AN INTEGRATED BEST-WORST METHOD AND ENTROPY APPROACH FOR SUSTAINABLE SUPPLIER SELECTION

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Highlights

- Measuring and evaluating supplier effectiveness is an indispensable process for every company.
- We aim to objectively and analytically evaluate a supplier evaluation process using Best-Worst (BWM)-based SAW and Entropy-based SAW two-stage MCDM methods.
- The supplier selection problem is evaluated from a multidimensional perspective with a two-stage analytical approach.

ABSTRACT

The intensely competitive environment, economic conditions, and constantly changing balances require businesses to take steps to strengthen themselves. Managing supply chain processes with proactive and multidimensional decision-making mechanisms is one of the keys to a successful position in the sector. This study examines a supplier evaluation process in a manufacturing company that assesses current key competitive conditions, such as environmental awareness and digital transformation efforts, as well as key factors that remain relevant, such as price, quality and delivery performance. First, the criteria weights were evaluated using the best-worst method (BWM) based on expert opinion. Then, the suppliers were ranked by adapting the weights of these criteria to the simple additive weighting (SAW) method. In this way, criterion weights were evaluated using the BWM method, which is a subjective approach based on expert opinion, and the SAW method, which is an objective approach based entirely on calculations. Secondly, the criteria weights were evaluated using the entropy method and then the suppliers were ranked with SAW method. In this regard, the supplier selection problem, which will always maintain its importance in the literature is evaluated from a multidimensional perspective with a two-stage analytical approach. The obtained results are expected to provide guidance for the improvement and investment decisions that company managers should prioritize.
Keywords: Best-Worst method (BWM), Entropy, Simple additive weighting (SAW), Supplier selection, Decision-making

1. Introduction

With the ambitious change in the level and status of competition conditions in the globalizing world, it has become imperative to carry out supply chain activities in the most effective way (Li et al., 2006). Because the changing and evolving world agenda requires the supply chain management process to be handled effectively and in a multifaceted way

with a new academic agenda every day, such as carbon footprint practices, sustainability, green management, digitalization and transition from Industry 4.0 to Industry 5.0, logistics 5.0, suitable strategies must be implemented (Rame et al., 2024).
Supply chain process management has been addressed by researchers for many years, both as a well-established subject of study and as a field that always remains up-to-date with current practical solution approaches (Knight et al., 2022). In light of all these explanations, this issue maintains its priority as it is the most important issue for businesses. Businesses manage the process of determining their suppliers by taking into consideration various priority factors. Supplier selection and assessment are one of the most significant actions that companies take for effective supply chain management (Araz and Özkarahan, 2007). Supplier evaluation should be based not only on traditional factors such as cost, quality, and delivery but also on additional criteria such as suppliers' cooperative attitude, responsiveness to company requests and environmental policies, which are important considerations in determining the selection of candidate suppliers. An objective supplier evaluation process implies a meaningful assessment of many relevant criteria in the decision-making process. However, not all criteria are of equal importance as they play different roles in the analysis process. This poses many challenges for researchers and managers aiming to improve better techniques and achieve satisfactory results (Dobos and Vörösmarty, 2019).
Measuring and evaluating supplier effectiveness is an indispensable process for every company. Businesses trying to determine their place in today's competitive and innovative economy determine their choices and goals by comparing their own situation with other businesses. In this process, many criteria should be taken into account and these strategic decisions should be handled in a well-structured and multifaceted manner. Multi-criteria decision-making methods (MCDM) have been very useful models for decision makers in this sense. Especially in the manufacturing industry, where competition intensifies under pandemic conditions, the fact that suppliers who work correctly, harmoniously and effectively, and who can adapt quickly to changes, play a key role in the smooth execution of the supply chain mechanism has re-emerged.
In this study, we aim to objectively and analytically evaluate a supplier evaluation process using Best-Worst (BWM)-based Simple Additive Weighting (SAW) and Entropy-based SAW method, thus providing a consistent result and a multidimensional perspective for the manufacturing firm. We first derived the criteria weights from the BWM and Entropy approaches and then calculated the supplier rankings using the SAW method based on the previously derived weights. We aim to offer a different approach to evaluation by presenting a two-stage approach based on the objective and subjective nature of the methods.

