Journal of Supply Chain Management Science

https://journals.open.tudelft.nl/jscms

http://dx.doi.org/10.18757/jscms.2021.5864

Supplier selection based on multi-stakeholder Best-Worst Method

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Article history: received 29-10-2020, accepted 22-06-2021, published 30-06-2021

Abstract – Supplier selection and supplier segmentation are two interdependent crucial steps of effective supplier relationship management. Supplier selection is formulated as a multi-criteria decision-making problem, in which evaluation criteria play a critical role in a realistic assessment of the suppliers. The evaluation criteria can be used to link supplier selection and segmentation steps to have a more efficient and effective supplier relationship management. A multi-stakeholder Best-Worst Method (BWM) is used for supplier selection. The proposed method is a proper tool to handle the optimal weights of the BWM, which are in the form of intervals. The proposed approach enables decision-makers to avoid information loss within their decision-making procedure resulting in more realistic decisions. A real-world case study is used to illustrate the proposed decision-making framework. The final results show the best suppliers based on both capabilities and willingness dimensions which can be selected by the case company.

Keywords: Supplier selection; Supplier potential matrix (SPM); Multi-stakeholder Best-Worst Method

1. Introduction

As the global market expands and becomes more competitive, firms try to focus their valuable resources on their own core competencies and outsource non-competitive activities. The importance of suppliers' performances increased significantly up to a level where a fine supplier is capable of creating value and competitiveness for the buyer (Sureeyatanapas et al. 2018). Poor supplier selection will inevitably have adverse consequences for the buyer. Supplier selection along with supplier segmentation and supplier development are three main steps of supplier relationship management (Rezaei et al. 2015). It has been emphasized in the existing literature that firms must adopt a strategic approach for effective supplier relationship management and avoid having a "one-size-fits-all" strategy (Dyer et al. 1998). To this end, various scholars highlighted the importance of strategic supplier segmentation (Day et al. 2010, Rezaei and Ortt 2013, Rezaei and Fallah Lajimi 2019, Parkouhi et al. 2019), by which firms are capable of classifying their numerous suppliers into different groups and choose the best strategy for each segment (Rezaei and Ortt 2012). Logically, supplier selection takes place prior to supplier segmentation. Therefore, having a comprehensive supplier selection method will provide a robust foundation for purchasing managers' strategic decision-making.

Supplier selection is a multiple-criteria decision-making (MCDM) problem that involves evaluating potential suppliers against a finite set of (conflicting) criteria. Accordingly, the criteria that are used to evaluate the performance of each supplier play a pivotal role in the process of supplier selection (Çelebi and Bayraktar 2008).

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Rezaei and Ortt (2012) argue that the majority of supplier segmentation criteria used in the literature are a distinct sub-group of supplier selection criteria. They proposed an overarching model (i.e., supplier potential matrix- SPM) to integrate an overwhelming number of supplier assessment criteria emanated from two main literature body of supplier selection and segmentation, and organized such criteria into two dimensions of 'supplier capabilities' and 'supplier willingness' (Rezaei and Ortt 2012). Since the two crucial tasks of supplier selection and segmentation are highly interdependent in nature, it seems logical that using the same framework for these functions can potentially lead to a more effective and efficient supply chain management system in which the strategic role of the purchasing management is underscored. To this end, the criteria proposed by Rezaei and Ortt (2012) in their SPM model are used in this study. The final product of the SPM is a matrix in which the position of each supplier represents its performances regarding the selection/segmentation criteria that in turn assists the progress of supplier development.

Criteria weight assignment is an imperative part of every MCDM problem. Addressing this significant component, the multi-stakeholder Best-Worst Method (BWM) is employed in this study to calculate each criterion interval weight to fuse more information into the decision-making process. Then the consensus model for BWM group decision-making is applied for aggregating the assessments of the various stakeholders (evaluators/experts).

The purpose of this study is to provide a supplier selection model that enables firms to integrate their supplier selection and segmentation processes more efficiently. The main contribution of this study is as follows. The proposed decision-making process in this study leads to more flexibility and provides more information for a buying company due to the application of the multi-stakeholder best-worst method to compute the interval weights of the evaluation criteria. More precisely, in the cases with a group of decision-makers, having multiple optimal solutions provides a great setting for a compromise solution that is equal or very close to one of the optimal solutions. In such a case, all decision-makers will be satisfied with the selected solution at the end, compared to the case that each decision-maker has a unique solution.

