

A Novel Integrated Provider Selection Multicriteria Model: The BWM-MABAC Model

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Abstract: *The supply chain is a very complex area aimed at obtaining the optimum from the point of view of all participants. In order to achieve the overall optimum and satisfaction of all participants, it is necessary to make an adequate evaluation and selection of providers at the initial stage. In this paper, the selection of providers is based on a new approach in the field of multicriteria decision-making. The weight coefficients were determined using the Best-Worst Method (BWM), whereas provider evaluation and selection were performed using the Multi-Attributive Border Approximation Area Comparison (MABAC) method, which is one of more recent methods in this field. In order to determine the stability of the model and the applicability of the proposed hybrid BWM-MABAC model, the results were compared with the MAIRCA and VIKOR models, and the results of the comparative analysis are presented herein. In addition, a total of 18 different scenarios were formed in the sensitivity analysis, in which the criteria change their original value. At the end of the sensitivity analysis, the statistical dependence of the results was determined using Spearman's correlation coefficient, which confirmed the applicability of the proposed multicriteria approaches.*

Key words: *multicriteria decision-making, BWM, MABAC, MAIRCA, VIKOR, supply chain.*

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1. Introduction

When looking at the efficiency of the entire supply chain, it is impossible not to notice that it largely depends on an adequate selection of providers, because this process is one of the most important factors that directly affect the performance of a company. With a proper valuation and selection of the right provider, this logistics subsystem can efficiently carry out tasks related to supplying a company, since the right providers can meet the requirements and needs posed in the procurement subsystem, which on their part relate to the quality, price and quantity of goods, delivery times and other deadlines, flexibility, reliability, and so on. A search for providers in order to fulfill this is a permanent and primary task. In order to enable the former, it is necessary to continuously collect and process providers' data, establish and maintain adequate links with them.

According to Soheilrad et al. (2017), provider selection is an important item when speaking about management decisions, which considers several qualitative and quantitative criteria. The importance of this process in organizations reflects in the formation of the final product price, since the price of raw materials plays a significant role in the price of the final product (Bai & Sarkis 2010; Ramanathan 2007). Provider selection is one of more important items in the supply chain management (Zhong & Yao, 2017), while managing and developing provider relationships is a critical issue for achieving competitive advantage (Bai and Sarkis, 2011). Considering the fact that provider selection in the supply chain is multicriteria group decision-making, according to Zolfani et al. (2012), it is necessary for managers to know the most appropriate method for them to use so as to choose the right provider. This is especially true when we know that modern supply chains require that stringent requirements should be met, for which reason managers are faced with a difficult task of properly evaluating potential providers that rarely price the products that affect the company's competitiveness in the market (Cox & Ireland, 2002).

Every day, a large number of decisions are made on the basis of certain criteria, so it can be safely said that multicriteria decision-making (MCDM) plays a significant role in real-life problems, including logistical problems. Particularly important is the role that multicriteria decision-making plays in the decision-making process that affects the business system or the environment. Therefore, MCDM is an efficient systematic and quantitative way to solve vital logistical problems, including supply chain management. The increasing use of multicriteria decision-making methods has contributed to the increasing popularity of this field on a daily basis (Zavadskas et al., 2014).

This paper presents a hybrid MCDM vendor evaluation model, which is based on the application of the two models, i.e. the Best-Worst Method (BWM) and the Multi-Attributive Border Approximation Area Comparison (MABAC) model. The BWM model (Rezaei, 2015) was used to determine criteria weights, while the MABAC model was used to evaluate the providers. The BWM and MABAC models had been opted for because of the many advantages that recommend them for use in this field. In addition to this, no application of the hybrid BWM-MABAC model has been reported in the literature yet, which enriches the methodology for provider evaluation and selection.

The paper is structured into several chapters. In the second section of the paper, a literature analysis is performed through an overview of the existing multicriteria decision-making methods in the field of supply chains. The analysis of the applied methods, as well as the criteria for the work done in the field of the selection of transport service providers is carried out. Based on the data obtained from the analysis of the work done, a new multicriteria decision-making model is proposed, as

well as the criteria that will be used to select the right transport service provider. In the third section, the mathematical foundations of the hybrid BWM-MABAC model are presented. In the fourth section, the testing of the proposed model is performed on a real-life example, in which the evaluation of providers at the Ministry of Defense of the Republic of Serbia is conducted. In the fourth section of the paper, the results are validated in three phases. The first phase involves comparing the results of the BWM-MABAC model with those obtained by applying other multicriteria decision-making methods. In the second phase, the validation is performed in a dynamic environment by applying dynamic initial decision matrices. The third phase of the validation includes a sensitivity analysis of the change in the weights of the criteria coefficients. The fifth section contains the conclusive considerations, where the presented conclusions are derived from the conducted research and the suggestions for further research.

