \left(0 \cdot w_1^*,\ 0 \cdot w_2^*, \ldots,\ 0 \cdot w_j^*, \ldots,\ 0 \cdot w_n^*\right) \quad (21)$$

Step 4. Calculating the separation distance of each outsourcing provider to the PIS and NIS

This article uses the Euclidean distance to measure the degree of separation of outsourcing provider h from PIS and NIS, as shown in Equations (22) and (23).

$$S_h^+ = \sqrt{\sum_{j=1}^{n}\left(z_j^+ - d_{hj}^{**}\right)^2} \quad (22)$$

$$S_h^- = \sqrt{\sum_{j=1}^{n}\left(d_{hj}^{**} - z_j^-\right)^2} \quad (23)$$

Step 5. Calculating the closeness coefficient

The closeness coefficient (CC_h) was proposed by Kuo [31]. This index improves many disadvantages of conventional TOPSIS to obtain more reliable ranking results, as shown in Equation (24). The new ranking index has an excellent basis for judgment. The range of CC_h is from −1 to 1 for each outsourcing provider h, and the total of CC_h for all outsourcing providers is 0.

$$CC_h = \frac{w^+ S_h^-}{\sum_{h=1}^{m} S_h^-} - \frac{w^- S_h^+}{\sum_{h=1}^{m} S_h^+},\ -1 \le CC_h \le 1. \quad (24)$$

where w^+ and w^- represents the relative importance of PIS and NIS, respectively. Since $w^+ + w^- = 1$, the settings of w^+ and w^- will affect each other. Generally, both w^+ and w^- are set to be 0.5.

However, the ranking index proposed by Kuo [31] has a disadvantage that when the number of outsourcing providers increases, CC_h will also decrease, making it difficult to interpret this value. Therefore, in this study, CC_h is further normalized to obtain a new ranking index CC_h^*, as shown in Equation (25).

$$CC_h^* = \frac{CC_h - CC^{worst}}{CC^{aspire} - CC^{worst}},\ 0 \le CC_h^* \le 1 \quad (25)$$

Step 6. Setting the threshold values of the classification levels and draw the classifying graph of the outsourcing providers

The closer the value of CC_h^* is to 1, outsourcing provider h is more preferred. On the other hand, when the value of CC_h^* is close to 0, outsourcing provider h should be eliminated. Here, according to the nature of CC_h^*, the threshold values are set by the decision-making team, and then the outsourcing providers are classified into four levels. We set the horizontal axis to be the indices of outsourcing providers, and the vertical axis to be the values of CC_h^*. According to the classification in Table 3, we can construct an outsourcing provider classification graph.

Table 3. Classification levels of outsourcing providers.

CC_h	Evaluation Level	Description
$0.9 \leq CC_h^* \leq 1$	A^+	Level A^+ outsourcing providers have performance close to the aspiration level and are excellent outsourcing providers.
$0.75 \leq CC_h^* < 0.9$	A	Level A outsourcing providers perform well, but they still need to strengthen some of their capabilities.
$0.5 \leq CC_h^* < 0.75$	B	The performance of Level B outsourcing providers is average, and it needs to be greatly improved to meet the requirements of enterprises.
$0 \leq CC_h^* < 0.5$	C	The performance of Level C outsourcing providers is close to the worst level, hardly meets the requirements of enterprises, and should be eliminated.

4. Illustration of a Real Case

This section uses a real case to illustrate the calculation procedure in Section 3.

4.1. Problem Description

The case company is a multinational machine tool manufacturing company in Taiwan, dedicated to the manufacture of cutting processing equipment and laser processing equipment. The company already has a number of intellectual property rights and invention patents related to machine tools. The accuracy and stability of the products are comparable to those of well-known equipment manufacturers in Europe and America. The products have been successfully sold to electronics, machinery, shipbuilding, aerospace, and other industries around the world. In recent years, the development trend of intelligent machinery has brought about many markets and opportunities. The case company actively expanded its sales channels (finding agents and distributors), and signed a joint cooperation with government agencies or labor union organizations, hoping to bring more profit to the enterprise. Due to the expansion of the company's business territory (the global dealers have exceeded 80 cities), coupled with factors such as global competition and high investment costs, the case company has implemented outsourcing policies for many years.

At present, the case company has an evaluation system for outsourcing providers, which mainly focuses on the business conditions and cooperation capabilities of its partners. Unfortunately, the weights of the evaluation criteria are only given directly from senior managers, and the method of performance integration of outsourcing providers is the simple additive weighting (SAW) method. The existing weight determination method is easily affected by the personal preferences of senior executives. In addition, although the SAW calculation process is simple, it does not take into account the comprehensiveness of the evaluation system. Therefore, it is obvious that a scientific and systematic analysis model is needed to support decision makers in formulating business policies.