As it is mentioned previously, supplier selection is an MCDM problem. Thus, in the following sub-sections, a brief review of the available supplier selection methods and criteria is given.

1.1. Supplier Selection Methods

In the past decades, numerous researchers addressed the supplier selection problem using various decision-making models (for the most recent comprehensive overview of these models see, Govindan et al. 2015, Wetzstein et al. 2016, Petrović et al. 2019). MCDM techniques such as Analytic Hierarchy Process (AHP) (Chan and Chan 2010' Maruffuzzaman et al. 2009, Levary 2008, Ishizaka et al. 2012, Awasthi et al. 2018) and Analytic Network Process (ANP) (Hsu and Hu 2009, Sarkis 2003, Gencer and Gurpinar 2007, Tseng et al. 2009, Büyüközkan and Çifçi 2011, Abdel-Baset et al. 2019) have been used frequently, either individually or combined with other methods in the literature (Govindan et al. 2015). Other methods used in the literature to solve supplier selection problem are as follows: BWM (Gupta and Barua 2017), Data Envelopment Analysis (DEA) (Wu et al. 2007, Alikhani et al. 2019), Case-Based Reasoning (CBR) (Choy and Lee 2002, Humphreys et al. 2003), Interpretive Structural Modeling (ISM) (Kannan and Haq 2007, Govindan et al. 2010, Mathiyazhagan et al. 2013, Gavareshki et al. 2017, Chauhan et al. 2020) and Genetic Algorithm (Ding et al. 2005, Luan et al. 2019). Moreover, mathematical programming techniques such as linear programming (Ng 2008), Goal Programming (Lee et al. 2009, Jolai et al. 2011, Ghoushchi et al. 2018), and Mixed Integer Linear Programming (Hong et al. 2005, Nasiri and Zia 2015) have been used in combination with other approaches to solve the supplier selection problem.

Despite the myriad of supplier selection models, there still exist a few shortcomings and limitations. For example, a lack of having an efficient weight assignment method is evident in the literature. In many cases, ANP and AHP methods are used to assign weights to the criteria. Nevertheless, when the number of criteria increases, calculating weights using these methods will become cumbersome, and the results will suffer from more inconsistencies (Shojaei et al. 2017). Therefore, in this study, this gap is bridged by using non-linear BWM. BWM was introduced by Rezaei (2015) as a pairwise comparison-based method that calculates the weights of the criteria in the context of an MCDM problem efficiently and with more consistency (Rezaei 2015, 2016). However, the weights which are gain by using non-linear BWM might be interval. It means that we may have multiple optimal results instead of a unique result (Rezaei 2016). Liang et al. (2021) proposed multi-stakeholder BWM to not only rank the alternatives by using these interval weights but also use this method in the context that multi-stakeholders are involved in the decision-making process. In this study, we use the method which is proposed by Liang et al. (2021).

BWM has attracted the researchers' attention from a variety of disciplines including, supply chain risk management (Shojaei and Haeri 2019), technology assessment (Kalpoe 2020), location analysis (Kheybari and Rezaei 2020, Ostein et al. 2020), and green supplier selection (Haeri and Rezaei 2019) (for a comprehensive literature review from the introduction of the method until January 2019, see Mi et al. 2019). Additionally, expansions to this method are also proposed, including multiplicative BWM (Brunelli and Rezaei 2019), Bayesian BWM (Mohammadi and Rezaei 2020), and multi-stakeholder BWM (Liang et al. 2021).

1.2. Supplier Selection Criteria

Along with the great significance of supplier selection function, supplier segmentation is also of the most important responsibilities of purchasing managers for the purpose of having effective supplier relationship management. On the other hand, supplier selection criteria are integral parts of supplier relationship management. Firms traditionally employed economic criteria to select the best supplier. However, as the global environmental protection significance increases, firms focused their efforts on incorporating environmental criteria in the supplier selection process (Govindan et al. 2015). Economic criteria used to evaluate suppliers are comprehensively investigated within the literature (Dickson 1966, Weber et al. 1991). Amongst all these criteria, quality, price, and delivery are the most frequent criteria which have been used throughout the literature (Ghodsypour and O'Brien 1998, Xia and Wu 2007, Talluri and Narasimhan 2003, Amid et al. 2006, Liao and Rittscher 2007, Talluri et al. 2006). Rezaei and Ortt (2012) examined the literature on supplier segmentation and proposed a multi-variable approach to supplier segmentation that involves traditional (economic) criteria along with environmental criteria. These criteria are classified into two main dimensions, namely, capabilities and willingness, that encompass a wide variety of most important variables to evaluate suppliers. These criteria are enumerated in Table 1. This framework is used to select supplier evaluation criteria in order to enable firms to integrate two important steps of supplier relationship management (i.e., supplier selection and supplier segmentation).

