Lecture Notes in Operations Research

Jafar Rezaei · Matteo Brunelli · Majid Mohammadi *Editors*

Advances in Best-Worst Method

Proceedings of the Fourth International Workshop on Best-Worst Method (BWM2023)

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Preface

This book contains the proceedings of BWM2023, The Fourth International Workshop on Best-Worst Method. The workshop, hosted by the Delft University of Technology, was organized hybrid on 2 days, 8 and 9 June 2023. BWM2023 aims to bring together researchers working on theoretical, methodological, and application studies on the Best-Worst Method, a multi-criteria decision-making method that was developed in 2015 and that since then has gained a lot of attention among researchers and practitioners from many different fields. Researchers can share their latest findings with their peers and discuss avenues for future research. Four lectures were given on the foundations of BWM on the morning of the first day, and 15 high-quality papers were accepted for presentation, which were presented in 8 sessions in 2 days chaired by experts on different areas, including supply chain management, health, energy, manufacturing and entrepreneurship as well as methodological advancement. This book contains 13 full papers. The first five papers are methodological contributions followed by nine papers on applications of the BWM in different fields.

We are very grateful to the authors for submitting their work and for having interactive discussions during the workshop. We also express our gratitude to the members of the scientific committee for reviewing the full papers. All papers were reviewed by at least two members of the scientific committee using a single-blind peer review process, and we did not use external reviewers. Reviewers evaluated the papers based on relevance, originality, rigor of the data collection and analysis, and presentation of the study.

We are also grateful to the Delft University of Technology for providing the infrastructure and to Springer for publishing the proceedings.

Delft, The Netherlands — Jafar Rezaei
Trento, Italy — Matteo Brunelli
Amsterdam, The Netherlands — Majid Mohammadi
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Chapter 1
Probabilistic Group Decision-Making Using BWT

Majid Mohammadi, Fuqi Liang, Matteo Brunelli, and Jafar Rezaei

Abstract In this study, we propose a probabilistic group decision-making method based on the Best-Worst Tradeoff method (BWT) and the Bayesian approach. BWT is a pairwise comparison method that is used to elicit the tradeoffs among a set of attributes (criteria) in a multi-criteria decision-making problem. While BWT is suitable for a single decision-maker situation, Bayesian BWT is suitable for aggregating the tradeoffs among a number of criteria coming from a number of decision-makers or experts. The proposed method aggregates the scaling constants (weights), and assigns a confidence number (between zero and one), to inform about the confidence we have about the ranking order of the criteria. We demonstrate how the method is used in a real-world setting. Data is collected from three experts on ranking a number of European seaports that are performing differently with respect to a number of relevant criteria. We think that the method has great potential in real-world group decision-making problems.

Keywords Best-Worst method · Best-Worst Tradeoff · Tradeoff procedure · Multi-attribute Value Theory (MAVT) · Bayesian · Group decision-making

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Introduction

Nowadays, an increasing number of decisions are made in complex contexts across various application domains, calling for mathematically sound methodologies in decision analysis. Multi-criteria decision analysis (MCDA), also known as multi-criteria decision-making (MCDM), encompasses a range of methodologies that excel in handling problems involving multiple and often conflicting objectives [12]. These methodologies share a common thread of representing the value of each alternative as a function of how well it satisfies a set of attributes or criteria, where each attribute approximates the achievement level of a specific objective.

In this study, we start with one of the most recently devised methods for eliciting preferences: The Best-Worst Tradeoff method (BWT) [7]. It combines the strengths of the Best-Worst Method (BWM) [10] and the Tradeoff procedure while maintaining their key features. It facilitates structured weight elicitation using the prescriptive Multi-Attribute Value Theory (MAVT) approach, accounting for attribute range effects, and ensures consistent preference assessments. The BWT method improves preference elicitation, conforms to MAVT theory, and avoids ratio scales for pairwise comparisons, mitigating personal interpretations. Additionally, it addresses biases such as anchoring bias and loss aversion bias by incorporating the consider-the-opposite strategy.

Despite the advantages of BWT, its process does not inherently account for the views of multiple decision-makers or provide a mechanism for aggregating multiple perspectives. For the BWT method to be used in a group decision-making context, it would likely need to be adapted or extended to handle the aggregation of judgments from multiple decision-makers.