Through literature review and the existing company outsourcing provider evaluation system, after discussion with the company's decision-making team, four dimensions, 15 criteria and 165 outsourcing providers were identified. The outsourcing providers evaluated in this case were all related to manufacturing. The decision-making team was composed of eight senior executives of the case company, including the chairman, the general manager, and six department managers. The six managers are from the business, manufacturing, purchasing, logistics, quality control, and marketing departments. Each expert had at least fifteen years of professional work experience in manufacturing industry and was specifically selected for their expertise in the evaluation process. In terms of academic qualifications, this team has three PhDs and five masters degrees. In addition, all experts have experience in the business activities of outsourcing strategies. They mainly assisted in drafting outsourcing provider evaluation framework (Table 4) and filling out the DEMATEL questionnaire.

Table 4. Outsourcing provider evaluation criteria and descriptions.

Dimension	Criterion	Description
Capacity of operation (D_1)	Enterprise size and financial capabilities (C_{11})	The criterion includes evaluating the capital, turnover, number of employees, market share, and organizational structure of the outsourcing providers. Moreover, information such as the company's solvency, the company's internal control, board functions, and business status are all very important basis for financial capability.
	Project management capabilities (C_{12})	The success factors of outsourcing providers working with the enterprise to promote projects include experience and technology. The outsourcing providers should have the experience of undertaking outsourcing, focusing on shortening the completion time and the ability of quality assurance.
	Supply chain audit planning (C_{13})	The outsourcing provider's ability to integrate the supply chain includes the process of inspecting the incoming, production, inventory, and sales of all products of the provider. Maintaining the stability of overall supply chain activities is a must for outsourcing providers.
	Maintenance of corporate confidentiality (C_{14})	All gold flow, information flow, and logistics of enterprises and outsourcing providers must be strictly controlled and kept secret.
Capacity of professional skills (D_2)	R&D and design capabilities (C_{21})	Whether the outsourcing provider has mastered leading technology and knowledge during the R&D and design stage, clearly understands the needs of the market, and can innovate products.
	Process quality control (C_{22})	Whether the outsourcing provider's manufacturing process is stable and whether the product meets the quality required by the customer.
	Key component inventory control (C_{23})	Whether the inventory of key components and their procurement channels are stable.
	Management information system integration (C_{24})	Outsourcing information should be published on a common information platform immediately and correctly, including all cash flows, information flows, and logistics.
	Finished product quality assurance and reliability (C_{25})	The outsourcing provider's ability to analyze the reliability of the product includes the formulation of the product's life, usage specifications, and maintenance methods.
Capacity of service (D_3)	After-sales service and improvement capabilities (C_{31})	Products should be continuously tracked and evaluated during the stages of design, manufacturing, and after-sale use. Outsourcing providers should take the initiative to actively optimize products to effectively reduce costs and improve quality.
	Customer relationship management and loyalty (C_{32})	Outsourcing providers use effective information technology to collect data and analyze customer needs and quickly process customer orders. In addition, the loyalty of outsourcing providers will affect the tacit understanding of long-term cooperation.
	Communication channels and message sharing (C_{33})	A good communication channel is a basis for stable cooperation. Enterprises and outsourcing providers must trust each other and open up more information conducive to cooperation.
Environment management (D_4)	Green resource integration (C_{41})	Outsourcing providers must respect the surrounding environment and protect the natural ecology in the production process, and create a green supply chain system. Outsourcing providers' emphasis on environmental protection can effectively enhance their corporate image.
	Environmental certification (C_{42})	Outsourcing providers must abide by the local government's environmental regulations and obtain relevant environmental certifications and certificates.
	Pollution emission treatment (C_{43})	Evaluate whether outsourcing providers are actively implementing pollutant emission reduction policies. Moreover, the utilization rate of renewable energy is also one of the evaluation projects.