The rest of the paper is organized as follows. In Section 2, the proposed decision-making model is developed. A real-world application is given in Section 3 to illustrate the proposed model. Discussion and conclusions are made in Section 4.

2. The Proposed Decision-Making Approach

The proposed approach involves four main phases including, criteria selection, criteria weight assignment by using BWM, alternatives' value determination, and supplier selection. First, decision-makers must decide on the most relevant supplier selection criteria and evaluate them. Then, in phase two, by applying the BWM, the interval weights of each criterion are computed based on the decision-makers' preferences. Afterward, different alternatives should be compared to each other based on the consensus model. Finally, to select the most favorable alternative, the resulting values have to be ranked based on both capabilities and willingness dimensions.

2.1. Best-Worst Method (BWM)

The best-worst method introduced by Rezaei (2015) is a multi-criteria decision-making (MCDM) method based on structured pairwise comparisons. Rezaei (2015) proposed five steps to apply BWM. These steps are as follows:

Step 1. The set of evaluation criteria is defined as $\{C_1, C_2, \dots, C_n\}$ by decision-makers or a panel of experts (we can call them all evaluator).

Step 2. The best and the worst criteria are determined by the evaluator(s). Please note that the best and the worst criteria can be different for each evaluator.

Step 3. Evaluators use a number from 1-9 to express the preference of the best criterion over the other criteria. This results in the Best-to-Others vector that is represented as $A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$, where a_{Bj} is the preference of the best criterion B over criterion j.

Table 1. Criteria used to measure capability and willingness (Rezaei et al. 2015).

Capabilities criteria	Willingness criteria
Industry knowledge	Commitment to continuous improvement in product and process
Design capability	Supplier's effort in eliminating waste
Supplier process capability	Supplier's effort in promoting JIT principles
Technology monitoring	Willingness to integrate supply chain management relationship
Technology development	Honest and frequent communications
Innovation	Willingness to share information, ideas, technology, and cost savings
	Open to site evaluation
Production, manufacturing/transformation	Mutual respect and honesty
facilities and capacity	Ethical standards
R&D expenditure	Impression
Quality	Dependency
Reliability of product	Long-term relationship
Ease of maintenance design	Commitment to quality
Ease of operation	Relationship closeness
Contribution to the production	Willingness to invest in specific equipment
Geographic location/proximity	Prior experience with the supplier
Delivery	Reciprocal arrangements
Reserve capability	Willingness to co-design and participate in new product development
Profit impact of supplier	Bidding procedural compliance
Packaging ability Lead time	Consistency and follow-through
Reputation and position in the industry	
Labor relations record	
Amount of past business	
Performance awards	
Performance history	
Repair services	
After-sales support	
Training aids	
Follow-up	
Supplier's order entry and invoicing system including EDI	
Financial position	
Price/cost	
Cost reduction program	
Cost control	
Hazardous air emissions management	
Hazardous waste management	
Environmentally friendly product packaging	
Recycling and reverse logistics program	
Pollution reduction capability	
Availability of clean technologies	
Public disclosure of the environmental record	
ISO 140 0 0 and 140 01 certification	
Environmental health and safety	
Impact on energy utilization	
Management and organization	
Human resource management	
Market sensing	
Operational controls	
Customer linking	
Communication system	
Desire for business	
Warranties and claims	

Step 4. The preferences of other criteria over the worst criterion are determined by the evaluator(s) using a number from 1 to 9, which will result in the Others-to-Worst vector as $A_W = (a_{1W}, a_{2W}, \dots, a_{nW})^T$, where a_{jW} indicates the preference of the criterion j over the worst criterion W.

Step 5. Find the optimal weights $(\omega_1^*, \omega_2^*, \dots, \omega_n^*)$.

