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A Novel BWM-RADAR Approach for Multi-Attribute Selection of Equipment in the Automotive Industry

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ABSTRACT

This study examines the application of Multi-Attribute Decision Making (MADM) techniques for selecting an optimal technical solution in the automotive industry, specifically addressing the automatic adjustment and control device of a parking brake cable. The research begins by using the Best-Worst Method (BWM) to determine the weights of criteria, such as device speed, price, weight, and calibration period, based on expert input from maintenance professionals and operators at an automotive original equipment manufacturer in automotive industry. The main objective is to identify the solution that best balances operational efficiency with long-term stability and adaptability to production requirements. In the subsequent phase, both the RADAR method and its modified version, RADAR II, are applied to rank the alternatives. The original RADAR method, which employs ratio-based normalization, tends to favor alternatives that demonstrate stable performance across all criteria, whereas RADAR II, utilizing difference-based normalization, accentuates alternatives that excel in particular aspects. Comparative analysis reveals that although both methods produce generally consistent overall rankings, nuances in the normalization process can lead to differences in the relative prominence of certain solutions. Sensitivity analysis further confirms the robustness and reliability of these approaches, underscoring the importance of selecting a method that aligns with the specific decision-making context. Ultimately, the study demonstrates that a carefully tailored MADM approach, integrating both RADAR and RADAR II techniques, provides valuable insights and supports effective decision-making in complex industrial environments.

1. Introduction

Decision-making is a process that occurs daily in business systems such as those found in automotive industry enterprises. Various types of decisions are made, and certain situations require the application of specific tools and techniques. One such tool is Multi-Attribute Decision-Making (MADM). Some of the problems that industrial management faces include the selection of

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suppliers [1], materials [2], equipment [3], risk assessment [4], and others. Therefore, it can be said that there is a wide range of issues in the industry to which MADM can be applied.

In general, there exists a relatively large number of different MADM methods. These methods can be classified according to various criteria [5,6]; however, they all share a similar problem-solving principle, that potential solutions, or alternatives, are evaluated or ranked based on a given set of criteria. Moreover, there are also special cases of MADM methods that are narrowly specialized or are most commonly used for determining the weights (importance) of the criteria on which the alternatives are evaluated.

The problem considered in this paper is the selection of the most reliable technical solution, namely a device for the automatic adjustment of the parking (hand) brake cable used in the automotive industry during the vehicle assembly process. The model was tested in an automotive industry enterprise that serves as an OEM (Overall Equipment Manufacturer) within the automotive supply chain. The research was conducted in collaboration with the company's professional maintenance sector.

To address the problem at hand, a combined MADM approach was employed. The Best-Worst Method (BWM), developed by Rezaei [7], was used to determine the weight coefficients (i.e., the weights) of the criteria. For the evaluation and ranking of the considered alternatives, specifically, five different devices for the stated purpose, the RAnking based on the Distances And Range (RADAR) method [8] was applied.

The basic RADAR method adopts a compromise approach to ranking alternatives by taking into account both the stability of values across all criteria and the deviations from ideal solutions. In other words, this method favors alternatives that are more stable across each considered criterion, as opposed to those alternatives that are extremely good in one or more criteria but exhibit relatively low values in others. In certain problems, this characteristic of the RADAR method can prove to be very useful.

However, in addition to the advantages offered by the basic RADAR method, it also has certain drawbacks, particularly regarding the objectivity of alternative evaluation. For this reason, this paper proposes a modification of the method, the so-called RADAR II method, in order to further enhance the robustness of the approach. In doing so, one of the key features of the RADAR method, the emphasis on the stability of an alternative across as many criteria as possible, is somewhat reduced, thereby enabling a more balanced approach to evaluating alternatives.

To examine the characteristics of both the basic RADAR method and its modification (RADAR II), the results obtained using these approaches were compared with those derived from other widely known and employed MADM methods: the Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) [9], VIKOR (Serbian: VlšeKriterijumska Optimizacija i Kompromisno Rešenje) [10], COmplex PRoportional Assessment (COPRAS) [11], Simple Additive Weighting (SAW) (see [12]), Additive Ratio Assessment (ARAS) [13], and Evaluation based on Distance from Average Solution (EDAS) (see [14]). These methods were chosen because they are based on different approaches to ranking alternatives. For example, TOPSIS and VIKOR assess the distance from the positive ideal and negative ideal solutions, COPRAS introduces the concept of the relative utility of alternatives, SAW and ARAS apply linear aggregation functions, while EDAS evaluates the positive and negative deviations of the alternatives.

By comparing the results of the RADAR and RADAR II methods with these widely used approaches, the study was able to highlight the specific advantages and limitations of the RADAR methodology. Specifically, the analysis examined whether the basic RADAR method favors more stable alternatives as opposed to those with pronounced values in individual criteria, and whether

RADAR II successfully mitigates this effect, thereby achieving a more objective evaluation of the alternatives. This approach allows for a deeper understanding of the compromise decision-making model introduced by the RADAR methods and their application in an industrial context, which is the primary aim of this research.