2. Literature Review

According to the literature reviews, there are numerous studies evaluating the supplier selection problem using MCDM tools due to the multidimensional nature of the issue.
Generally utilized methods comprise the Analytic Hierarchy Process (AHP)(Saaty,1980) and Analytic Network Process (ANP) (Saaty,1996) , Data Envelopment Analysis (DEA) (Charnes et al.,1978) and the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) (Huang and Yoon, 1981). One of the key benefits of such approaches is clarity and explainability. However, this advantage is countered by limited scalability in terms of the number of criteria and alternatives (Kuo et al., 2010; Junior et al., 2014).

Recently, the supplier selection process has been evaluated with applications based on data analytics and machine learning approaches in addition to classical decision making methods (Ho et al., 2010). Moreover hybrid approaches based on combination of artificial intelligent, most often machine learning, along with a MCDM approach have been adapted to optimal supplier selection problem (Golmohammadi et al.(2009), Ha and Krishnan (2008), Fallahpour et al. (2016), Abdulla et al. (2019)).
When we investigated BWM applications for supplier selection issue, we have faced implementations integrated with other concepts such as combined compromise solutions, goal programming, or fuzzy applications with BWM. Although the BWM or Entropy method has been applied separately for optimum supplier selection, the two methods have not been used together. In this way, this study eliminates this gap and contributes to the literature on combined method supplier selection task with its practicality and consistency. Tavana et al. (2021) discussed a fuzzy-based approach that incorporates the fuzzy group best-worst method (FG-BWM) and the fuzzy combined compromise solution (FCoCoSo) method for supplier selection in a reverse supply chain mechanism under lean, agile, resilient, and green strategy. The FG-BWM is applied to calculate the significance weights of the supplier selection criteria. FCoCoSo is used to select the most suitable supplier. Rostami et al. (2023) mentioned a new approach integrated goal programming and fuzzy best–worst method (GP-FBWM) to evaluate viable supplier selection problem for the medical devices industry. Hailiang et al. (2023) proposed FBWM to evaluate supplier selection subject based on multi-stage fuzzy sustainable supplier index considering COVID-19 pandemic harms. Ecer and Pamucar (2020) analyzed SSCM by FBWM and a combination of the CoCoSo method, to best reflect interactions of the attributes in an ambiguous decision-making environment.

3. Methodology

In this section, the Best-Worst method will be clarified, and then the Entropy method will be explained.

3.1. Best-Worst Method

The best-worst method (BWM) is one of the prominent multi-criteria decision-making tools established by Rezaei in 2015. The BWM approach is based on pairwise comparisons of the best and worst criteria to obtain importance levels. In the model, verbal descriptions of the evaluation process were transformed into scales ranging from 1 to 9. Although this approach is criticized for being quite similar to the AHP method, it is a more practical and easier implementation approach than AHP due to the small number of pairwise comparison matrices. The basic steps of the BWM method are summarized as follows:
Step 1 - Specifying the set of decision criteria
In this phase, we describe the set of criteria $\{c_1, c_2, \dots, c_n\}$ which are employed in obtaining the ultimate decision.
Step 2- The best criterion (C_B) and the worst criterion $(C_W)$are defined by decision makers.
Step 3 - Defining the preference of the best criterion over the other criteria using a number between 1 and 9. The vector of the best to other criteria is:

$$A_B = (a_{B1}, a_{B2}, \dots, a_{Bn})$$

where A_B vector shows how much priority the best criterion has over criterion j.
Step 4 - Describing the preference of other criteria over the worst criterion by means of a number between 1 and 9.

$$A_W = (a_{1W}, a_{2W}, \dots, a_{\mathrm{n}W})$$

where A_w vector denotes the importance preference of criterion j over the worst criterion.Step 5- Obtaining the ideal weights $\{w_1, w_2, \dots, w_n\}$ using the following model and the ε value, which aids to analyze the consistency ratio, is also considered at the solution stage:

$$\begin{gathered} \min \varepsilon \\ s.t. \\ \left|\frac{\mathrm{W}_B}{\mathrm{W}_j} - a_{Bj}\right| \leq \varepsilon, \forall j \\ \left|\frac{\mathrm{W}_j}{\mathrm{W}_W} - a_{jW}\right| \leq \varepsilon, \forall j \\ \sum_j \mathrm{w}_j = 1 \\ \mathrm{w}_j \geq 0, \forall j \end{gathered}$$

Step 6- In the latest step of the model, the consistency ratio is considered by substituting the value of ε and the consistency index value into following equation. When the consistency ratio is close to zero, the obtained result is consistent, and when it is close to one, the consistency of the model declines.

$$\textit{Consistency ratio (CR)} = \frac{\varepsilon}{Consistency\ index\ (CI)}$$