The existing limitation in the Best-Worst Tradeoff (BWT) method, is its focus on single decision-maker scenarios, which creates a gap in group decision-making contexts where multiple preferences must be harmonized. Furthermore, the BWT method does not inherently consider uncertainty and variability in expert judgments, aspects often present in group decision-making.

To address this, we propose a Bayesian Best-Worst Tradeoff method (BBWT), which aims to integrate the Bayesian approach from the Bayesian Best-Worst Method, enabling probabilistic group decision-making and accommodating diverse preference uncertainty, with the consistency-checking framework of the BWT method to ensure rational and reliable criteria weighting. Consequently, the BBWT method could offer a comprehensive, flexible, and robust tool for complex decision-making scenarios involving multiple decision-makers and varied preferences, enhancing the reliability and quality of group decision outcomes.

Multi-attribute Value Theory

The basic assumption of MAVT is that each alternative can be characterized by a list of its relevant attributes. Assuming the existence of n attributes, then a generic alternative can be described by a list $\mathbf{x} = (x_1, \ldots, x_n) \in X_1 \times \cdots \times X_n$, where X_i is the space of variation of the ith attribute. It is useful to denote with $\underline{x}_i$ and $\overline{x}_i$ the worst and best levels of the ith attribute, respectively.

In this setting, MAVT is concerned with the definition of functions $V : X_1 \times \cdots \times X_n \to \mathbb{R}$ which can be representative of the preferences of a decision maker. That is, given a set $X \subseteq X_1 \times \cdots \times X_n$ of alternatives and a preference relation $\succsim$ on X, then a *value function* V is representative of $\succsim$ if

$$V(\mathbf{x}) \geq V(\mathbf{y}) \;\Rightarrow\; \mathbf{x} \succsim \mathbf{y} \;\; \forall \mathbf{x}, \mathbf{y} \in X.$$

A number of theoretical results from the literature are useful to restrict the set of compatible value function. Under mild conditions (preference independence), there always exists attribute value functions $v_i : X_i \to [0, 1]$ and scaling constants (also called weights) w_i such that

$$V(\mathbf{x}) = \sum_{i=1}^{n} w_i v_i(x_i)$$

with $w_i \geq 0 \; \forall i$ and $w_1 + \cdots + w_n = 1$. A value function in this form is called *additive*. Roughly speaking, the value of alternative $\mathbf{x}$ is a weighted sum of the contributions of its attributes. There exists many techniques to estimate the attribute value functions v_i and most of them are based on the identification of few points of the function followed by an interpolation/regression. Similarly, methods have been developed to aid the estimation of the weights. The best known of them is probably the tradeoff method.

Trade-Off Method

The trade-off method [6] consists in asking simple questions, in the form of tradeoffs between attribute levels, to a decision maker. Interestingly, values of weights w_i are never asked directly to the decision maker, but are deduced at the end of the process. Let us consider an example with two possible alternatives $\mathbf{x} = (x_1, x_2, x_3, x_4)$ and $\mathbf{y} = (y_1, y_2, y_3, y_4')$ where y_4' is unknown. If we assume the use of an additive value function and $x_1 = y_1$ and $x_3 = y_3$, then the two alternatives are equivalent, which can be written $\mathbf{x} \sim \mathbf{y}$, if and only if $w_2 v_2(x_2) + w_4 v_4(x_4) = w_2 v_2(y_2) + w_4 v_4(y_4')$, which can be rearranged into $w_2(v_2(x_2) - v_2(y_2)) = w_4(v_4(x_4) - v_4(y_4'))$. In this case, the question to be asked to the DM is what value of y_4' makes the two alternatives indifferent. If we call such value y_4, then we also know the value of the ratio between weights, i.e.

$$\frac{w_2}{w_4} = \frac{v_4(x_4) - v_4(y_4)}{v_2(x_2) - v_2(y_2)}$$

Let us note that answering $(n-1)$ properly chosen questions like the one exemplified above may be sufficient. They can be arranged into a system of equations, with the normalization constraints and a unique solutions shall be found. Nevertheless, it seems safe to ask more than the minimum number of questions [1].