The structure of the paper is as follows: Chapter 2 presents a review and analysis of the relevant literature. Chapter 3 explains the proposed MADM model and outlines the steps for applying the proposed algorithm. Chapter 4 presents a case study, while Chapter 5 provides a comparative analysis and a sensitivity analysis of the obtained results. Finally, the conclusions of the research are presented in Chapter 6.

2. Literature Review

The methods employed in this paper to address the problem under consideration are relatively new. The RADAR method was published in 2024 [8] and can still be considered to be in the development and testing phase. On the other hand, the Best-Worst Method (BWM) was developed in 2015 [7] and has since become one of the most significant MADM methods; along with the Analytic Hierarchy Process (AHP) [15,16], it is undoubtedly the most popular method for determining the weights of criteria.

The application of the BWM method in the relevant literature is wide. It is frequently used to solve optimization problems in the industry. For example, in numerous studies, authors have employed the method for supplier selection problems [17–20]. Furthermore, this method has also been used in the industry for equipment [21] and material selection [22–24]. Moreover, it is often found in problems across other sectors of the economy, such as energy [25], education [26], etc. It should be noted that in the vast majority of cases, the method is used for determining the weights of criteria, while the ranking of alternatives is performed using another method.

In addition to the BWM method, this research employed the TOPSIS, COPRAS, VIKOR, SAW, ARAS, and EDAS methods for ordering and analyzing the obtained results, as most of these methods have already been applied for similar purposes in the relevant literature.

The problem of equipment selection in the industry has also been previously examined in the literature. In study, Mathew and Sahu [3] used several MADM approaches, including the COPRAS and EDAS methods, to carry out the selection of proper material handling equipment and to determine whether differences existed among the approaches used. A similar problem was addressed using the COPRAS and ARAS methods [27].

MADM approaches were also applied for the selection of equipment for open-pit mining. In paper [28], authors analyzed the application of the TOPSIS and VIKOR methods, while in [29] authors employed only the VIKOR method to solve a similar type of problem. Additionally, TOPSIS, EDAS, and COPRAS have been used for the selection of stacker machines [30]. The equipment used for maintenance was analyzed and selected by applying a combined AHP-VIKOR approach in the study by [31].

The choice of methods for the comparative analysis in this research is based on their widespread application and relevance in the industry, as demonstrated by previous studies in which these methods were employed to solve similar problems.

3. The Proposed MADM Model

To address the problem under consideration, several MADM methods were employed. The model itself can be divided into two phases, with a sensitivity analysis performed in a third phase. Firstly, in the first phase, the weights of the criteria, ω_i, were determined at the level of each decision maker, $e, e = 1, \ldots, E$, using the BWM method. In the second phase, the ranking of alternatives, that is, the devices, was carried out using both the RADAR method and the new RADAR II method, while in the third phase the results were compared with those obtained through the application of the TOPSIS, COPRAS, VIKOR, SAW, ARAS, and EDAS methods. The comparative analysis of the results was based on a procedure for comparing the rankings of alternatives [32]. Figure 1 provides a graphical representation of the proposed model.

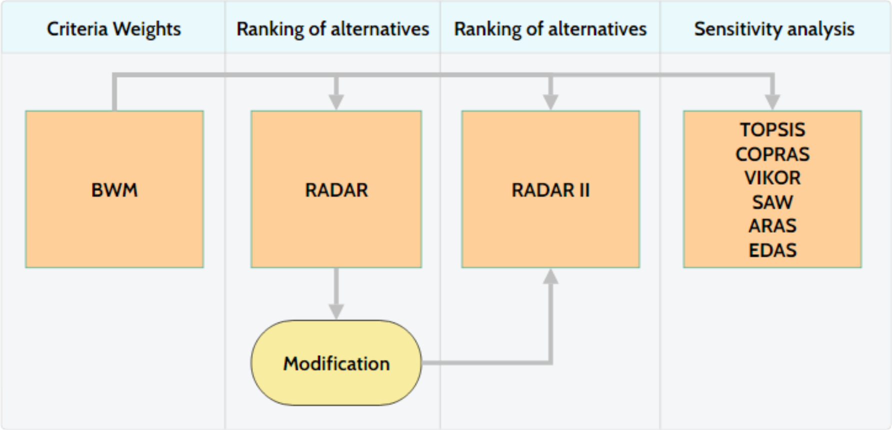

Fig. 1. The proposed model

In the following section of this chapter, a detailed explanation of the proposed methodology is provided through the proposed algorithm.

1.1 The Proposed Algorithm

Phase one of the proposed algorithm, as already mentioned, is the application of the BWM method. The implementation of this method is carried out through the following steps [7]:

Step 1. In collaboration with the maintenance sector of the considered enterprise, a set of criteria, $\{1, \ldots j, \ldots, J\}$, was determined. In this case, four criteria were considered, which will be explained in the Case Study section. Additionally, a set of decision makers, $\{1, \ldots e, \ldots, E\}$, who assess the relative importance of the criteria, was established. In this instance, three decision makers were selected.

Step 2. The most important criterion (the best) is determined based on the knowledge and experience of the decision makers.

Step 3. For each decision maker, the preference of the best criterion over all the other criteria is assessed using a measurement scale [1–9]. This step can be formally expressed by Eq. (1):

$$A_B^e = \left(a_{B1}^e, \ldots, a_{Bj}^e, \ldots, a_{BJ}^e\right) \tag{1}$$

Step 4. The least important (the worst) criterion is determined based on the knowledge and experience of the decision makers.