Definition 2.1. If $a_{ik} \times a_{kj} = a_{ij},\ \forall\, i, j$, the pairwise comparison vectors will be perfectly consistent.

Definition 2.2. The optimal weight for each criterion is the one where for each pair of ω_B/ω_j and ω_j/ω_W, we have $\omega_B/\omega_j = a_{Bj}$ and $\omega_j/\omega_W = a_{jW}$.

The abovementioned definitions imply that a solution that minimizes the maximum absolute differences $\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right|$ and $\left|\frac{\omega_j}{\omega_W} - a_{jW}\right|$ for all j can be found. By solving the following optimization problem with non-negativity and sum conditions, the optimal weights are obtained:

$$min\ max_j \left\{\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right|, \left|\frac{\omega_j}{\omega_W} - a_{jW}\right|\right\}$$

s.t.

$$\sum_j \omega_j = 1$$

$$\omega_j \geq 0,\ \ \forall j \qquad (1)$$

Model (1) can be rewritten as model (2), and be used to calculate the optimal weights and ξ^* as follows:

$$min\ \xi$$

s.t.

$$\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right| \leq \xi,\ \ \forall j$$

$$\left|\frac{\omega_j}{\omega_W} - a_{jW}\right| \leq \xi,\ \ \forall j$$

$$\textstyle\sum_j \omega_j = 1$$

$$\omega_j \geq 0,\ \ \forall j \qquad (2)$$

In cases where the comparison is not fully consistent, it is likely to have multi-optimal solutions. This unique characteristic of BWM enables us to compute criteria optimal weights in the form of interval values, in which more information is encapsulated. To obtain the lower and upper bounds of the interval weight of criterion j, models (3) and (4) are proposed by Rezaei (2016) to be solved after model (2) is solved and the value of ξ^* is obtained.

$$min\ \ \omega_j$$

s.t.

$$\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right| \leq \xi^*,\ \ \forall j$$

$$\left|\frac{\omega_j}{\omega_W} - a_{jW}\right| \leq \xi^*,\ \ \forall j$$

$$\textstyle\sum_j \omega_j = 1$$

$$\omega_j \geq 0,\ \ \forall j \qquad (3)$$

$$\max\ \omega_j$$
s.t.
$$\left|\frac{\omega_B}{\omega_j} - a_{Bj}\right| \le \xi^*,\ \ \forall j$$
$$\left|\frac{\omega_j}{\omega_W} - a_{jW}\right| \le \xi^*,\ \ \forall j$$
$$\sum_j \omega_j = 1$$
$$\omega_j \ge 0,\ \ \forall j \tag{4}$$

Rezaei (2015) proposed a consistency ratio to examine the pairwise comparisons. In other words, to check the reliability of the comparison, we have to compute the consistency ratio. This ratio is formulated as follows.

$$Consistency\ Ratio = \frac{\xi^*}{Consistency\ Index} \tag{5}$$

where ξ^* is calculated by solving model (2). *"Consistency Index"* is determined based on a set of fixed values (Table 2) that represents the corresponding indices for all possible values of a_{BW}. In other words, *"Consistency Index"* is the maximum value that ξ can get for each a_{BW}.

Table 2. Consistency Index Table (Rezaei 2015).

a_{BW}	1	2	3	4	5	6	7	8	9
Consistency Index	0.00	0.44	1.00	1.63	2.30	3.00	3.73	4.47	5.23

In order to investigate whether the judgments of evaluators/experts are acceptable based on these consistency ratios, we need to use thresholds, which are offered by Liang et al. (2020) (see Table 3). This table contains the threshold for a different combination of scales (from 3 to 9) and a different number of criteria (from 3 to 9). Scale is the number that the evaluator gives for comparing the best to the worst.

Table 3. BWM Consistency Ratio Thresholds (Liang et al. 2020).