4.2. Using DEMATEL–CRITIC to Calculate the Influential Weights of the Criteria

According to the implementation process of DEMATEL in Section 3.1.1, the eight experts used linguistic variables (Table 2) to evaluate the influence among the criteria. Table 5 presents the results of the DEMATEL questionnaire filled by the first expert. In order to check the consensus level (consistency) of the eight experts, the average sample gap (ASG) index can be calculated through Equation (26) [19,21].

$$ASG = (n(n-1)(p-1))^{-1} \times \sum_{k=2}^{p}\sum_{i=1}^{n}\sum_{j=1}^{n}\left(\frac{\left|a_{ij}^{(k)} - a_{ij}^{(k-1)}\right|}{a_{ij}^{(k)}}\right) \times 100\% \tag{26}$$

where n is the number of criteria (15), and $a_{ij}^{(k)}$ is the evaluation value of the k^{th} expert, $k = 1, 2, \ldots, p$. According to the index, the average gap of the eight experts is 3.8%, indicating that there is 96.2% of the confidence level that these experts have achieved a consensus.

Table 5. The direct relation matrix of the first expert.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}
C_{11}	0	3	3	3	3	3	2	2	2	3	3	4	2	0	1
C_{12}	1	0	3	2	3	0	1	3	2	1	3	4	4	3	3
C_{13}	2	3	0	1	2	2	2	4	4	2	2	3	3	2	3
C_{14}	1	4	3	0	4	2	2	4	2	2	3	4	0	0	0
C_{21}	1	2	2	3	0	4	2	3	4	2	2	4	4	2	4
C_{22}	0	2	1	2	1	0	3	2	3	4	2	2	4	3	4
C_{23}	1	2	3	1	1	4	0	4	2	4	3	1	1	1	1
C_{24}	1	4	4	4	2	2	4	0	2	2	4	4	2	2	2
C_{25}	1	2	2	4	1	4	2	1	0	4	3	3	3	3	2
C_{31}	1	4	3	2	4	1	1	1	4	0	2	2	2	1	2
C_{32}	4	4	4	4	4	1	1	3	2	1	0	4	3	3	3
C_{33}	1	4	4	4	4	0	4	4	2	1	4	0	4	2	2
C_{41}	2	2	3	0	4	2	1	4	1	3	3	1	0	4	4
C_{42}	3	3	3	2	3	2	2	4	1	1	1	1	4	0	4
C_{43}	2	2	3	1	0	2	1	0	0	3	1	1	4	4	0

Table 6 shows the total influence ($r_i + s_i$) and net influence ($r_i - s_i$) of all criteria. Enterprise size and financial capabilities (C_{11}) has the largest net influence (0.838), indicating that many criteria are affected by this criterion. Moreover, green resource integration (C_{41}) has the highest total influence ($r_{41} + s_{41} = 8.886$) in the overall evaluation system, and its influential weight is 0.076. DEMATEL's results not only facilitate decision-makers to quickly understand which criteria are the main causes or consequences, but also generate a set of subjective influential weights. Next, we adopt the CRITIC method, using the performance matrix as input data to derive a set of objective influential weights.

Table 6. DEMATEL calculation results and subjective influential weights.

	r	s	$r + s$	$r - s$	DEMATEL Weight
C_{11}	3.437	2.599	6.037	0.838	0.052
C_{12}	3.934	4.195	8.130	−0.261	0.069
C_{13}	4.004	4.477	8.481	−0.473	0.072
C_{14}	3.454	3.745	7.198	−0.291	0.062
C_{21}	4.442	4.049	8.491	0.393	0.073
C_{22}	3.654	3.128	6.782	0.526	0.058
C_{23}	4.208	3.554	7.762	0.654	0.066
C_{24}	4.079	3.968	8.047	0.111	0.069
C_{25}	4.243	3.407	7.650	0.836	0.065
C_{31}	3.952	3.442	7.394	0.509	0.063
C_{32}	4.308	4.204	8.511	0.104	0.073
C_{33}	4.092	4.121	8.212	−0.029	0.070
C_{41}	4.000	4.886	8.886	−0.886	0.076
C_{42}	3.867	4.276	8.142	−0.409	0.070
C_{43}	2.831	4.453	7.284	−1.621	0.062

The off-site auditors of the case company surveyed a total of 165 manufacturing-related outsourcing providers, and each outsourcing provider was summed up with 15 performance scores, with a maximum score of 100 points and a minimum score of 0 points. The performance matrix of outsourcing providers is 165 × 15 and there is no missing value for the data in this matrix. Table 7 presents the first 10 data of outsourcing providers. The calculation is performed through the steps in Section 3.1.2. The standard deviation (σ), influence degree (φ), and objective influential weights are presented in Table 8.