2. Literature Review

According to a large number of authors, provider selection is one of the most challenging management problems in logistics (Stojicic et al., 2019). As a result, a number of methods for the evaluation of transport service providers have been developed to date. In the literature (Fallahpour et al., 2017), the author uses the fuzzy modifications of the Analytic Network Process (ANP) method and the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Govindan et al. (2013) used the fuzzy TOPSIS method to rank the sustainable performance of a transport service provider. In order to make a choice of a logistics provider from the sustainability perspective while keeping an eye on the company's goals, Dai & Blackhurst (2012) introduced a new integrated approach based on the AHP and the Quality Function Deployment (QFD) methods, with four hierarchical stages. Rezaei et al. (2016) introduced a new approach to selecting a transport service provider, which consists of three phases, the essential one being the phase in which the implementation of the Best-Worst Method (BWM) is demonstrated. This approach can benefit companies looking for new markets. Azadnia et al. (2015) propose an integrated approach to choosing a logistics provider, which, in addition to the application of the fuzzy AHP method, is also based on multi-objective mathematical programming, as well as the rule-based weighted fuzzy method. Luthra et al. (2017) introduced an integrated approach to selecting a transport service provider from the sustainability perspective. The approach was implemented through a combination of the AHP and VIKOR methods based on 22 criteria. Barata et al. (2014) demonstrated the application of MCDM methods in the evaluation of the degree of the organizational sustainability of a company.

Hsu et al. (2014) presented an approach based on several MCDM methods in order to select a transport service provider from the environmental point of view, i.e. with respect to carbon emissions. Also, Validi et al. (2014) ranked logistics providers and traffic routes based on CO₂ emissions by using the TOPSIS method. The evaluation of the performance of logistics providers in the electronics industry is the topic of the research conducted in the paper (Chatterjee et al., 2018) from the environmental point of view as well. In this paper, the rough DEcision-MAking Trial and Evaluation Laboratory (DEMATEL) model is used in combination with the rough Multi-Attribute Ideal Real Comparative Analysis (MAIRCA) method. A quantitative assessment of the performance of transport service providers is presented in the paper from the sustainability perspective (Erol et al., 2011). In addition to MCDM methods, fuzzy

techniques are used in this paper because of the presence of indeterminacy. More specifically, the fuzzy Entropy and fuzzy Multi-Attribute Utility Theory (MAUT) methods are used. Kusi-Sarpong et al. (2018) presented a framework for the ranking and selection of sustainable innovation in logistics, given the fact that innovation plays a very significant role in sustainability. This framework is based on the BWM method, which has been tested and applied by several companies in India. Managing the evaluation of providers from the sustainability perspective is significant for many industries, and for logistics as well. Therefore, it is an increasingly common research topic. Table 1 presents an analysis of the papers dedicated to this topic that have been published in the last few years.

Table 1. The application of MCDM methods in supply chains

The problem solved by applying MCDM methods	Applied Methods	Literature
Sustainable provider selection	FPP, Fuzzy TOPSIS, AHP, VIKOR, Fuzzy ELECTRE, Fuzzy AHP, Fuzzy Multiplicative AHP, Fuzzy SMART, Fuzzy VIKOR, Fuzzy MAUT, BWM, AHP-QFD, Delphi, Fuzzy DEMATEL	Dai and Blackhurst (2012), Erol et al. (2011), Fallahpour et al. (2017), Govindan et al. (2013), Kusi-Sarpong et al. (2018), Luthra et al. (2017), Luthra et al. (2018) and Padhi et al. (2018)
Provider evaluation from the environmental point of view	Fuzzy Entropy-TOPSIS, ELECTRE TRI	Barata et al. (2014) and Zhao and Guo (2014)
Assessing provider performance in supply chains	DEMATEL, ANP, MAIRCA, fuzzy Delphi, DANP, VIKOR, TOPSIS	Chatterjee et al. (2018), Hsu et al. (2014) and Validi et al. (2014)
Suggesting an innovative provider selection methodology	BWM, DANP, DEMATEL, VIKOR, MULTIMOORA, AHP, Fuzzy TOPSIS	Das and Shaw (2017), Entezaminia et al. (2016), Kuo et al. (2015), Liu et al. (2018) and Rezaei et al. (2016)
An integrated approach to identifying and analyzing criteria and alternatives under uncertain conditions	Grey-DEMATEL, FAHP	Azadnia et al. (2015) and Su et al. (2016)

Also, MCDM methods have been applied in solving a broad range of problems in the logistics field. Depending on a specific problem in the logistics field, various MCDM methods have been used, such as: AHP, TOPSIS, VIKOR, MAIRCA, ELECTRE, fuzzy AHP, fuzzy TOPSIS and DEMATEL (Alikhani et al., 2019; Ahmadi & Amin, 2019; Buyukozkan & Gocer, 2017). According to the table, it is possible to see that the AHP, TOPSIS and fuzzy TOPSIS methods have been applied to the greatest extent in the logistics field. The BWM and Fuzzy Preferences Programming (FPP) methods have most commonly been used to determine weight coefficients. This literature review allows us to see that the BWM and MABAC models have not yet been applied in providers' supply chain. Due to the aforementioned fact, as well as the numerous advantages of the BWM and MABAC models (Pamucar & Cirovic, 2015; Gigovic et al., 2017; Pamucar et al., 2018a, 2018b), a hybrid BWM-MABAC model is proposed in this paper. Based on the search

of the most important index databases of international journals, Table 2 presents an analysis of the criteria that have been applied in the MCDM methods for optimizing the selection of providers in supply chains.