Step 5. For each decision maker, the preference of all the other criteria over the worst criterion is assessed using a measurement scale [1–9]. This step can be formally expressed by Eq. (2):

$$A_W^e = \left(a_{1W}^e, \ldots, a_{jW}^e, \ldots, a_{JW}^e\right)^T \tag{2}$$

It is important to note that in the cases of a_{BB} and a_{WW} the comparison value is always 1.

Step 6. By applying the procedure from the basic BWM method, first, the optimal weights for the criteria $\left(\omega_1^*, \ldots, \omega_j^*, \ldots, \omega_J^*\right)$ are determined according to Eq. (3):

$$min \max_j \left\{ \left| \frac{\omega_B}{\omega_j} - a_{Bj} \right|, \left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \right\} \tag{3}$$

S. t. (Eq. (4)):

$$\sum_{j=1}^{J} \omega_j = 1 \ \wedge \ \omega_j \geq 0, j = 1, .., J \tag{4}$$

Through the transformation of the presented model into a linear programming model, the following constraints are obtained:

The objective function, Eq. (5):

$$\min \xi \tag{5}$$

S. t. (Eq. (6, 7 and 8)):

$$\left| \frac{\omega_B}{\omega_j} - a_{Bj} \right| \leq \xi, \ j = 1, \dots, J \tag{6}$$

$$\left| \frac{\omega_j}{\omega_W} - a_{jW} \right| \leq \xi, \ j = 1, \dots, J \tag{7}$$

$$\sum_{j=1}^{J} \omega_j = 1 \ \wedge \ \omega_j \geq 0, j = 1, .., J \tag{8}$$

Step 7. By solving the formulated linear programming problem, the weights of the criteria at the level of each decision maker, $e, e = 1, \dots, E$, are determined according to Eq. (9):

$$\left(\omega_1^e, \dots, \omega_j^e, \dots, \omega_J^e\right) \tag{9}$$

Consistency is checked according to the procedure developed in the standard BWM method.

Step 8. The aggregated criteria weights are determined by applying the arithmetic mean operator and equation Eq. (10):

$$\omega_j = \frac{1}{E} \cdot \sum_{e=1,\dots,E} \omega_j^e \ , \ j = 1, .., J \tag{10}$$

Where the aggregated value of the criteria weights can be formally expressed with Eq. (11):

$$\left(\omega_1, \dots, \omega_j, \dots, \omega_J\right) \tag{11}$$

In the second phase of applying the proposed model, for ranking the considered devices, the RADAR, or rather RADAR II method, was used. The application steps are as follows [8]:

Step 1. Based on the available data, the value of the considered alternatives was determined for each criterion, and a decision-making matrix was formed according to Eq. (12):

$$\left[M_{ij}\right]_{I \times J} \tag{12}$$

Step 2. The maximum proportion matrix, α, according to Eq. (13):

$$\left[a_{ij}\right]_{I \times J} \tag{13}$$

For the benefit type of criteria according to Eq. (14):

$$a_{ij} = \frac{\frac{\max\limits_i M_{ij}}{M_{ij}}}{\left(\left(\frac{\max\limits_i M_{ij}}{M_{ij}}\right) + \left(\frac{M_{ij}}{\min\limits_i M_{ij}}\right)\right)} \tag{14}$$

For the cost type of criteria according to Eq. (15):

$$\alpha_{ij} = \frac{\frac{M_{ij}}{\min\limits_i M_{ij}}}{\left(\left(\frac{\max\limits_i M_{ij}}{M_{ij}}\right) + \left(\frac{M_{ij}}{\min\limits_i M_{ij}}\right)\right)} \tag{15}$$

In this study, a modification of the RADAR method was introduced, which pertains to steps 2 and 3. Therefore, the maximum proportion matrix, α, for the RADAR II method is calculated as follows:

For the benefit type of criteria according to Eq. (16):

$$a_{ij} = \frac{\max\limits_i M_{ij} - M_{ij}}{\left(\left(\max\limits_i M_{ij} - M_{ij}\right) + \left(M_{ij} - \min\limits_i M_{ij}\right)\right)} \tag{16}$$

For the cost type of criteria according to Eq. (17):

$$\alpha_{ij} = \frac{M_{ij} - \min_i M_{ij}}{\left(\left(\max_i M_{ij} - M_{ij}\right) + \left(M_{ij} - \min_i M_{ij}\right)\right)} \tag{17}$$

In this case, the difference between the considered alternatives is calculated rather than the ratio. In doing so, one of the main characteristics of the RADAR method is excluded. Namely, reducing the influence of dominant alternatives for a given criterion and pursuing stability of the alternative across all criteria. This phenomenon will be explained through a case study and a comparison of the results. Therefore, such a modification may be called the RADAR II method.

Step 3. The minimum proportion matrix, β, Eq. (18):

$$\left[\beta_{ij}\right]_{I\times J} \tag{18}$$

To avoid unnecessary repetition of patterns (see [8]), it is necessary to emphasize the following rule:

- β_{ij} for benefit-type criteria is computed as α_{ij} for cost-type criteria, and
- β_{ij} for cost-type criteria is computed as α_{ij} for benefit-type criteria.