Table 7. Performance matrix of the first 10 data of the outsourcing providers.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}
A_1	77	87	82	77	69	84	80	76	87	60	80	82	95	80	93
A_2	71	80	91	77	85	56	73	76	87	67	67	82	98	80	67
A_3	83	80	100	77	90	72	73	76	100	73	73	87	95	90	60
A_4	89	80	96	71	88	80	73	68	80	40	80	39	90	85	100
A_5	71	73	87	77	88	64	80	80	73	67	73	73	94	80	93
A_6	83	80	100	77	90	64	73	76	100	73	80	82	88	100	33
A_7	60	80	73	71	88	56	60	72	67	35	60	31	81	40	80
A_8	89	80	100	83	98	72	80	80	100	87	100	91	95	100	67
A_9	83	93	91	66	93	84	60	80	93	73	67	64	87	65	93
A_{10}	77	53	87	54	81	56	67	64	87	60	67	69	85	85	93

Table 8. CRITIC calculation results and final weights.

	σ	φ	CRITIC Weight	DEMATEL Weight	Final Weight	Ranking
C_{11}	0.152	1.082	0.063	0.052	0.057	14
C_{12}	0.145	1.067	0.062	0.069	0.066	8
C_{13}	0.106	0.687	0.040	0.072	0.056	15
C_{14}	0.141	0.916	0.053	0.062	0.057	13
C_{21}	0.104	0.857	0.050	0.073	0.061	10
C_{22}	0.151	1.027	0.060	0.058	0.059	11
C_{23}	0.182	1.352	0.078	0.066	0.072	5
C_{24}	0.155	1.121	0.065	0.069	0.067	6
C_{25}	0.160	1.110	0.064	0.065	0.065	9
C_{31}	0.190	1.544	0.090	0.063	0.076	4
C_{32}	0.168	1.437	0.083	0.073	0.078	2
C_{33}	0.160	1.479	0.086	0.070	0.078	3
C_{41}	0.097	0.676	0.039	0.076	0.058	12
C_{42}	0.156	1.078	0.063	0.070	0.066	7
C_{43}	0.184	1.807	0.105	0.062	0.084	1

DEMATEL–CRITIC overcomes the traditional problem of considering only subjective or objective perspectives, and generates a final influential weight with a more comprehensive perspective. The top five criteria with the highest weights are pollution emission treatment (C_{43}), customer relationship management and loyalty (C_{32}), communication and information sharing (C_{33}), after-sales service and improvement capabilities (C_{31}), and key component inventory control capabilities (C_{23}).

4.3. Using a Classifiable TOPSIS Rating for the Performance of Outsourcing Providers

The process of evaluation and classification of green outsourcing providers is complex and difficult. It is one of the purposes of this study to use simple and clear reports or diagrams to help operators understand the performance of outsourcing providers. The proposed classifiable TOPSIS technique introduces the concept of aspiration level and avoids considering only the relative preference solution of the current scheme. Therefore, the first 10 outsourcing provider performance data are taken as an example (Table 7), and all scores are divided by 100 (the aspiration level) to convert the value range from 0 to 1 to form a normalized performance matrix, as shown in Table 9. Here, the aspiration level and the worst level are considered as alternatives, so their scores are 1 and 0, respectively. Table 10 presents the weighted normalized performance matrix.

Table 9. Normalized performance matrix of the first 10 data of outsourcing providers.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}
A_1	0.772	0.866	0.823	0.772	0.685	0.840	0.800	0.760	0.866	0.600	0.800	0.823	0.952	0.800	0.933
A_2	0.714	0.800	0.911	0.772	0.855	0.560	0.734	0.760	0.866	0.666	0.666	0.823	0.976	0.800	0.667
A_3	0.828	0.800	1.000	0.772	0.903	0.720	0.734	0.760	1.000	0.734	0.734	0.867	0.952	0.900	0.600
A_4	0.886	0.800	0.956	0.714	0.879	0.800	0.734	0.680	0.800	0.400	0.800	0.389	0.903	0.850	1.000
A_5	0.714	0.734	0.867	0.772	0.879	0.640	0.800	0.800	0.734	0.666	0.734	0.733	0.940	0.800	0.933
A_6	0.828	0.800	1.000	0.772	0.903	0.640	0.734	0.760	1.000	0.734	0.800	0.823	0.879	1.000	0.333
A_7	0.600	0.800	0.733	0.714	0.879	0.560	0.600	0.720	0.666	0.350	0.600	0.305	0.807	0.400	0.800
A_8	0.886	0.800	1.000	0.828	0.976	0.720	0.800	0.800	1.000	0.866	1.000	0.911	0.952	1.000	0.667
A_9	0.828	0.934	0.911	0.658	0.927	0.840	0.600	0.800	0.934	0.734	0.666	0.644	0.867	0.650	0.933
A_{10}	0.772	0.534	0.867	0.542	0.807	0.560	0.666	0.640	0.866	0.600	0.666	0.689	0.855	0.850	0.933
A^{aspire}	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
A^{worst}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

Table 10. Weighted normalized performance matrix of the first 10 data of outsourcing providers.