To compute the upper and lower limits of the criteria, the two models (*for minimization aim and maximization aim*) in the following equation need to be solved. The solution of these two models is applied to all criteria, to decide on their ideal weights.

$$\begin{gathered} max\ \ \mathrm{w}_j\ or\ min\ \mathrm{w}_j \\ \left|\frac{\mathrm{W}_B}{\mathrm{W}_j} - a_{Bj}\right| \leq \varepsilon, \forall j \\ \left|\frac{\mathrm{W}_j}{\mathrm{W}_W} - a_{jW}\right| \leq \varepsilon, \forall j \\ \sum_j \mathrm{w}_j = 1 \\ \mathrm{w}_j \geq 0, \forall j \end{gathered}$$

3.2. Entropy Method

The concept of entropy is employed in diverse scientific areas (e.g., physics, chemistry, mathematics, and information theory); in information theory, this expression plays an important role in determining the ambiguity related to arbitrary occurrences of the expected information content. The Entropy technique is used to calculate the relative ranking of criteria based on the DM produced from the hierarchical model. The basic steps of the Entropy method are summarized as follows:

Step 1 – Building the decision matrix.

$$\begin{bmatrix} x_{11} & \cdots & x_{1n} \\ \vdots & \ddots & \vdots \\ x_{m1} & \cdots & x_{mn} \end{bmatrix}_{m*n}$$

where x_{ij}: The success value of alternative i according to criterion j, i = 1,2, …, m and j = 1,2, …, n.

Step 2- Normalization of decision matrix.

$$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^{j} x_{ij}}$$

where r_{ij} is the normalized value of the criteria/sub-criteria rate

Step 3- Obtaining entropy values of the criteria.

The entropy value measures the degree of uncertainty among the set of alternatives in the DM when no choice can be made between the criteria

$$e_j = -k \sum_{j=1}^{n} r_{ij} \ln(r_{ij}) \qquad i = 1 \dots m \; j = 1 \dots n$$

$$k = 1/\ln(m)$$

where k is the entropy constant, e_j is entrophy value

Step 4- Calculating the degree of diversification based on the entropy values.

$$d_j = 1 - e_j$$

Step 5-Measurement of entropy criteria weights.

$$w_j = \frac{d_j}{\sum_{i=1}^{m} d_j}$$

$$\sum_{i=1}^{n} w_j = 1$$

where w_j is the degree of importance of criterion j.

4. Application of The Method

The evaluation of the optimal supplier selection issue is a complicated decision-making process that involves several conflicting factors (or criteria/alternatives). For this reason, MCDM techniques have been applied in the supplier selection process, and several researchers (Chen et al.,2019; Fallahpour et al.,2017; Govindan et al.,2015; Kannan et al.,2014; Luthra et al.,2017; Memari et al.,2019) have mentioned the advantages and applicability of various MCDM techniques.

Table 1. Definition of the variables

Variables	***Definition***
Price	It refers to the unit price of the material.
Quality	It is the degree of conformity of product to the qualitative and quantitative standards. The score reflects the supplier's compliance with product standards, as a result of evaluating accepted materials delivered by the supplier, based on the form prepared by the experts from the quality, R&D, purchasing, planning, and logistics departments.
Delivery Performance	It represents the percentage of deliveries that meet the specified dates and quantities.
Environmental Sensitivity	It involves evaluating the supplier's attitude towards protecting the environment and reducing environmental pollution, as well as the compliance of its products with these criteria.
Digital Transformations Efforts	It is the process of using technology to store and process data in a computerized environment. The activities and efforts made for the transition to digital platforms. The use of ERP/SAP includes situations such as storing documents in a software environment instead of as printed documents, and processing documents and processes through digital software and programs.

In MCDM, the most complex task is to describe the relative significance of the criteria, which is commonly determined subjectively. Since criteria weights are defined based on the judgment of decision-makers or any expert from the department, evaluation of the objective weights is required to fill a gap in the decision-making process. Therefore, in this study, first, the BWM based SAW method and then the entropy based SAW method were applied as a tool for supplier selection, i.e., to analyze and select the most critical factors based on criteria weights and rank them accordingly. Firstly, the BWM measures the relative importance of factors that influence optimal supplier selection by calculating their objective weights. Secondly, the SAW method was applied to rank the best suppliers according to the weights of the criteria.