The same applies to the procedure in the RADAR II modification. Furthermore, the procedure remains the same in both the RADAR and RADAR II methods.

Step 4. The empty range matrix according to Eq. (19):

$$\left[E_{ij}\right]_{I\times J} \tag{19}$$

where, Eq. (20):

$$E_{ij} = \left|\alpha_{ij} - \beta_{ij}\right| \tag{20}$$

Step 5. The relative relationship matrix according to Eq. (21):

$$\left[RR_{ij}\right]_{I\times J} \tag{21}$$

where: Eq. (22):

$$RR_{ij} = \frac{\alpha_{ij}}{\beta_{ij} + E_{ij}} \tag{22}$$

Step 6. The weighted relative relationship matrix according to Eq. (23):

$$\left[WRR_{ij}\right]_{I\times J} \tag{23}$$

where, Eq. (24):

$$WRR_{ij} = RR_{ij} \cdot \omega_j \tag{24}$$

Step 7. The aggregated ranking index, RI_i according to Eq. (25):

$$RI_i = \frac{\min \sum_{j=1}^{J} WRR_i}{\sum_{j=1}^{J} WRR_i} \tag{25}$$

The highest value of the coefficient RI_i (always equal to 1) indicates that the alternative is ranked first. The lowest value of RI_i indicates the alternative that is ranked last.

In the third phase, the results obtained by applying the RADAR and RADAR II methods are compared with those obtained using the TOPSIS, COPRAS, VIKOR, SAW, ARAS, and EDAS methods. The basic versions of these methods were applied, where linear normalization was used, and the weighting of the values from the normalized decision matrix was performed by multiplying by the weighting coefficients of the criteria.

4. Case Study

4.1 Problem Description

Many operations in the production and assembly of components in the automotive industry are automated, primarily to reduce operation execution time (i.e., decrease takt time) and to ease the workload for operators. One such instance involves the device for automatically adjusting the automobile's parking brake cable. In collaboration with maintenance engineers from the company, an OEM in the automotive supply chain, an analysis of the solutions offered by potential suppliers was conducted.

This chapter presents the procedure for selecting the best device for the automatic adjustment and control of an automobile's parking brake cable. The primary function of the device is to automatically tighten the brake cable while monitoring its tension/elongation. In doing so, the process is automated, and the possibility of failures due to human factors is eliminated. In this procedure, the operator's task is solely to install the device in the vehicle, wait for it to complete the specified operation, and then prepare the device for use in the next vehicle on the production line.

Figure 2a shows the device configured for use. The accuracy check of the device, i.e., the quality control of the performed operation, is carried out using a dynamometer. The force required to position the handbrake (to a specific notch) serves as an indicator for controlling the quality of the operation. A deviation from the threshold values indicates that the device is not properly calibrated or that recalibration is necessary. The control procedure is illustrated in Figure 2b.


(a) (b)

Fig. 2. Device configured for use (a) and control of the performed operation (b)

In the case that the device does not operate properly, the process of tightening the brake cable is performed manually, which significantly slows down this process and, consequently, the entire production line. A vehicle delivered from the production line that fails to meet all safety tests, including the proper functioning and performance of the braking system, is not considered ready for shipment to the customer. Typically, such a vehicle is returned for additional inspection and rework.

In the production process at the company under consideration, it is sufficient to have just one such device. The design, that is, the shape and dimensions of the device, depends on the specific model of the car in which it is used. Therefore, it can be said that the manufacturer produces the device based on customer requirements. In this case, the company was offered five variants of the device, i.e., five technical solutions. It is important to note that a new device is purchased if the existing device does not comply with the vehicle's requirements, which most often occurs when modifications in the vehicle design are implemented or when a new model is introduced into production.

The devices under consideration were analysed and evaluated based on four criteria, which are further explained:

i. Device operating speed ($k = 1$): Represents the time required for the device to complete the operation. The shorter the execution time, the more time is available for the operator to perform the setup and removal of the device from the vehicle.
ii. Price ($k = 2$): The price of the device depends on its key characteristics, manufacturing complexity, and the materials used. Since the device is custom-made/modified for each car model, additional costs related to the design and testing of the new device are incorporated into the selling price. Moreover, the device's price includes a one-year maintenance and calibration cost.
iii. Device weight ($k = 3$): A fundamentally important criterion from the perspective of handling the device. It is more convenient for the operator if the device has a lower weight, so that executing the operation requires less effort. The device weight is calculated including the weight of the entire structure (holder).
iv. Calibration/inspection period ($k = 4$): The manufacturer guarantees that the device can perform a certain number of operations without supervision or additional adjustments. The device's setup/calibration process can take longer than a single work shift (sometimes even more) and requires the engagement of an authorized service technician (usually from the manufacturer).

The fourth criterion is of the benefit type, while the other criteria are of the cost (non-benefit) type. In other words, a higher value for the alternative is desirable for the fourth criterion, whereas for the other criteria it is preferable for the alternative's value to be as low as possible.