Table 2. Applied criteria in MCDM methods in the field of transport service provider selection:

Area	Literature	C1	C2	C3	C4	C5	C6	C7	C8	C9
Sustainable provider selection in supply chains	Alikhani et al. (2019)	+	+	+	+	X	X	X	X	X
	Fallahpour et al. (2017)	+	+	+	X	X	X	+	+	X
	Memari et al. (2019)	+	+	+	X	X	X	X	X	+
	Yu et al. (2019)	+	+	+	+	+	X	X	X	X
	Fashoto et al. (2016)	+	+	+	X	X	X	X	+	X
Provider evaluation from an environmental point of view	Razaei and Haeri (2019)	+	+	+	+	+	+	+	+	+
	Parkouhi et al. (2019)	+	+	+	+	+	X	+	+	X
	Dobos and Vorosmarty (2019)	+	+	+	+	X	X	X	X	X
	Lin et al. (2011)	+	+	+	X	+	X	X	X	X
An integrated provider evaluation approach	Fu (2019)	+	+	+	X	X	+	+	X	X
	Ahmadi and Amin (2019)	+	+	+	X	+	+	X	X	X
	Rouyendegh and Saputro (2014)	+	+	+	X	+	X	X	X	X
	Wu et al. (2019)	+	+	+	X	X	+	X	X	X
	Liu et al. (2019)	+	+	+	X	+	X	X	X	X
Provider Selection - Application of Fuzzy Theory in MCDM models	Buyukozkan and Gocer (2017)	+	+	+	X	X	X	X	X	X
	Sarkar et al. (2017)	+	+	+	X	X	X	X	+	X
	Zhang et al. (2015)	+	+	+	X	X	+	X	+	X
Provider Selection - ANP approach	Lima-Junior and Carpinetti (2016)	+	+	+	X	X	X	X	X	X
	Dargi et al. (2014)	+	+	+	X	+	+	X	X	X
	Gupta et al. (2015)	+	+	X	X	X	X	+	X	X

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Based on the literature review presented, the following criteria are identified in order to address the provider evaluation issues in supply chains: C1 – Price (min.), C2 – Quality (max.), C3 – Service and Delivery (max.), C4 – Flexibility (max.), C5 – Technological capabilities (max.), C6 – Trust (max.), C7 – Relationship (max.), C8 – Risk (min.) and C9 – Innovation (max.).

Based on Table 2, a conclusion can be drawn that the criteria C1, C2 and C3, i.e. the price, the quality and the service and delivery, respectively, are indispensable when choosing a provider, regardless of the specific situation. Another important criterion is C5, i.e. technological capabilities, which was applied in eight papers, only to be followed by the criteria C6 and C8, i.e. trust and risk, respectively, which were applied in six papers, and C4 and C7, i.e. flexibility and relationship (trust), respectively, which were applied in five papers. As a criterion, innovation (C9) is used least in solving the transport service provider selection problem, having only been used in two papers. In this paper, all the analyzed criteria will be included for the purpose of a comprehensive consideration of the problem.

3. The BWM-MABAC Hybrid Provider Evaluation Model

In this paper, a new hybrid BWM-MABAC model (Figure 1) for provider evaluation is presented. The model includes the application of the two methods: (1) the BWM method, which is used to determine the weight criteria, and (2) the MABAC method, which is used to evaluate the ranking of the alternatives.