	Criteria						
Scales	**3**	**4**	**5**	**6**	**7**	**8**	**9**
3	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087	0.2087
4	0.1581	0.2352	0.2738	0.2928	0.3102	0.3154	0.3273
5	0.2111	0.2848	0.3019	0.3309	0.3479	0.3611	0.3741
6	0.2164	0.2922	0.3565	0.3924	0.4061	0.4168	0.4225
7	0.2090	0.3313	0.3734	0.3931	0.4035	0.4108	0.4298
8	0.2267	0.3409	0.4029	0.4230	0.4379	0.4543	0.4599
9	0.2122	0.3653	0.4055	0.4225	0.4445	0.4587	0.4747

2.2. Alternatives' Value Determination by Using The Consensus Model

Based on the consensus model which is offered by Liang et al. (2021), to determine the overall value V_i^k of each alternative i for expert k based on the weights of criteria w_j^k and the normalized evaluations p_{ij} , we can use the following formula: the following formula:

$$V_i^k = \sum_{j=1}^{n} w_j^k p_{ij} \tag{6}$$

All criteria in this study are based on the same scale (10-point scale), and they are all benefit criteria. Therefore, normalization is not necessary. As the wights which are calculated by using BWM might be interval, we use the interval calculation of the values of alternatives ($\bar{V}_i^k$):

$$\bar{V}_i^k = \sum_{j=1}^{n} \bar{w}_j^k p_{ij} = \left[\sum_{j=1}^{n} p_{ij} w_j^{k,min},\ \sum_{j=1}^{n} p_{ij} w_j^{k,max}\right] \tag{7}$$

As the obtained interval form Equation (7) might be unrealistically wide, we need to use constrained interval arithmetic and the following Equation:

$$\bar{V}_i^k = \sum_{j=1}^{n} \bar{w}_j^k p_{ij} = \left[\sum_{j=1}^{n} p_{ij} w_j^{k,min},\ \sum_{j=1}^{n} p_{ij} w_j^{k,max}\right] \tag{8}$$

where

$$V_i^{k,min} = \min\left\{\sum_{j=1}^{n} p_{ij} w_j \middle| w_j \in \left[w_j^{k,min}, w_j^{k,max}\right]\ j = 1, \dots, n, \quad \sum_{j=1}^{n} w_j = 1\right\}$$
$$V_i^{k,max} = \max\left\{\sum_{j=1}^{n} p_{ij} w_j \middle| w_j \in \left[w_j^{k,min}, w_j^{k,max}\right]\ j = 1, \dots, n, \quad \sum_{j=1}^{n} w_j = 1\right\}$$

To calculate the aggregated value for all evaluators after calculation of value for each evaluator, the following Equation is used:

$$\bar{V}_i^{agg} = \left\{x^* \middle| x^* = \arg\min_x \sum_{k=1}^{K} \left|x - V_i^{k,max}\right| + \left|x - V_i^{k,min}\right|\right\} \tag{9}$$

As it is clear, the aggregated values are interval implying that we need to follow the interval analysis to compare the alternatives.

2.3. Interval Analysis

To compare interval values in this study, the interval analysis approach proposed by Wang et al. (2005) is employed as follows:

Definition 2.3. Let $A = [\underline{a}, \overline{a}]$ and $B = [\underline{b}, \overline{b}]$ be two interval values. The level of preference of A over B (or $A > B$) is defined as (Wang et al. 2005):

$$P(A > B) = \frac{\max(0, \overline{a} - \underline{b}) - \max(0, \underline{a} - \overline{b})}{(\overline{a} - \underline{a}) + (\overline{b} - \underline{b})} \tag{10}$$

The level of preference of B over A is also computed as:

$$P(B > A) = \frac{\max(0,\ \overline{b} - \underline{a}) - \max(0,\ \underline{b} - \overline{a})}{(\overline{a} - \underline{a}) + (\overline{b} - \underline{b})} \tag{11}$$

Thus, $P(A > B) + P(B > A) = 1$ and $P(A > B) = P(B > A) = 0.5$ when $A = B$.

Definition 2.4. If $P(A > B) > 0.5$ (or similarly $P(A > B) > P(B > A)$) then A is considered to be superior to B to the degree of $P(A > B)$, that is showed by $A \overset{P(A>B)}{\succ} B$; if $P(A > B) = P(B > A) = 0.5$, then A is said to be indifferent to B, that is shown by $A \sim B$; if $P(B > A) > 0.5$ (or similarly $P(B > A) > P(A > B)$), then A is said to be inferior to B to the degree of $P(B > A)$, that is showed by $A \overset{P(B>A)}{\prec} B$.