4.2 Determining Criteria Weights Using the BWM Method

In the first phase of the proposed algorithm, the weights of the considered criteria are determined. In the first step of this phase, the criteria are defined by the maintenance department of the enterprise under consideration: device operating speed ($k = 1$), price ($k = 2$), device weight ($k = 3$) and calibration/inspection period ($k = 4$). Subsequently, the best and worst criteria are identified (step 2 and step 4 of the proposed algorithm) at the level of each decision maker.

To determine the weights of the considered criteria using the BWM method, it is first necessary for each decision maker to compare the best criterion with all the others (step 3) and, correspondingly, all the other criteria with the worst criterion (step 5). In this case, the decision makers who assess the relative importance of the criteria are the professional maintenance manager ($e = 1$), the professional maintenance specialist ($e = 2$) and the device operator ($e = 3$). It is assumed that all three decision makers have equal importance in the decision-making process. The following are the assessments provided by the decision makers:

$$A_B^1 = (2, 5, 8, 1) \qquad A_W^1 = (5, 4, 1, 7)^T$$
$$A_B^2 = (1, 5, 8, 3) \qquad A_W^2 = (9, 3, 1, 6)^T$$
$$A_B^3 = (2, 9, 1, 7) \qquad A_W^3 = (6, 1, 8, 3)^T$$

By applying the basic BWM, the weights of the criteria at the level of each decision maker were calculated (step 6 and step 7 of the proposed algorithm):

$$e = 1 \qquad\qquad e = 2 \qquad\qquad e = 3$$
$$(0.31, 0.12, 0.06, 0.51) \qquad (0.57, 0.14, 0.06, 0.23) \qquad (0.31, 0.06, 0.54, 0.09)$$

aggregated criterion weights, obtained by applying the arithmetic mean operator, are:

$\omega_1 = 0.39$ $\omega_2 = 0.11$ $\omega_3 = 0.22$ $\omega_4 = 0.28$

It can be concluded that, based on the application of the BWM method, the most important criterion is the device's operating speed $(k = 1)$, while the least important is the price $(k = 2)$. This is indeed clear in this case, as the price of the device (including design modifications, calibration, and maintenance) does not objectively represent a significant cost for the company. On the other hand, the device's operating speed is very significant, as it can affect the production line's takt time and/or overall operating speed, and consequently, the operator's workload.

4.3 Ranking Devices Using the RADAR and RADAR II Methods

In the first step of the proposed algorithm, a decision matrix is formed (Table 1). In this case, the data were obtained from the company.

Table 1
The decision matrix

	$k = 1$ Device operating speed (s)	$k = 2$ Price (€)	$k = 3$ Device weight (kg)	$k = 4$ Calibration/inspection period (expected number of operations · 10^3)
$i = 1$	115	7500	8	205
$i = 2$	110	9500	6.5	340
$i = 3$	90	12900	7	470
$i = 4$	80	10100	6.5	350
$i = 5$	100	8800	10.5	255

By applying steps 2 and 3, the maximum and minimum proportion matrices, α and β, respectively, are determined (Tables 2 and 3).

Table 2
The maximum proportion matrix for RADAR

	$k = 1$	$k = 2$	$k = 3$	$k = 4$
$i = 1$	0.590	0.368	0.484	0.696
$i = 2$	0.568	0.483	0.382	0.455
$i = 3$	0.468	0.632	0.418	0.304
$i = 4$	0.410	0.513	0.382	0.440
$i = 5$	0.521	0.445	0.618	0.597

Table 3
The minimum proportion matrix for RADAR

	$k = 1$	$k = 2$	$k = 3$	$k = 4$
$i = 1$	0.410	0.632	0.516	0.304
$i = 2$	0.432	0.517	0.618	0.545
$i = 3$	0.532	0.368	0.582	0.696
$i = 4$	0.590	0.487	0.618	0.560
$i = 5$	0.479	0.555	0.382	0.403

Also, according to the aforementioned steps of the proposed algorithm, the maximum and minimum proportion matrices, α and β, for the RADAR II method are calculated (Tables 4 and 5).

Table 4
The minimum proportion matrix for RADAR II

	$k=1$	$k=2$	$k=3$	$k=4$
$i=1$	1	0	0.375	1
$i=2$	0.857	0.370	0	0.491
$i=3$	0.286	1	0.125	0
$i=4$	0	0.481	0	0.453
$i=5$	0.571	0.241	1	0.811

Table 5
The minimum proportion matrix for RADAR II

	$k=1$	$k=2$	$k=3$	$k=4$
$i=1$	0	1	0.625	0
$i=2$	0.143	0.630	1	0.509
$i=3$	0.714	0	0.875	1
$i=4$	1	0.519	1	0.547
$i=5$	0.429	0.759	0.000	0.189

In both cases, i.e., with the RADAR and RADAR II methods, the condition: $\alpha_{ij} + \beta_{ij} = 1$.

According to step 4 of the proposed algorithm, an empty range matrix was formed, as shown in Table 6 for RADAR and Table 7 for the RADAR II method.