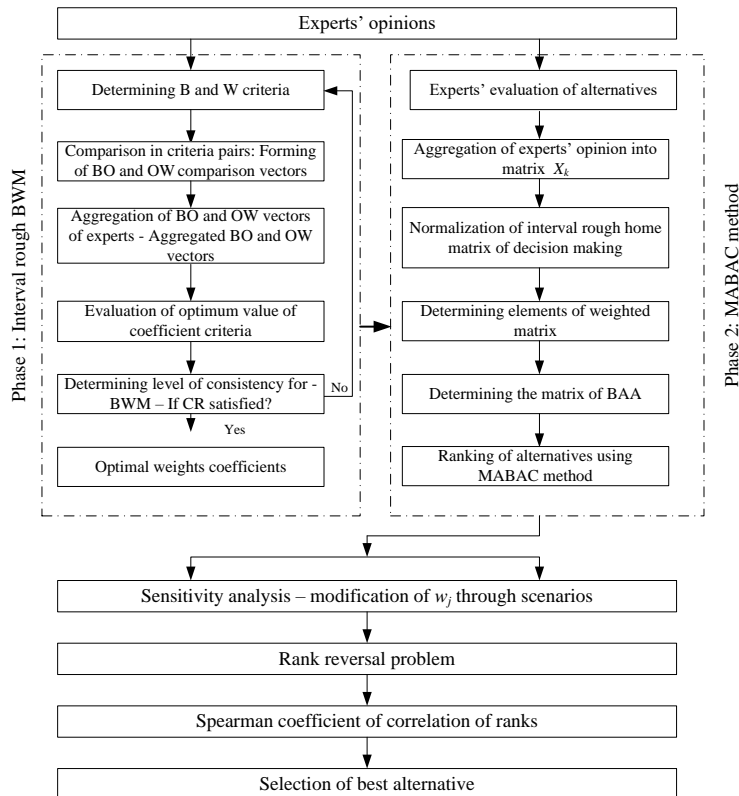


Figure 1. The BWM-MABAC model

The model is implemented through three phases. In the first phase, the criteria are evaluated by using the BWM method. Based on a questionnaire and the experts' evaluation, the ranking of the criteria and the comparison of the ranking criteria are made. The values of the weight coefficients of the criteria are obtained as the output from the BWM method. The output data from the BWM are further processed through the MABAC method algorithm. In the second phase, the alternatives are ranked by applying the MABAC method. In the third phase, the results are validated.

3.1. The BWM algorithm

Like the AHP model, the BWM is one of the models of a more recent data based on comparison principles in criteria pairs and the validation of results through a deviation from the maximum consistency (Pamucar et al., 2018a, 2018b). The BWM is a model which eliminates the drawbacks of the AHP model to some extent. The advantages of the implementation of the BWM are a small number of comparisons in criteria pairs, the ability to validate results by defining the consistency deviation (CR) of the comparisons, and taking into consideration transitivity during comparisons in criteria pairs. Also, the BWM methodological procedure eliminates the problem of a comparison redundancy in criteria pairs, which is present in some subjective criteria weight determination models.

Suppose that there are the n evaluation criteria in the multicriteria model that are denoted as $w_j, j = 1, 2, \dots, n$ and that their weight coefficients need to be determined. Subjective weighting models based on comparisons in criteria pairs require that the decision-maker should determine the degree of the influence of the criterion i on the criterion j as well. In accordance with the defined settings, the following section introduces the BWM algorithm (Pamucar et al., 2018a, 2018b).

Algorithm: BWM

Input: The experts' comparison in criteria pairs

Output: The optimal values of criteria/sub-criteria weight coefficients

Step 1: The experts' ranking of the criteria/sub-criteria.

Step 2: The determination of the BO and OW vectors of the comparative significance of the evaluation criteria.

Step 4: Defining a model for the determination of the final values of the weighting coefficients of the evaluation criteria:

$$\min \xi$$

s.t.

$$\left\{ \begin{array}{l} \left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \xi; \quad \left| \frac{w_j}{w_w} - a_{jw} \right| \leq \xi; \\ \sum_{j=1}^n w_j = 1; w_j \geq 0; \quad \forall j = 1, 2, \dots, n \end{array} \right.$$

Step 5: The calculation of the final values of the evaluation criteria/sub-criteria

$$(w_1, w_2, \dots, w_n)^T$$

3.2. The MABAC model algorithm

The MABAC method is one of more recent methods (Pamucar & Cirovic, 2015). To date, it has been broadly applied in solving numerous problems in the multicriteria decision-making field. The basic assumption of the MABAC method is that the distance

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of the criterion function of the observed alternative from the boundary approximate area should be defined. The following section introduces the MABAC method algorithm (Pamucar & Cirovic, 2015).

Algorithm: MABAC method

Input: BWM weights and the initial decision matrix

Output: The ranking of the alternatives

Step 1: The formation of the initial decision matrix (X).

Step 2: The normalization of the elements of the initial matrix.

Step 3: The calculation of the elements of the weighted matrix (V).

Step 4: The determination of the matrix of the boundary approximate regions (G). The matrix of the boundary approximation domains G (12) format $n \times 1$:

$$G = \begin{bmatrix} C_1 & C_2 & \dots & C_n \\ g_1 & g_2 & \dots & g_n \end{bmatrix}, \text{ where } g_i = \left(\prod_{j=1}^m v_{ij} \right)^{1/m} \quad (v_{ij} \text{ represents the elements of}$$

the weighted matrix).

Step 5: The calculation of the elements of the distance matrix of the alternatives from the boundary approximation region (Q). The distance of the alternatives from the boundary approximation region (q_{ij}) is determined as the difference between the elements of the constrained matrix (V) and the value of the boundary approximation regions (G).

$$Q = \begin{bmatrix} v_{11} - g_1 & v_{12} - g_2 & \dots & v_{1n} - g_n \\ v_{21} - g_1 & v_{22} - g_2 & \dots & v_{2n} - g_n \\ \dots & \dots & \dots & \dots \\ v_{m1} - g_1 & v_{m2} - g_2 & \dots & v_{mn} - g_n \end{bmatrix} = \begin{bmatrix} q_{11} & q_{12} & \dots & q_{1n} \\ q_{21} & q_{22} & \dots & q_{2n} \\ \dots & \dots & \dots & \dots \\ q_{m1} & q_{m2} & \dots & q_{mn} \end{bmatrix}$$

Step 6: The ranking of the alternatives. The calculation of the values of the criteria functions is obtained as the sum of the distances of the alternatives from the boundary approximation regions (q_i).