To compare interval numbers, 'matrix of degree of preference' that is denoted by DP_{ij} and the 'matrix of preferences' denoted by P_{ij}, are computed as follows:

$$DP_{ij} = \begin{array}{c} \\ A \\ B \\ \vdots \\ N \end{array} \begin{array}{c} \begin{matrix} A & B & \dots & N \end{matrix} \\ \begin{pmatrix} P(A > A) & P(A > B) & \cdots & P(A > N) \\ P(B > A) & P(B > B) & \dots & P(B > N) \\ \vdots & \vdots & \ddots & \vdots \\ P(N > A) & P(N > B) & \cdots & P(N > N) \end{pmatrix} \end{array} \tag{12}$$

$$P_{ij} = \begin{matrix} & A & B & \dots & N \\ A & P_{AA} & P_{AB} & \cdots & P_{AN} \\ B & P_{BA} & P_{BB} & \dots & P_{BN} \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ N & P_{NA} & P_{NB} & \cdots & P_{NN} \end{matrix} \tag{13}$$

where

$$P_{ij} = \begin{cases} 1, & if \quad P(i > j) > 0.5, \\ 0, & if \quad P(i > j) \leq 0.5, \end{cases} \quad i, j = A, B, \dots, N \tag{14}$$

The interval values are compared by computing the total of each row in the matrix P_{ij}, and they are ranked based on the rule that the higher the sum of the row, the better preferred the corresponding number.

2.4. Supplier Selection

In this step, the appropriate suppliers based on the criteria are selected. More precisely, the values are ranked from high to low in order to select the most desirable alternatives.

3. A Real-World Application

Generally, computer hardware companies in Iran are limited to assembly lines that use the imported products from various suppliers to deliver a final product to the consumers. Given that there are numerous importing suppliers providing specific products, and these suppliers face a considerable amount of uncertainty associated with importing operations, it is important for hardware companies to carefully select their suppliers. In this study, a computer hardware company, which due to a confidentiality agreement, remains anonymous in this study, desires to select the most proper supplier for one of the key components in its assembly line. Twelve suppliers are listed, and a decision-making committee comprised of 5 evaluators with at least ten years of experience in supply chain management within the computer hardware industry is formed to evaluate and rank these suppliers. As elaborated in Section 2, the proposed decision-making model involves four phases including, criteria selection, criteria weight assignment by using BWM, alternatives' value determination by using consensus model, and supplier selection. The results obtained by the application of the proposed method to the case company is given for each phase in the followings:

Phase I (criteria selection): In a discussion session, the supplier potential matrix (SPM) concept is introduced to the evaluators, and the relevance of the criteria (see Table 1) within this model is discussed for the computer hardware industry in general and with respect to their company. After a 6-hour session, a total number of 9 criteria were selected by consensus between the evaluators with five criteria from the capability dimension (i.e., price, delivery, quality, reserve capacity, and after-sales support), and four criteria from the willingness dimension (i.e., honest and communication openness, reciprocal arrangement, willingness to share information, and long-term relationship).

Phase II (criteria weight assignment): Another two-part discussion session was held to accomplish Phase II and III. In the first part of the session, evaluators were asked to select one criterion as the best criterion (the most important one) and another as the worst criterion (the least important one) by consensus for each dimension. Subsequently, they were asked to collectively compare and determine the preference of the best criterion to other criteria and other criteria to the worst criterion using numbers from 1 to 9. Quality and reserve capacity are selected as the best and worst criteria respectively for the capability dimension, while willingness to share information and reciprocal arrangement are selected as the best and worst criteria for the willingness dimension. Best-to-Others and Others-to-Worst pairwise comparisons for each dimension are conducted and reported in Tables 1 to 4 in the Appendix. By solving models 3 and 4 for each dimension, the interval weights of each criterion are calculated and reported in Tables 4 and 5.

Table 4. Interval weights of the capability dimension criteria.

Criteria / Interval weight	Price	Delivery	Quality	Reserve capacity	After-sales support	Consistency Ratio
Lower, Upper	[0.1689,0.1758]	[0.1206,0.1256]	[0.4927,0.5128]	[0.0580,0.0603]	[0.1256,0.1597]	0.2051

Table 5. Interval weights of the willingness dimension criteria.