Table 6
The empty range matrix for RADAR

	$k=1$	$k=2$	$k=3$	$k=4$
$i=1$	0.179	0.265	0.032	0.393
$i=2$	0.136	0.035	0.235	0.091
$i=3$	0.064	0.265	0.164	0.393
$i=4$	0.179	0.026	0.235	0.119
$i=5$	0.042	0.111	0.235	0.194

Table 7
The empty range matrix for RADAR II

	$k=1$	$k=2$	$k=3$	$k=4$
$i=1$	1	1	0.250	1
$i=2$	0.714	0.259	1	0.019
$i=3$	0.429	1	0.750	1
$i=4$	1	0.037	1	0.094
$i=5$	0.143	0.519	1	0.623

By applying step 5 of the proposed algorithm, the relative relationship matrix was determined, and then in step 6 these values were weighted to obtain the weighted relative relationship matrix (Table 8 for RADAR and Table 9 for the RADAR II method).

Table 8
The weighted relative relationship matrix for RADAR

	$k = 1$	$k = 2$	$k = 3$	$k = 4$
$i = 1$	0.390	0.045	0.194	0.280
$i = 2$	0.390	0.096	0.099	0.200
$i = 3$	0.307	0.110	0.123	0.078
$i = 4$	0.208	0.110	0.099	0.181
$i = 5$	0.390	0.073	0.220	0.280

Table 9
The weighted relative relationship matrix for RADAR II

	$k = 1$	$k = 2$	$k = 3$	$k = 4$
$i = 1$	0.390	0	0.094	0.280
$i = 2$	0.390	0.046	0	0.260
$i = 3$	0.098	0.110	0.017	0
$i = 4$	0	0.095	0	0.198
$i = 5$	0.390	0.021	0.220	0.280

According to step 7 of the proposed algorithm, the aggregated ranking index was determined and the ranking of alternatives was carried out by applying the RADAR and RADAR II methods (Table 10).

Table 10
The aggregated ranking index and rang of alternatives

	RADAR		RADAR II	
	RI	Rank	RI	Rank
$i = 1$	0,658	4	0,294	4
$i = 2$	0,762	3	0,323	3
$i = 3$	0,968	2	1,000	1
$i = 4$	1,000	1	0,766	2
$i = 5$	0,621	5	0,246	5

In the following section, a sensitivity analysis of the obtained results was performed by comparing them with other MADM methods. Additionally, a comparative analysis of the application of the RADAR and RADAR II methods was carried out.

4.4 Comparative Analysis of the Results Obtained Using the RADAR and RADAR II Methods

As can be seen from Table 10, the modification of the RADAR method in the second and third steps of the proposed algorithm resulted in certain changes in the ranking of the alternatives. Since the ratio (quotient) of an alternative relative to the best/worst according to a given criterion was replaced by its difference, the characteristics of the method changed, and consequently, the ranking of the alternatives was affected.

In both cases, alternatives $i = 1$, $i = 2$, and $i = 5$ retained the same positions in the ranking. However, a difference in ranking is observed between alternatives $i = 3$ and $i = 4$. In the case of the RADAR method, $i = 4$ is ranked first, while $i = 3$ is ranked second. In the RADAR II method, the situation is reversed.

The differences in ranking between the RADAR and RADAR II methods actually stem from the different ways of normalizing the values:

i. RADAR method: It uses normalization based on the ratios (proportions) between the maximum and minimum values for each criterion. This approach reduces the impact of dominant alternatives for a given criterion and favors alternatives that are stable with respect to each individual criterion.
ii. RADAR II method: It uses normalization based on the differences between the maximum and minimum values for each criterion. This approach can increase the influence of alternatives that have extreme values for a given criterion, which may lead to a different ranking.

In this particular case, it can be observed that alternative $i = 3$ has an exceptionally high value for criterion $k = 4$, which led to its improved ranking in the RADAR II method. On the other hand, alternative $i = 4$ is the best according to the most important criterion $k = 1$, is ranked fourth according to the least important criterion $k = 2$, is tied for first in criterion $k = 3$, and is ranked second in criterion $k = 4$.

Alternative $i = 3$ is ranked second for the first (most important) criterion, last for the second (least important) criterion, and third for the third criterion, while it is ranked first for the fourth criterion. This clearly indicates that the extremely high value of alternative $i = 3$ for criterion $k = 4$ has significantly contributed to its being ranked first when using the RADAR II method. To clarify the comparison, the rankings of alternatives $i = 3$ and $i = 4$ for each criterion individually are graphically presented (Figure 3).

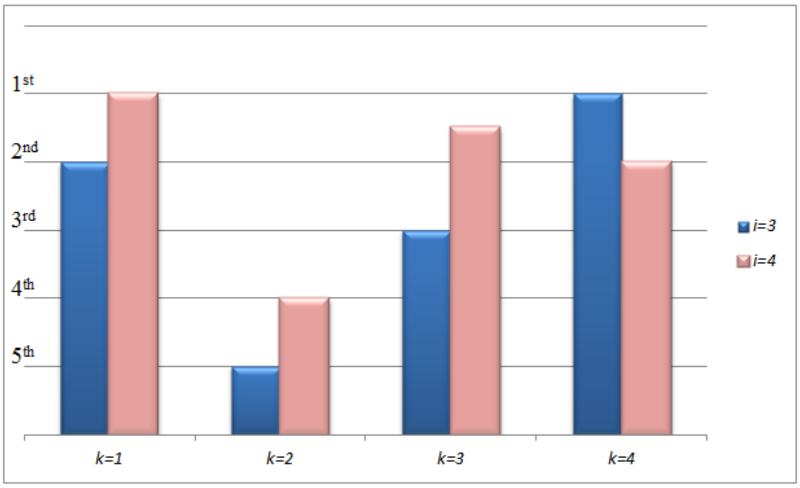

Fig. 3. Comparison of the rankings of the two best alternatives according to the RADAR and RADAR II methods