	C_{11}	C_{12}	C_{13}	C_{14}	C_{21}	C_{22}	C_{23}	C_{24}	C_{25}	C_{31}	C_{32}	C_{33}	C_{41}	C_{42}	C_{43}
A_1	0.044	0.057	0.046	0.044	0.042	0.049	0.058	0.051	0.056	0.046	0.062	0.064	0.055	0.053	0.078
A_2	0.041	0.053	0.051	0.044	0.052	0.033	0.053	0.051	0.056	0.051	0.052	0.064	0.056	0.053	0.056
A_3	0.047	0.053	0.056	0.044	0.055	0.042	0.053	0.051	0.065	0.056	0.057	0.068	0.055	0.059	0.050
A_4	0.051	0.053	0.054	0.041	0.054	0.047	0.053	0.045	0.052	0.031	0.062	0.030	0.052	0.056	0.084
A_5	0.041	0.048	0.049	0.044	0.054	0.038	0.058	0.054	0.048	0.051	0.057	0.057	0.054	0.053	0.078
A_6	0.047	0.053	0.056	0.044	0.055	0.038	0.053	0.051	0.065	0.056	0.062	0.064	0.051	0.066	0.028
A_7	0.034	0.053	0.041	0.041	0.054	0.033	0.043	0.048	0.043	0.027	0.047	0.024	0.046	0.026	0.067
A_8	0.051	0.053	0.056	0.047	0.060	0.042	0.058	0.054	0.065	0.066	0.078	0.071	0.055	0.066	0.056
A_9	0.047	0.061	0.051	0.038	0.057	0.049	0.043	0.054	0.061	0.056	0.052	0.050	0.050	0.043	0.078
A_{10}	0.044	0.035	0.049	0.031	0.049	0.033	0.048	0.043	0.056	0.046	0.052	0.054	0.049	0.056	0.078
A^{aspire} (z^+)	0.057	0.066	0.056	0.057	0.061	0.059	0.072	0.067	0.065	0.076	0.078	0.078	0.058	0.066	0.084
A^{worst} (z^-)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0

According to the calculation steps in Section 3.2, the analysis results can be summarized in Table 11. The degrees of separation of outsourcing provider A_h from PIS and NIS (S^+ and S^-) can be determined. In particular, the degree of separation between the aspiration level and PIS must be 0 (the aspiration level is PIS). Conversely, the degree of separation between the worst level and the negative ideal solution is also 0 (the worst level is NIS). The degree of separation between the aspiration level and the worst level is 0.260 (the Euclidean distance between PIS and NIS is 0.260).

Table 11. Calculation results of the classifiable TOPSIS and the rating scale of the first 10 data of outsourcing providers.

	S^+	S^-	CC (Equation (24))	CC^* (Equation (25))	*Gap*	*Rating*
A_1	0.056	0.211	0.0003	0.792	0.208	A
A_2	0.068	0.200	−0.0005	0.746	0.254	B
A_3	0.059	0.211	0.0001	0.782	0.218	A
A_4	0.080	0.203	−0.0011	0.712	0.288	B
A_5	0.061	0.205	−0.0001	0.771	0.229	A
A_6	0.074	0.207	−0.0007	0.732	0.268	B
A_7	0.109	0.168	−0.0030	0.595	0.405	B
A_8	0.044	0.229	0.0011	0.843	0.157	A
A_9	0.064	0.207	−0.0002	0.762	0.238	A
A_{10}	0.079	0.192	−0.0012	0.704	0.296	B
A^{aspire}	0.000	0.260	0.0037	1		
A^{worst}	0.260	0.000	−0.0128	0		

The case company uses the values of 0.5, 0.75, and 0.9 as the classification thresholds. All outsourcing providers are then classified into four levels, including A^+, A, B, and C. Furthermore, the gap between each outsourcing provider and the aspiration level has also been determined. The larger the gap, the greater the room for improvement is for the corresponding outsourcing provider. For example, although outsourcing provider A_1 is rated as a Level A outsourcing provider, its overall evaluation performance is still 0.208 units away from the aspiration level. The proposed model has many potential management implications, as detailed in Section 4.3.