Criteria / Interval weight	Honest and communication openness	Reciprocal arrangement	Willingness to share information	Long term relationship	Consistency Ratio
Lower, Upper	[0.2880,0.3732]	[0.0522,0.0593]	[0.4255,0.4833]	[0.1491,0.1693]	0.3072

By checking the consistency thresholds in Table 3, we see that evaluators' judgments are acceptable for both capability and willingness dimensions.

Phase III (alternatives' value determination by using consensus model): In the second part of the discussion session, evaluators were asked to assess each supplier against each criterion using numbers from 1 to 9. More precisely, the four experts were asked to rate the performance level of each supplier based on each capability and willingness dimension on a nine-point Likert scale (1: very low to 9: very high). We used the mean to determine the aggregated weight of each dimension. These evaluations are presented in Table 6.

Table 6. Supplier evaluation.

Criteria / Supplier	C_1	C_2	C_3	C_4	C_5	w_1	w_2	w_3	w_4
S_1	4.8	3.2	4.6	7.4	4.8	4.8	5.2	6.8	6.2
S_2	6.8	5.0	3.6	7.2	5.0	5.8	6.0	6.2	5.4
S_3	4.8	4.6	6.4	4.8	4.8	5.2	5.4	4.8	4.6
S_4	5.4	5.4	5.8	6.6	6.2	4.6	7.2	4.2	3.8
S_5	5.2	6.0	3.2	5.4	4.2	3.6	7.0	4.2	5.4
S_6	6.2	5.0	4.8	5.2	3.6	3.2	6.8	5.0	3.6
S_7	3.4	5.2	6.4	6.2	5.4	5.0	3.6	5.4	5.0
S_8	5.0	3.4	4.6	5.4	4.4	2.4	5.0	2.8	3.8
S_9	2.8	4.8	7.0	4.4	3.2	4.8	3.2	4.4	4.2
S_{10}	4.8	6.4	2.2	5.6	4.0	6.2	4.8	7.0	5.0
S_{11}	4.2	4.6	3.2	6.0	3.6	4.4	3.2	5.6	2.2
S_{12}	4.2	6.2	4.6	6.8	3.6	5.4	3.2	4.4	5.0

In order to find the value assigned to each supplier, we combined the criteria weight intervals (Tables 4 and 5) with and supplier evaluation numbers (Table 6) by using Equation (7). The results can be seen in Table 7.

Phase VI (supplier selection): By using the interval analysis (Equations (10) and (11)) the level of preference of all 12 suppliers based on capability and willingness values are computed. Then in order to compare the interval numbers, matrix of degree of preference' that is denoted by DP_{ij} and the 'matrix of preferences' denoted by P_{ij}, are computed respectively based on Equation (12) and (13). Finally, the interval values are compared by computing the sum of each row in the matrix P_{ij}, See the result in Table 8.

Table 7. Values of suppliers.

Criteria / Supplier	Capability		Willingness	
S_1	5.622	5.990	5.311	6.271
S_2	5.844	6.251	5.020	5.979
S_3	4.845	5.193	4.285	5.116
S_4	5.800	6.170	4.469	5.408
S_5	4.755	5.054	5.390	6.445
S_6	4.596	4.876	4.161	5.040
S_7	5.646	6.021	4.304	5.054
S_8	4.346	4.593	3.874	4.630
S_9	4.611	4.938	3.572	4.205
S_{10}	5.116	5.504	4.509	5.342
S_{11}	4.880	5.207	2.485	2.971
S_{12}	5.839	6.234	3.950	4.634

Table 8. Final score of the suppliers.

Suppliers	Capability	Willingness
S_1	6	9
S_2	3	10
S_3	8	8
S_4	11	6
S_5	2	3
S_6	4	4
S_7	9	7
S_8	7	0
S_9	10	1
S_{10}	1	11
S_{11}	1	2
S_{12}	4	5

A supplier has a higher rank in capabilities or willingness dimension when it gets a high score from Table 8.

All suppliers are plotted based on both willingness and capability dimensions in Figure 1. In order to develop a competitive supply chain, the case company can select the suppliers who have higher scores in both capabilities and willingness dimensions. This improves the company's business. Based on the results, four suppliers S1, S3, S4, and S7, are the most suitable options to supply one of the key components in the assembly line as they are categorized as the suppliers with the highest capabilities and willingness (see the upper-right side of Figure 1).

In order to do a kind of validation of the results, we discuss the results with the five evaluators after doing the analysis. The evaluators mentioned that the results meet their expectations. They found the results and the process of selecting the proper suppliers very helpful.