Table 2. Decision matrix

Suppliers	Price	Quality	Delivery Performance	Environmental Sensitivity	Digital Transformations Efforts
S1	0.0071	0.2499	0.2569	0.2736	0.2280
S2	0.3108	0.2335	0.1978	0.2736	0.2280
S3	0.1224	0.2249	0.1490	0.2189	0.2280
S4	0.2860	0.2335	0.2492	0.2189	0.2676
S5	0.2585	0.2270	0.2569	0.1642	0.2082
S6	0.3600	0.2292	0.2569	0.1642	0.2280
S7	0.0901	0.2263	0.1927	0.2189	0.2181
S8	0.2713	0.2013	0.2055	0.1642	0.2280
S9	0.0364	0.2185	0.2569	0.1642	0.2280
S10	0.0443	0.2377	0.2569	0.2736	0.1586

An extensive list of factors for supplier selection was obtained from the relevant literature in order to identify the most appropriate criteria for selecting the best supplier. The basic five criteria are determined and evaluated by the supply chain management unit using the BWM method. The basic criteria are considered price, quality, delivery performance, environmental sensitivity and digital transformation efforts, as given in Table 1, the constructed decision matrix is given in Table 2. The consistency matrix and best to others (Table 3) and others to worst matrix (Table 4) are constructed with regard to the decision maker's opinion.

Table 3. Pairwise comparison for the most important quality criterion

Best to Others	Quality	Price	Delivery Performance	Environmental sensitivity	Digital transformation efforts
Quality	1	2	3	4	5

Table 4. Pairwise comparisons for the least important digital transformation efforts criterion

Others to the Worst	Digital transformation efforts
Quality	4
Price	4
Delivery Performance	3
Environmental sensitivity	2
Digital transformation efforts	1

Table 5 shows the weights of each criterion in descending order, providing a clear understanding of their relative significance. The obtained results emphasize the importance of the overall criteria in the decision-making process for choosing the ideal supplier criteria for the manufacturing sector under study.

Table 5. Final weights obtained for each criterion

Weights	Quality	Price	Delivery Performance	Environmental sensitivity	Digital transformation efforts
	0.40	0.24	0.16	0.12	0.08

According to the consistency ratios offered in Table 6, it can be concluded that a consistent result is obtained and the determined factors can be included in the supplier selection issue.

Table 6. Consistency ratios

Input-Based CR	0.20	The pairwise comparison consistency level is acceptable.
Associated Threshold	0.2306	

After obtaining the criteria weights using the BWM method, the ideal supplier ranking was made by assigning five important criteria according to the importance of the weights obtained using the SAW method in the second stage. In the SAW method, after linear normalization of the decision matrix, the weights obtained from the BWM are multiplied and then sorted in descending order according to the value obtained (in Table 7).

Table 7. BWM weighted SAW results

Weights	*0.24*	*0.40*	*0.16*	*0.12*	*0.08*	*SAW Values*	*Rank*
S1	1	1	1	1	0.8520	0.9881	1
S2	0.0228	0.9343	0.7699	1	0.8520	0.6905	5
S3	0.0580	0.8999	0.5799	0.8000	0.8520	0.6308	9
S4	0.0248	0.9343	0.9700	0.8000	1	0.7109	3
S5	0.0274	0.9083	1	0.6001	0.7780	0.6641	7
S6	0.0197	0.9171	1	0.6001	0.8520	0.6717	6
S7	0.0788	0.9055	0.7500	0.8000	0.8150	0.6623	8
S8	0.0261	0.8055	0.7999	0.6001	0.8520	0.5966	10
S9	0.1950	0.8743	1	0.6001	0.8520	0.6967	4
S10	0.1602	0.9511	1	1	0.5926	0.7463	2

In the entropy method, firstly the normalized decision matrix was obtained in Table 8.

Table 8. Normalized decision matrix

Price	**Quality**	**Delivery Perf.**	**Envir. Sent.**	**Digital Trasn.**
0.6199	0.110	0.1127	0.1282	0.1027
0.0142	0.102	0.0868	0.1282	0.1027
0.0360	0.099	0.0654	0.1026	0.1027
0.0154	0.102	0.1094	0.1026	0.1205
0.0170	0.099	0.1127	0.0769	0.0938
0.0122	0.100	0.1127	0.0769	0.1027
0.0488	0.099	0.0846	0.1026	0.0982
0.0162	0.088	0.0902	0.0769	0.1027
0.1209	0.096	0.1127	0.0769	0.1027
0.0994	0.104	0.1127	0.1282	0.0714

The entropy values for the criteria are presented in the Table 9 below. In the previous table, the normalized values are multiplied by the logarithm values. Then, the values calculated from this process are added to obtain the entropy value. The entropy coefficient k in the formula was found by calculating $1/ln10$ (0.434), and adapted to the formula.