Mathematically speaking, the transition from ratio-based normalization to difference-based normalization significantly alters the dynamics of alternative evaluation. While the original RADAR method uses ratios (quotients) that mitigate the impact of extreme values, thus favoring alternatives with consistent performance, the RADAR II method directly considers the absolute differences between the best and worst values for each criterion, thereby amplifying the influence of extreme values of alternatives on a given criterion. This transformation results in alternative $i = 3$, which achieves the maximum value on criterion $k = 4$, gaining significantly greater importance in the final index, while alternative $i = 4$, which has the highest value for the most important criterion $k = 1$ (and is better according to the other two criteria), is moved to second place.

5. Comparative and Sensitivity Analysis of RADAR and other MADM methods

As already stated in the previous part of the paper, the comparison of the results obtained using the RADAR and RADAR II methods in this chapter was carried out with the results obtained using the TOPSIS, COPRAS, VIKOR, SAW, ARAS, and EDAS methods. For all methods, linear normalization was used, and the weighting of the normalized values was performed by multiplying them with the criterion weights. In addition, it is important to note that for the VIKOR method, the ranking coefficient was chosen as $v = 1$, which means that when ranking the alternatives, priority is given to maximizing the collective perception of performance, i.e., the overall utility.

This comparison was conducted to ensure that the results obtained using the RADAR and RADAR II methods can be compared with a wide range of MADM techniques, thereby confirming the reliability and robustness of these methods in various decision-making scenarios.

The use of the same procedure for linear normalization and the weighting of values by multiplying the normalized values with the criterion weights for all methods allows for a fair and consistent comparison. With this approach, the aim is to identify similarities and differences in the ranking of alternatives, thus providing deeper insight into the advantages and limitations of the RADAR and RADAR II methods. Table 11 presents the ranking of alternatives obtained using various MADM methods.

Table 11
Ranking of alternatives using the RADAR, RADAR II, TOPSIS, COPRAS, VIKOR, SAW, ARAS, and EDAS methods

	RADAR	RADAR II	TOPSIS	COPRAS	VIKOR	SAW	ARAS	EDAS
$i = 1$	4	4	5	5	4	5	5	4
$i = 2$	3	3	3	3	3	3	3	2
$i = 3$	2	1	1	1-2	2	1	1	3
$i = 4$	1	2	2	1-2	1	2	2	1
$i = 5$	5	5	4	4	5	4	4	5

In order for the ranking of alternatives obtained using various methods to be better visualized and more easily compared, Figure 4 presents a graphical representation of the ranking of each alternative according to each method used.

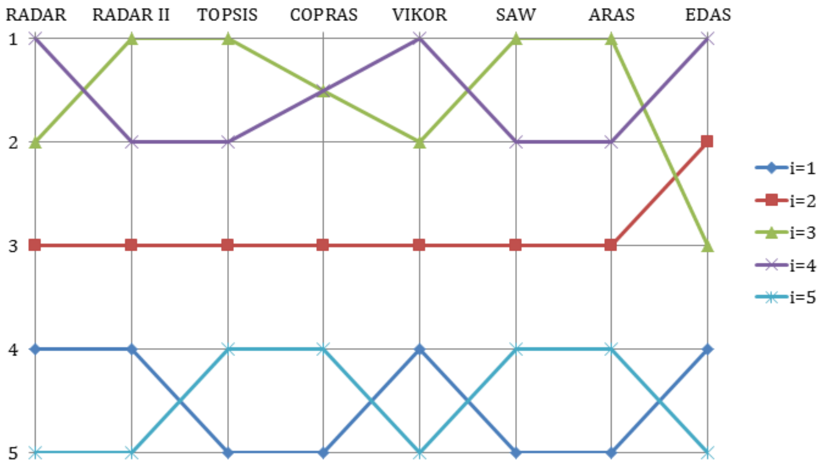

Fig. 4. Graphical representation of the ranking of the considered alternatives according to various MADM methods

The analysis of the obtained results indicates a significant degree of consistency among the different MADM methods, although there are minor variations in the ranking of individual alternatives. For example, alternatives $i = 3$ and $i = 4$ clearly stand out as the best options. RADAR, VIKOR, and EDAS favor alternative $i = 4$, while RADAR II, TOPSIS, SAW, and ARAS give preference to alternative $i = 3$. It is also interesting that the COPRAS method positions these two alternatives tied for first place, which indicates that there is very little difference between the considered alternatives and that their ranking depends on the inherent characteristics of the chosen method.

The most stable ranking, when considering all methods, is that of alternative $i = 2$, which occupies a middle position in all methods (third place), except in the EDAS method where it leaps to second place in the ranking. Alternatives $i = 1$ and $i = 5$ alternate between fourth and fifth place in the ranking, depending on the method.