4. Conclusion

This study proposed a decision-making approach for supplier selection based on a multi-stakeholder Best-Worst Method (BWM). The four phases of the model involve: (1) criteria selection, (2) criteria weight assignment by using BWM, (3) alternatives' value determination, and (4) supplier ranking. A real-world application is provided to illustrate the proposed model.

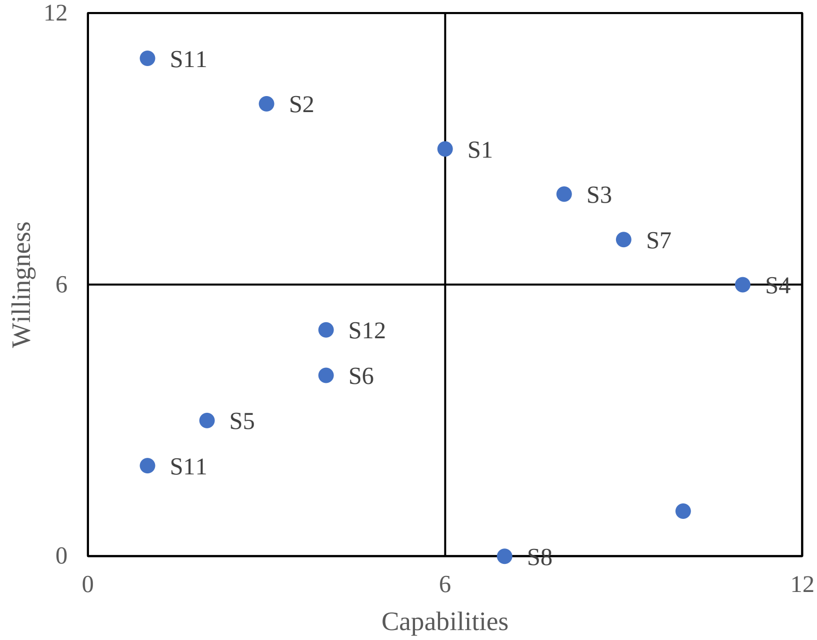

Figure 1. Scatter plots of 12 suppliers based on capability and willingness dimensions.

Applying the multi-stakeholder best-worst method in this study brings more satisfaction for the decision-makers as having multiple optimal solutions provides a great setting for a compromise solution that is equal or very close to one of the optimal solutions.

This study has some limitations that can be considered opportunities for possible future research and development in this area. In this study, early-stage investigation (screening) for the pre-selection of suppliers is overlooked. There are different ways of screening, such as conjunctive, disjunctive, or lexicographical screening methods. For instance, for applying the conjunctive screening, the suppliers who satisfy a minimum level of performance based on some qualification criteria (a sub-set of all criteria) are pre-selected from the pool of suppliers. Finally, the most suitable suppliers will be selected from the pre-selected suppliers. The main benefit of supplier screening is the reduction of the time and energy decision-makers spend on gathering information about suppliers based on all criteria for the selection phase.

In this study, four suppliers are selected as the proper ones for supplying the key component of the assembly line in the case company based on both capabilities and willingness dimensions. Although this categorization gives some freedom for the decision-makers to select one supplier from the most suitable ones, if the idea is to select only one from the four, we can use an aggregation method to reach this goal.

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Appendix

Experts' evaluations of criteria for each dimension are given in the following (Table 1-4).

Table 1. Best-to-Others pairwise comparison for capability dimension.

Other criteria	Price	Delivery	Quality	Reserve capacity	After-sales support
Best criterion: Quality	2	5	1	8	4

Table 2. Others-to-Worst pairwise comparison for capability dimension.

Other criteria	**Worst criterion:** Reserve capacity
Price	2
Delivery	3
Quality	8
Reserve capacity	1
After sales support	3

Table 3. Best-to-Others pairwise comparison for willingness dimension.

Other criteria	Honest and communication openness	Reciprocal arrangement	Willingness to share information	Long term relationship
Best criterion: Willingness to share information	2	7	1	5

Table 4. Others-to-Worst pairwise comparison for willingness dimension.

Other criteria	**Worst criterion:** Reciprocal arrangement
Honest and communication openness	6
Reciprocal arrangement	1
Willingness to share information	7
Long term relationship	4