4. The Application of the BWM-MABAC Model

The model has been tested on a real issue, which includes the evaluation of the providers of spare parts for transport vehicles at the Ministry of Defense of the Republic of Serbia. A total of eight providers were considered, whose names were not included in this survey because of the confidentiality of the tender documents. The study involved four experts with at least 10 years of experience in supply chain evaluation.

In the first phase of the implementation of the BWM-MABAC model, it is necessary to define the weight coefficients of the criteria by using the BWM. The first phase of the BWM involves the experts' ranking of the criteria. Based on the significance of the criteria presented in the BO and OW vectors, a nonlinear model was formed for the calculation of the optimal values of the weight coefficients. A total of four models were formed, one for each expert. The following section provides the model for the calculation of the optimal values of the weighting coefficients for the first expert.

Expert 1 – min ξ

s.t.

$$\left\{ \begin{array}{l} \left| \frac{w_1}{w_2} - 7 \right| \leq \xi; \left| \frac{w_1}{w_3} - 2 \right| \leq \xi; \dots; \left| \frac{w_1}{w_7} - 3 \right| \leq \xi; \\ \left| \frac{w_3}{w_2} - 6.00 \right| \leq \xi; \left| \frac{w_4}{w_2} - 3 \right| \leq \xi; \dots; \left| \frac{w_7}{w_2} - 2 \right| \leq \xi; \\ \sum_{j=1}^7 w_j = 1; w_j \geq 0; \forall j = 1, 2, \dots, 7 \end{array} \right.$$

By solving the nonlinear models, the optimal values of the weight coefficients for each expert were defined, as in Table 3.

Table 3. The criteria weight coefficients

Experts	E ₁	E ₂	E ₃	E ₄	Medium
C1	0.311	0.100	0.117	0.030	0.1395
C2	0.207	0.120	0.180	0.149	0.1640
C3	0.076	0.299	0.269	0.149	0.1982
C4	0.104	0.067	0.096	0.149	0.1040
C5	0.060	0.086	0.054	0.075	0.0687
C6	0.065	0.120	0.077	0.075	0.0842
C7	0.052	0.050	0.045	0.149	0.0740
C8	0.086	0.075	0.128	0.149	0.1095
C9	0.039	0.054	0.034	0.075	0.0505

By averaging the obtained values, the optimal values of the weight coefficients of the criteria were defined, which were further used to evaluate providers by applying the MABAC method. The paper evaluates a total of eight providers, designated A1 through A8. Based on the provider data, the MABAC model was implemented through the following six steps:

Step 1. In the MABAC model, the initial decision matrix (X) was the starting point:

$$X = \begin{bmatrix} \min f_1 & \max f_2 & \max f_3 & \max f_4 & \max f_5 & \max f_6 & \max f_7 & \min f_8 & \max f_9 \\ A1 & 65 & 23 & 56 & 53 & 54 & 95 & 53 & 59 & 62 \\ A2 & 45 & 29 & 50 & 49 & 49 & 44 & 87 & 63 & 73 \\ A3 & 56 & 43 & 70 & 57 & 41 & 59 & 41 & 52 & 59 \\ A4 & 70 & 35 & 82 & 43 & 91 & 93 & 38 & 41 & 66 \\ A5 & 82 & 68 & 63 & 95 & 35 & 81 & 79 & 39 & 49 \\ A6 & 90 & 56 & 71 & 80 & 62 & 71 & 91 & 23 & 81 \\ A7 & 48 & 39 & 63 & 74 & 25 & 66 & 66 & 72 & 52 \\ A8 & 76 & 56 & 59 & 61 & 53 & 67 & 59 & 46 & 77 \end{bmatrix}$$

Step 2. Using linear normalization, the elements of the matrix X were normalized, thus obtaining the normalized matrix N:

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	$\min f_1$	$\max f_2$	$\max f_3$	$\max f_4$	$\max f_5$	$\max f_6$	$\max f_7$	$\min f_8$	$\max f_9$
A1	0.556	0	0.188	0.192	0.439	1	0.283	0.265	0.406
A2	1	0.133	0	0.115	0.364	0	0.925	0.184	0.750
A3	0.756	0.444	0.625	0.269	0.252	0.294	0.057	0.408	0.313
A4	0.444	0.267	1	0	1	0.961	0	0.633	0.531
A5	0.111	1	0.406	1	0.152	0.725	0.774	0.673	0
A6	0	0.733	0.656	0.712	0.561	0.529	1	1	1
A7	0.933	0.356	0.406	0.596	0	0.431	0.528	0	0.094
A8	0.311	0.733	0.281	0.346	0.424	0.451	0.396	0.531	0.875

Step 3. By multiplying the optimal values of the weighting coefficients obtained by applying the BWM by the elements of the normalized matrix N a weighted normalized matrix V was obtained.