The minor variations in ranking, particularly between $i = 3$ and $i = 4$, indicate that regardless of the method applied, there are clear indications of the superiority of certain alternatives, thereby confirming the robustness of the analysis. Additionally, the ranking of the other alternatives does not deviate significantly, except in the case of the EDAS method, which ranks alternative $i = 3$ in third place and the aforementioned alternative $i = 2$ in second place.

In addition to the graphical approach, the comparative analysis can also be performed in a mathematically based manner. Sałabun and Urbaniak [32] developed a methodology for comparing the ranking of alternatives obtained using different methods. This is certainly an effective way to conduct sensitivity analysis. In this case, a comparison was made between the ranking of alternatives obtained by applying the RADAR method and the ranking of alternatives obtained by applying the other methods. The same procedure was carried out for the RADAR II method. In Table 12, the WS coefficient [32], which determines the degree of similarity between the rankings obtained by applying RADAR and the other methods, is presented. The same was done for the RADAR II method.

Table 12
Comparison of rankings using the WS coefficient

	RADAR	RADAR II	TOPSIS	COPRAS	VIKOR	SAW	ARAS	EDAS
WS coeff.		0.792	0.763	0.867	1	0.763	0.763	0.854
WS coeff.	0.792		0.971	0.867	0.792	0.971	0.971	0.604

Based on [32], if the WS coefficient is below 0.234, the rankings are considered completely dissimilar. When the WS coefficient lies between 0.352 and 0.689, there is some degree of similarity, although the correlation is not particularly strong. Conversely, if the coefficient exceeds 0.808, the similarity among the rankings is considered complete. All values between these limits belong to the “gray” or indeterminate zone.

In the case of the RADAR method, there is an absolute correlation in ranking with the VIKOR method (100% overlap), while an absolutely high degree of similarity is achieved with the COPRAS and EDAS methods. With all the other methods, the similarity in ranking is moderate to high (within the indeterminate zone).

Regarding the RADAR II method, there is no absolute overlap with any other method in terms of alternative ranking. However, with the TOPSIS, COPRAS, SAW, and ARAS methods, there is an absolutely high correlation in ranking, while with all the others, except for EDAS, the correlation is between moderate and high. With the EDAS method, there is a certain degree of similarity, but the correlation is not sufficiently high.

It should be emphasized that this analysis was conducted for the case study under consideration and is only valid for it. The results may vary significantly depending on the number of criteria, the criterion weights, the normalization procedure, the method of weighting the values, the chosen methods, the type of problem under consideration, and many other factors.

6. Conclusions

Based on the presented research and the obtained results, it has undoubtedly been demonstrated that both the RADAR and RADAR II methods are reliable techniques for multi-attribute decision making, as the results of their application, when compared with other MADM methods, show a high degree of similarity, thereby confirming the robustness of these approaches. The original RADAR method, which employs ratio-based normalization, is recommended in situations where ranking stability and minimizing the influence of extreme values are important, while the modified RADAR II method, relying on the difference between values, has proven more useful in identifying alternatives that achieve exceptionally good performance on individual criteria. Therefore, the choice of method should be aligned with the specifics of the problem: if the goal is to ensure consistency and balanced evaluation, priority should be given to the original RADAR approach, whereas the RADAR II method can be used when highlighting the superiority of certain alternatives is paramount. Both approaches, whether considered individually or in comparative analysis, demonstrate their validity and applicability.

In this specific case, the solution obtained using the RADAR method (as well as VIKOR and EDAS, and partially COPRAS) was ultimately selected by the decision makers in the company under consideration, with the key factors in the decision-making process being the criteria related to the long-term stability of the solution and its adaptability to operational requirements. Although other methods yielded similar results, it was the balanced evaluation provided by the RADAR method that was recognized as the most suitable for the company’s needs.

However, it is important to emphasize that such an outcome is specific to the analyzed problem and cannot be generalized as the superiority of one method over any other. Each MADM method has its own advantages and limitations, and its effectiveness depends on the context of its application and the criteria that are crucial for decision making. Therefore, although quantitative methods such as the RADAR and RADAR II approaches provide objective and structured data that facilitate the decision-making process, they cannot fully replace the human factor. The final decision remains in the hands of the decision makers, who, with the support of analytical methods, assess the relevant factors and make a decision in line with the company's objectives.

One of the potential drawbacks of the basic RADAR method is its tendency to favor alternatives with more stable values across all criteria, which may lead to the neglect of solutions that achieve exceptional performance in certain key aspects. On the other hand, the modified RADAR II method, although more effective in identifying alternatives with pronounced advantages in certain criteria, may increase the variability of the rankings in cases where the data are subject to larger fluctuations or when there is significant uncertainty in the evaluation of the criteria.

Future research directions may include broader applications of the RADAR and RADAR II methods in various industrial fields as well as in other economic sectors. Moreover, the application of fuzzy logic could help reduce the uncertainty and subjectivity that may potentially arise in the evaluation of the criteria, thereby improving the accuracy and reliability of the alternative rankings. Additionally, the integration of RADAR methods with other quantitative and qualitative decision-making approaches and other MADM methods should be considered.

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Data Availability Statement

Data are available based on the request to the author.

Conflicts of Interest

The author declares no conflicts of interest.

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