5. Management Implications and Discussion

Due to the development trend of artificial intelligence, many machine tool equipment companies have created customized machines for customers. This also increases the research and development and manufacturing costs for the companies. Therefore, co-production through outsourcing providers becomes a good strategy. Under the Taiwan government's "5 + 2 Industry Innovation Program" policy, the machinery industry has become one of the emerging high-tech industries, and many organizations have invested huge amounts of money to promote the industry. In order to improve the level of machine intelligence, machine tools related to smart machines have been continuously developed. Compared with other manufacturing industries, the manufacturing technology threshold for smart machinery is relatively high, and most companies will use outsourcing strategies to reduce research and development (R&D) and production costs.

According to DEMATEL–CRITIC analysis, pollution emission treatment (C_{43}) is the most important criterion, with a weight of 0.084. The waste reduction and carbon reduction are among the most critical evaluation indicators for manufacturing. Facing the rise of environmental awareness, many international environmental protection and trade organizations have formulated many environmental protection regulations to require companies to pay attention to environmental issues. Customer relationship management and loyalty (C_{32}) is the second most important criterion. The customer relationship management capabilities of an outsourcing provider will directly affect the willingness of the company to sign a contract, especially the coordination of design changes and the enthusiasm of after-sales service. In addition, the loyalty of outsourcing companies is particularly valued by the company's senior management, which involves a long-term willingness to sign a contract. The weights of communication and message sharing (C_{33}) and C_{32} are very close, indicating that the degree of information sharing by outsourcing providers is also highly valued. The remaining criteria can also give outsourcing providers suggestions for improvement through the weight values.

The proposed model establishes a visual rating diagram to help decision-makers to judge the performance of outsourcing providers more clearly, as shown in Figure 2. The diagram clearly classifies all outsourcing providers into four levels, including 11 in Level A^+, 100 in Level A, 50 in Level B, and 4 in Level C. The thresholds for these classifications are determined by the decision-making team established by the company. The analysis results are verified by the case company to be both reasonable and helpful. Most of the outsourcing companies in Level A have cooperated with the company for more than 10 years, and their performance in all aspects has met the requirements of the senior management. Although the outsourcing providers of Level A have a good rating score, there are still some gaps from the aspiration level. Outsourcing companies at this level can focus on improving the criteria with greater weights first, including C_{43}, C_{32}, C_{33}, C_{31}, and C_{23}. Level B outsourcing providers should conduct a comprehensive review of the company's current operating conditions and provide complete improvement measures in four major directions: operation (D_1), professional skills, (D_2), service (D_3), and environment management (D_4) to move toward Level A. Otherwise, they will face elimination in the future. Finally, the performance of the outsourcing providers at Level C does not meet the expectations of the case company at all, so the partnership of outsourcing providers at this level should be dissolved.

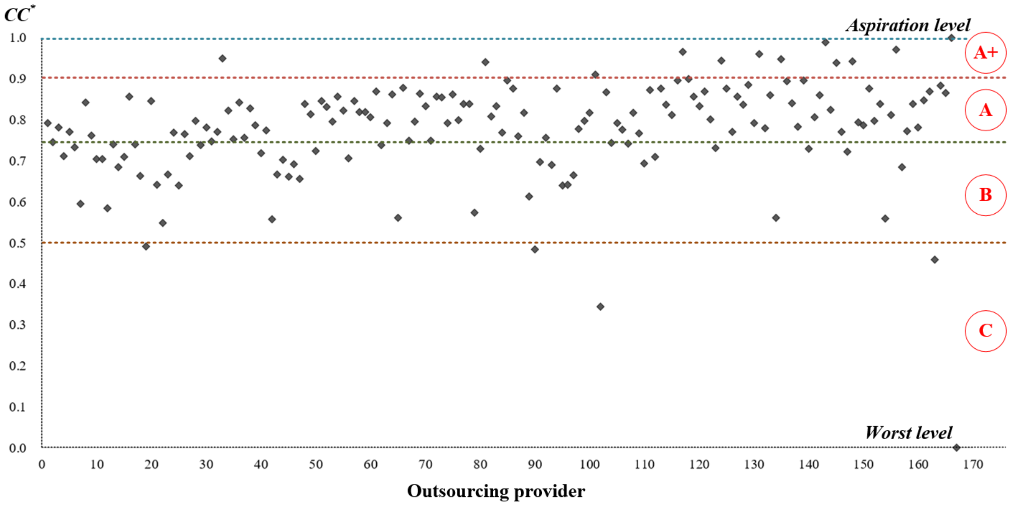

Figure 2. One hundred and sixty-five outsourcing providers' CC^* and their classification levels.