Table 9. Entropy values

Price	**Quality**	**Delivery Perf.**	**Envir. Sent.**	**Digital Trasn.**
-0.296	-0.242	-0.246	-0.263	-0.234
-0.060	-0.233	-0.212	-0.263	-0.234
-0.120	-0.228	-0.178	-0.234	-0.234
-0.064	-0.233	-0.242	-0.234	-0.255
-0.069	-0.230	-0.246	-0.197	-0.222
-0.054	-0.231	-0.246	-0.197	-0.234
-0.147	-0.229	-0.209	-0.234	-0.228
-0.067	-0.214	-0.217	-0.197	-0.234
-0.255	-0.225	-0.246	-0.197	-0.234
-0.229	-0.236	-0.246	-0.263	-0.188

Accordingly, the obtained values were 0.5919; 0.9994; 0.9940; 0.9902; 0.9970, respectively. Then by subtracting from 1, the diversification degrees (d_j) of information were calculated (0.4081; 0.0006; 0.0060; 0.0098;0.0030). According to Table 10, the entropy degrees of the factors and the weight value of each criterion were found as follows.

Table 10. Entropy and weight values of factors

Entropy	0.5919	0.9994	0.9940	0.9902	0.9970
w_j	0.954518	0.001432	0.01404	0.022961	0.00705
rank	1	3	4	2	5

Entropy based SAW results are given in Table 11.

Table 11. Entropy based SAW results

Weights	*0.9545*	*0.0014*	*0.0140*	*0.0229*	*0.0070*	*SAW Values*	*Rank*
S1	1	1	1	1	0.8520	0.9989	1
S2	0.0228	0.9343	0.7699	1	0.8520	0.0629	7
S3	0.0580	0.899	0.5799	0.8000	0.8520	0.0891	5
S4	0.0248	0.9343	0.9700	0.8000	1	0.0640	6
S5	0.0274	0.9083	1	0.6001	0.7780	0.0608	8
S6	0.0197	0.9171	1	0.6001	0.8520	0.0539	10
S7	0.0788	0.9055	0.7500	0.8000	0.8150	0.1111	4
S8	0.0261	0.8055	0.7999	0.6001	0.8520	0.0571	9
S9	0.1950	0.8743	1	0.6001	0.8520	0.2212	2
S10	0.1602	0.9511	1	1	0.5926	0.1955	3

The rankings based on the BWM-Entropy method, and Entropy weighted method are given in Table 12.

Table 12. Comparison of the obtained results

BWM weighted SAW		Entropy weighted SAW	
Suppliers	Rank	Suppliers	Rank
S1	1	S1	1
S10	2	S9	2
S4	3	S10	3
S9	4	S7	4
S2	5	S3	5
S6	6	S4	6
S5	7	S2	7
S7	8	S5	8
S3	9	S8	9
S8	10	S6	10

As can be seen from Table 12; S1, S10 and S4 appear as the top three important suppliers in the BWM weighted SAW method. On the other hand, S7, S3, S8 have emerged as the last ranked suppliers. In the entropy weighted SAW method, S1, S9 and S10 are evaluated as the top three important suppliers, while S5, S8, and S6 are the last ranked suppliers. When the method results are compared, similar rankings are obtained. In the results, S1 and S10 are the most important suppliers ranked in the top three in both methods. S8 is the least important suppliers and are ranked last.

5. Conclusions Future Directions

The complex nature of the supply chain process presents a complex structure as many parameters, alternative criteria and constraints need to be evaluated. Therefore, there is a need for decision-making models that enable objective evaluation. In this study, in addition to the basic factors that are always included in the literature, criteria such as digital transformation and environmental sustainability from current supply chain management themes are also evaluated. In this study, firstly, the importance level of the criteria is determined with the BWM method and then the suppliers are ranked with the SAW approach. The BWM method is a similar but not identical approach to the AHP method. Here, the weights of the criteria are obtained subjectively based on the judgment of the decision maker. In the second case, the criteria weights are obtained objectively and ranked using only the Entropy-based SAW approach. In this respect, the study provides insights in terms of comparing objective and subjective approaches and testing their consistency. The results are similar.

For future research, methods that include more criteria and alternatives and integrate different fuzzy approaches can be used to evaluate a wider range of aspects. The fact that the subject is always up to date and an important topic will contribute to all research conducted in this field.

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