	$\min f_1$	$\max f_2$	$\max f_3$	$\max f_4$	$\max f_5$	$\max f_6$	$\max f_7$	$\min f_8$	$\max f_9$
A1	0.217	0.164	0.235	0.124	0.099	0.168	0.095	0.139	0.071
A2	0.279	0.186	0.198	0.116	0.094	0.084	0.142	0.130	0.088
A3	0.245	0.237	0.322	0.132	0.085	0.109	0.078	0.154	0.066
A4	0.202	0.208	0.396	0.104	0.137	0.165	0.074	0.179	0.077
A5	0.155	0.328	0.279	0.208	0.079	0.145	0.131	0.183	0.051
A6	0.140	0.284	0.328	0.178	0.107	0.129	0.148	0.219	0.101
A7	0.270	0.222	0.279	0.166	0.069	0.121	0.113	0.110	0.055
A8	0.183	0.284	0.254	0.140	0.098	0.122	0.103	0.168	0.095

Step 4. In Step 4, the defined matrix of the boundary approximate regions (G) was approached. The boundary approximation area (GAO) for each criterion was determined by geometrically averaging the values of the matrix V.

	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
G	0.2055	0.2335	0.2807	0.1425	0.0942	0.1276	0.1074	0.1568	0.0736

Step 5. In this step, the distance of the elements V of the matrix from the matrix G was calculated. Thus, the matrix Q, which represents the distance of the alternatives from the GAO, was obtained.

	$\min f_1$	$\max f_2$	$\max f_3$	$\max f_4$	$\max f_5$	$\max f_6$	$\max f_7$	$\min f_8$	$\max f_9$
A1	0.011	-0.070	-0.045	-0.018	0.005	0.041	-0.012	-0.018	-0.003
A2	0.073	-0.048	-0.083	-0.026	-0.001	-0.043	0.035	-0.027	0.015
A3	0.039	0.003	0.041	-0.010	-0.009	-0.019	-0.029	-0.003	-0.007
A4	-0.004	-0.026	0.116	-0.038	0.043	0.037	-0.033	0.022	0.004
A5	-0.051	0.094	-0.002	0.066	-0.015	0.018	0.024	0.026	-0.023
A6	-0.066	0.051	0.048	0.036	0.013	0.001	0.041	0.062	0.027
A7	0.064	-0.011	-0.002	0.024	-0.025	-0.007	0.006	-0.047	-0.018
A8	-0.023	0.051	-0.027	-0.0020	0.004	-0.005	-0.004	0.011	0.021

Step 6. The ranking of the alternatives was performed based on the value of the alternative score functions. The criteria functions of the alternatives were obtained by

summing up the elements of the matrix Q by rows. Thus, the values of the criteria functions of the alternatives were obtained for each provider:

$$S_2 = -0.104 \quad S_3 = 0.007 \quad S_4 = 0.120 \quad S_5 = 0.137 \quad S_6 = 0.212 \quad S_7 = -0.018 \quad S_8 = 0.025$$

Based on the values of the criteria functions, the final ranking of the alternatives was defined as: $A_6 > A_5 > A_4 > A_8 > A_3 > A_7 > A_2 > A_1$.

Before making a decision, it is necessary to evaluate the reliability of the results obtained. The validation of the results of the BWM-MABAC model was carried out through three phases. In the first phase, the initial ranking of the alternatives was compared with that of the other MCDM models, as in Figure 2. Since the MABAC method uses linear normalization, the Multi Attributive Ideal-Real Comparative Analysis (MAIRCA) method and the Multicriteria Compromise Ranking (VIKOR) method also have linear normalization.

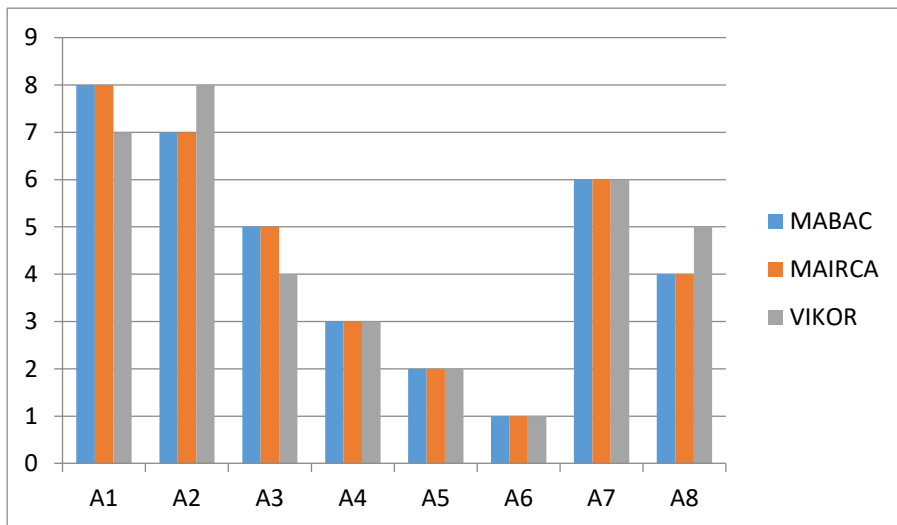


Figure 2. The ranks of the alternatives

According to the presented methods, the ranking of the alternatives shows that the alternative A6 remained the first-ranked by all the methods. The same rank was obtained by the MAIRCA method as it was by the MABAC method, whereas the ranking changed with the VIKOR method (the alternative A1 replaced its rank with the alternative A2, and the alternative A3 replaced the rank with the alternative A8). In order to determine the statistical significance between the rankings obtained by the BWM-MABAC model and the other approaches, the Spearman correlation coefficient (SCC) was used. This correlation coefficient is a simple linear correlation coefficient between the ranks. The Spearman rank correlation coefficient is a non-parametric method for the estimation of the strength of the association that is applied when data for at least one variable are given as ordinal data or a rank, when at least one variable has no normal distribution and when the relationship between the variables is not linear. The results of the ranking comparisons by using the SCC are given in Table 4.