Next, we discuss whether the proposed DEMATEL–CRITIC method will affect the results of the classifiable TOPSIS because of the change in the ratio of subjectivity and objectivity. Therefore, the sensitivity analysis was performed nine times to test whether the priorities of outsourcing providers have changed significantly. By changing the parameters of Equation (19) from 0.1 to 0.9, all the criteria weights are changed, as shown in Table 12.

Table 12. Weight configuration of sensitivity analysis performed nine times.

	Run 1	Run 2	Run 3	Run 4	Run 5	Run 6	Run 7	Run 8	Run 9
	$\alpha = 0.1$	$\alpha = 0.2$	$\alpha = 0.3$	$\alpha = 0.4$	$\alpha = 0.5$	$\alpha = 0.6$	$\alpha = 0.7$	$\alpha = 0.8$	$\alpha = 0.9$
C_{11}	0.062	0.061	0.059	0.058	0.057	0.056	0.055	0.054	0.053
C_{12}	0.063	0.063	0.064	0.065	0.066	0.066	0.067	0.068	0.069
C_{13}	0.043	0.046	0.050	0.053	0.056	0.059	0.063	0.066	0.069
C_{14}	0.054	0.055	0.056	0.057	0.057	0.058	0.059	0.060	0.061
C_{21}	0.052	0.054	0.057	0.059	0.061	0.063	0.066	0.068	0.070
C_{22}	0.059	0.059	0.059	0.059	0.059	0.059	0.058	0.058	0.058
C_{23}	0.077	0.076	0.075	0.074	0.072	0.071	0.070	0.069	0.068
C_{24}	0.065	0.066	0.066	0.067	0.067	0.067	0.068	0.068	0.068
C_{25}	0.064	0.065	0.065	0.065	0.065	0.065	0.065	0.065	0.065
C_{31}	0.087	0.084	0.082	0.079	0.076	0.074	0.071	0.068	0.066
C_{32}	0.082	0.081	0.080	0.079	0.078	0.077	0.076	0.075	0.074
C_{33}	0.084	0.083	0.081	0.080	0.078	0.076	0.075	0.073	0.072
C_{41}	0.043	0.047	0.050	0.054	0.058	0.061	0.065	0.069	0.072
C_{42}	0.063	0.064	0.065	0.065	0.066	0.067	0.067	0.068	0.069
C_{43}	0.101	0.096	0.092	0.088	0.084	0.079	0.075	0.071	0.067

Figure 3 shows the ranking results after the nine times of sensitivity analysis performed. Obviously, the ranking of outsourcing providers will not be changed significantly because of the excessive emphasis on the weight of subjectivity or objectivity. The sensitivity analysis shows that the proposed model is robust.

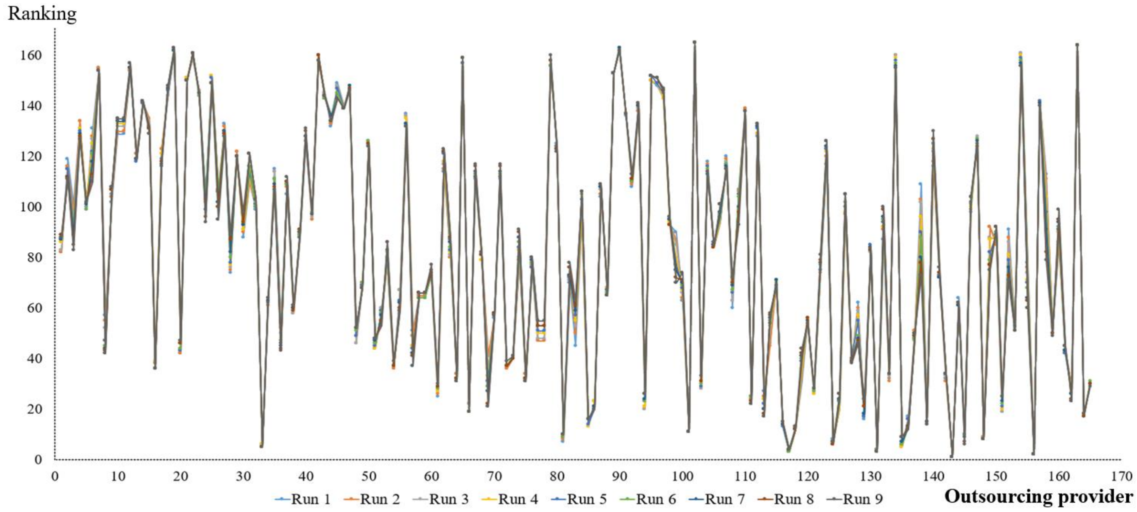

Figure 3. Results of the sensitivity analysis performed nine times.