Table 4. The rank correlation of the tested methods

Method	MCDM	MABAC	MAIRCA	VIKOR
	SCC	1.000	1.000	0.952

Table 5 allows us to see that the MABAC and MAIRCA methods are in a complete correlation. Also, the VIKOR method shows a high correlation compared to the MABAC method. Given the fact that, in this particular case, all the SCC values are significantly higher than 0.9 (exceptional correlation) and the mean value is 0.976, it can be concluded that there is a very large correlation (closeness) between the proposed model and the other MCDM methods. In doing so, we can conclude that the proposed ranking is validated and credible.

In the second stage of the results validation, a performance analysis of the proposed model was conducted under the conditions of the dynamic initial matrix. In the dynamic starting matrix for each scenario, the number of the alternatives was changed and the obtained ranks were analyzed. Scenarios are formed for situations where one inferior alternative is removed from subsequent considerations, while the remaining dominant alternatives are ranked according to a newly-acquired initial decision matrix. In this study, the initial solution $A6 > A5 > A4 > A8 > A3 > A7 > A2 > A1$ was obtained. Clearly, the alternative A1 is the worst option. In the first scenario, the alternative A1 was eliminated from the list of the alternatives and a new decision matrix with a total of seven alternatives was obtained. The new decision matrix was re-solved by using the BWM-MABAC model. In the following scenario, the next worst alternative was eliminated and the remaining alternatives were ranked. Thus, a total of seven scenarios were formed, which are shown in Table 5.

Table 5. The ranks of the alternatives within the dynamic decision matrix

Scenario	Rang
S1	$A6 > A5 > A4 > A8 > A3 > A7 > A2 > A1$
S2	$A6 > A5 > A4 > A8 > A3 > A7 > A2$
S3	$A6 > A5 > A4 > A8 > A3 > A7$
S4	$A6 > A5 > A4 > A8 > A3$
S5	$A6 > A5 > A4 > A8$
S6	$A6 > A5 > A4$
S7	$A6 > A5$

It is clear from Table 5 that, when the worst-case alternative is eliminated, there is no change in the best-ranked alternative in the rearranged matrix. Based on this, it can be concluded that the BWM-MABAC model does not lead to a rank reversal among the alternatives. The alternative A6 remained the best-ranked across all the scenarios, thus confirming the robustness and accuracy of the resulting rankings of the alternatives in the dynamic environment.

Since the results of multicriteria decision-making depend on the values of the weighting coefficients of the evaluation criteria, an analysis of the sensitivity of the results to a change in the criteria weights was performed. The analysis of the sensitivity of the rankings of the alternatives to changes in the weight coefficients of the criteria was conducted through the 18 scenarios given in Table 6.

Table 6. The sensitivity analysis scenarios

Scenario	Criteria weights	Scenario	Criteria weights
S1	$w_{c1}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S10	$w_{c1}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S2	$w_{c2}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S11	$w_{c2}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S3	$w_{c3}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S12	$w_{c3}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S4	$w_{c4}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S13	$w_{c4}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S5	$w_{c5}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S14	$w_{c5}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S6	$w_{c6}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S15	$w_{c6}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S7	$w_{c7}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S16	$w_{c7}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S8	$w_{c8}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S17	$w_{c8}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$
S9	$w_{c9}=1.25 \times w_{c11(OV)}$; $w_{ci}=0.25 \times w_{ci(OV)}$	S18	$w_{c9}=1.55 \times w_{c11(OV)}$; $w_{ci}=0.55 \times w_{ci(OV)}$

*OV (old value)

The sensitivity analysis scenarios for the change in the criteria weights are grouped into two groups. Within each group, the weighting coefficients of the criteria were increased by 25% and 55%, respectively. In each of the 18 scenarios, one criterion was favored within the two groups, by which the weight coefficient increased by the indicated values. In the same scenario, the weighting coefficients were reduced by 75% (S1-S9) and 45% (S10-S18), respectively. The changes in the ranking of the alternatives across the 18 scenarios are shown in Table 7.