In addition, we conducted model comparisons to demonstrate the differences between this study and previous studies. Model 1 is the original SAW analysis method of the case company, and the criteria weights are directly given by the senior executives. Model 2 uses the weights of DEMATEL–CRITIC and uses SAW for performance integration. Model 3 is the proposed model. Figure 4 shows the ranking results of all the outsourcing providers in the three models. It can be found that the ranking results of Models 1 and 2 are almost the same. There are 14 outsourcing providers in the first place in these two models. In this case, the company cannot distinguish the pros and cons of these 14 outsourcing providers. Moreover, each outsourcing provider will not be able to know what the gap is from the aspiration level. Although the SAW method is simple, it has not considered the comprehensiveness of the evaluation system, only the scores are multiplied by the weight values. The ranking result of the proposed model (Model 3) is significantly different from the other models. We determine the whole range of performance by formulating PIS and NIS, and use the concept of distance to define the relative position of each outsourcing provider. Moreover, the new index proposed by the model clearly points out the gap between the outsourcing provider and the aspiration level.

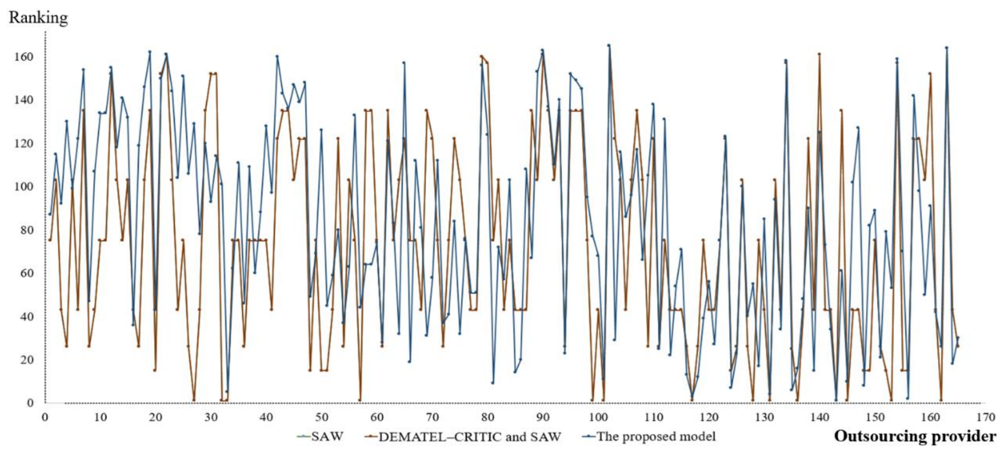

Figure 4. Comparisons of the proposed model with other methods.

6. Conclusions

This study contributes to the research of green outsourcing evaluation. The contribution and advantages of this research include four aspects: (i) integrating environmental protection criteria in the evaluation framework of outsourcing providers, to reflect the awareness that enterprises should pay attention to environmental protection. (ii) By considering the mutual influence of the criteria, it overcomes the shortcomings of the previous studies that need to assume the criteria to be independent. (iii) Aspect three involves using the DEMATEL–CRITIC method, which considers both subjectivity and objectivity; the impact of the criteria on the evaluation system is also explored. (iv) Aspect four involves proposing a classifiable TOPSIS to classify a large number of outsourcing providers, and give appropriate suggestions for improvement according to their levels. In addition to the above contributions, our research has also discovered some findings, including the robustness of the proposed model being confirmed through the sensitivity analysis, which means that the analysis results will not be significantly affected by the changes in weights. Moreover, the model comparisons confirmed that our model is more practical and effective. In short, the research method in this paper can be copied to other MCDM evaluation and selection topics, especially the classification of information with big data.

The analysis process of this study is highly dependent on the judgment of experts, so there are several limitations on its use, including the following: (i) the selected experts are sufficiently representative; (ii) the evaluation criteria need to be repeatedly confirmed, whether it is appropriate or not; and (iii) the analysts must be able to interpret the results of each method. Moreover, the classification of TOPSIS in terms of setting the classification thresholds can be further determined by more scientific methods.

Since the methodology proposed in this study is novel, there are some suggestions for further studies in the future. The proposed model has not yet taken into consideration the uncertainty of the information and evaluation environment. Future research can combine fuzzy or grey or Z-number or neutrosophic logic theories to enhance the adaptability of the model. Finally, the proposed model can be coded and incorporated into business software to facilitate the convenient use in industry.

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