Table 7. The changes in the ranking due to the changes in the criteria weights

Scenario	Rank
S1	A7>A2>A3>A4>A6>A1>A5>A8
S2	A5>A6>A8>A3>A4>A7>A2>A1
S3	A4>A6>A3>A5>A7>A8>A1>A2
S4	A5>A6>A7>A8>A4>A3>A1>A2
S5	A4>A6>A5>A8>A3>A1>A2>A7
S6	A4>A6>A5>A1>A8>A7>A3>A2
S7	A6>A5>A2>A8>A7>A4>A3>A1
S8	A6>A5>A4>A8>A3>A1>A7>A2
S9	A6>A4>A8>A5>A3>A2>A7>A1
S10	A4>A7>A6>A3>A5>A2>A8>A1
S11	A5>A6>A8>A4>A3>A7>A2>A1
S12	A4>A6>A5>A3>A7>A8>A1>A2
S13	A6>A5>A4>A7>A8>A3>A1>A2
S14	A6>A4>A5>A8>A3>A7>A1>A2
S15	A6>A4>A5>A8>A3>A7>A1>A2

Scenario	Rank
S16	A6>A5>A4>A8>A7>A2>A3>A1
S17	A6>A5>A4>A8>A3>A7>A1>A2
S18	A6>A4>A5>A8>A3>A7>A2>A1

The results show that assigning different criteria weights across the 18 scenarios presented does not lead to a significant change in the ranking of the alternatives. In the scenarios S2-S9 and S11-S18, the fact that the alternative A6 ranks either first or second is noticed. In the scenarios S1 and S10, the alternative A6 is not among the top two alternatives, due to the high value of the A6 provider engagement price, whereas in the scenarios S1 and S10, the impact of the weighting factor on the final decision only increased.

The results (Table 7) show that assigning different weights to the criteria across the scenarios leads to a change in the rank of the alternatives, thus confirming that the model is sensitive to changes in weight coefficients. The following section compares the ranks in Table 7 with the initial ranks. The SCC values are shown in Figure 3.

Based on Figure 3, it can be concluded that there is a high rank correlation in the 12 scenarios, since the SCC value is greater than 0.80, whereas in the four scenarios, that correlation is satisfactory, i.e. it is greater than 0.50. In the two scenarios, the SCC value is below 0.50. However, the mean SCC across the scenarios is 0.778, which shows a satisfactory average correlation. Based on this, it can be concluded that there is a satisfactory closeness of the ranks and the proposed ranking is validated and credible.

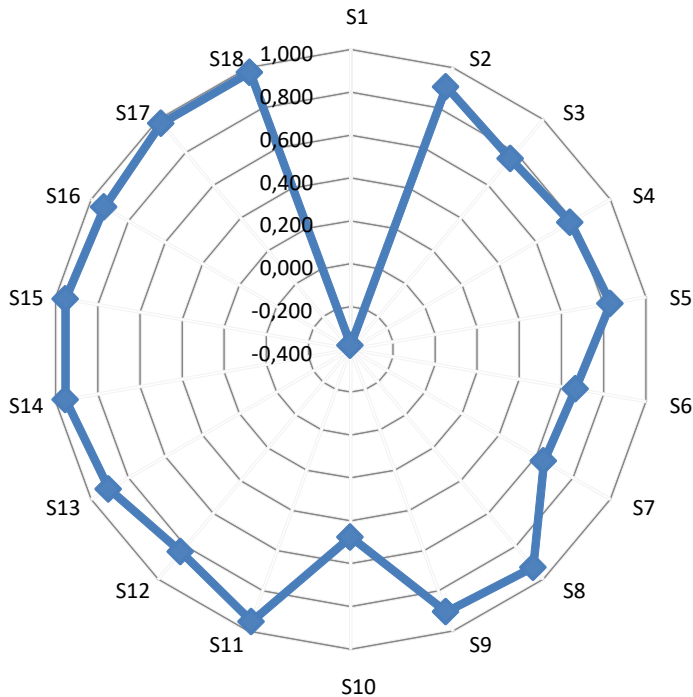


Figure 3. The correlation of the ranks

5. Conclusion

The multicriteria model presented in this paper is an integration of the BWM and MABAC methods, where the BWM was used to calculate the values of the criteria weights, while the MABAC method was applied for provider evaluation and selection. The model was verified through the provider selection process in a real system, based on the nine criteria. The results show that Provider 6 is the best solution in all the scenarios including different criteria values, except in the two scenarios in which the price criterion was favored. The analysis of the results has shown that the obtained ranks of the alternatives of the BWM-MABAC model completely correlate with the ranks of the other multicriteria models which they were compared with.

One of the contributions of this paper is the BWM-MABAC model that provides us with an objective aggregation of experts' decisions. In addition, another contribution of the paper reflects in the improvement of the methodology of provider evaluation and selection through a new hybrid multicriteria model. No use of this or a similar approach in the selection of providers has been seen in the literature analysis.

By applying the developed approach, it is possible to approach multicriteria decision-making in an easy way and evaluate and select those providers who have a significant impact on the achievement of the efficiency of the whole of the supply chain. The four-stage model may also be applied so as to make other decisions. It is applicable in the provider evaluation process in all areas and may be particularly suitable for manufacturing companies. The flexibility of the model reflects in the fact that it can be verified by integrating any multicriteria decision-making methods. Further research related to this paper pertains to the application of uncertainty theories (fuzzy, rough, neutrosophic, etc.) together with this and other multicriteria methods in this field.

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