Best-Worst Trade-off

The goal of BWT is to merge the advantageous aspects of both the traditional BWM and the Tradeoff procedure while retaining the defining characteristics that have made these methods popular. With BWT, we can obtain weights in a more organized manner by employing the prescriptive MAVT approach, which takes into account the attribute range effect. Additionally, BWT offers a guided selection of attributes to be compared, ensuring consistency of preferences. The initial steps of the BWT method are as follows:

Step 1. Identification of alternatives and attributes

We begin by assuming that the DM has established a set of m alternatives, denoted as $A = \{A_1, A_2, \ldots, A_m\}$, and a set of n attributes, denoted as $C = \{C_1, C_2, \ldots, C_n\}$. Furthermore, compatibly with MAVT, each alternative is associated with a consequence vector $\mathbf{x} = (x_1, x_2, \ldots, x_n)$.

Step 2. Determination of value function for each attribute

To determine the value function for each attribute, various methods can be employed, such as those discussed in Refs. [2–5]. Among these methods, one commonly used approach is the mid-value splitting technique introduced by Keeney and Raiffa [5].

Step 3. Identification of best and worst attributes

In this step, the DM selects the "best" attribute C_B and the "worst" attribute C_W. These attributes serve as reference points for comparison, minimizing anchoring bias. The DM ranks n created hypothetical consequences $\mathbf{x}^j$, $j = 1, 2, \ldots, n$, representing the best performance of jth attribute while considering the worst performance of other attributes. Comparing and ranking these hypothetical consequences helps identify C_B and C_W.

Step 4. Comparison of best to others tradeoff

To compare the best attribute C_B with other attributes, we introduce two auxiliary consequences: $\mathbf{x}^{B,k}$ and $\mathbf{x}^k$. In $\mathbf{x}^{B,k}$, all attributes, except for attribute C_B, are set to their lowest levels $(v_j(x_j) = 0)$, while the level of the best attribute remains undetermined. The meaning of $\mathbf{x}^k$ can be seen in Step 3. We seek to find the satisfaction level of C_B in $\mathbf{x}^{B,k}$ that makes $\mathbf{x}^{B,k}$ and $\mathbf{x}^k$ equally desirable. That is,

$$\overbrace{\left(\underline{x}_1, \ldots, x_B^{B,k}, \ldots, \underline{x}_n\right)}^{\mathbf{x}^{B,k}} \sim \overbrace{\left(\underline{x}_1, \ldots, \overline{x}_k, \ldots, \underline{x}_n\right)}^{\mathbf{x}^k} \Leftrightarrow V\left(\mathbf{x}^{B,k}\right) = V\left(\mathbf{x}^k\right). \tag{1.1}$$

Assuming the use of an additive value function, the indifference relation (1.1) can be simplified into:

$$w_B v_B\left(x_B^{B,k}\right) = w_k. \tag{1.2}$$

We can use a_{Bk} to represent (1.2):

$$a_{Bk} = \frac{w_B}{w_k} = \frac{1}{v_B\left(x_B^{B,k}\right)}. \tag{1.3}$$

Then we use $A_{BO} = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ to indicate the Best-to-Others vector.

Step 5. Comparison of others to worst attribute tradeoff

Similarly, the DM can apply the same procedure to compare each attribute C_k ($C_k \neq C_W$) to the worst attribute C_W. This involves using two auxiliary consequences: $\mathbf{x}^W$ and $\mathbf{x}^{k,W}$, where all components in $\mathbf{x}^W$ are set to the lowest level ($v_j\left(\underline{x}_j\right) = 0$), except for the worst attribute, which is set to the highest level ($v_W(\overline{x}_W) = 1$; $\mathbf{x}^{k,W}$ has all components set to the lowest level, except for the kth attribute, which remains undetermined. The DM needs to determine the value of x_k in $\mathbf{x}^{k,W}$ to make $\mathbf{x}^W \sim \mathbf{x}^{k,W}$, meaning that the values of the two consequences are equal:

$$V(\underline{x}_1, \ldots, \overline{x}_W, \ldots, \underline{x}_n) = V(\underline{x}_1, \ldots, x_k, \ldots, \underline{x}_n), \tag{1.4}$$

By using the additive value function, it can be simplified into:

$$w_W = w_k v_k(x_k) \tag{1.5}$$

We can use a_{kW} to represent (1.5):

$$a_{kW} = \frac{w_k}{w_W} = \frac{1}{v_k(x_k)}. \tag{1.6}$$

Then we use $A_{OW} = (a_{1W}, a_{2W}, \ldots, a_{nW})$ to indicate the Others-to-Worst vector.

Step 6. Finding the optimal weights

Once we have obtained the pairwise comparison system represented by the vectors A_{BO} and A_{OW}, we can estimate the weights of the attributes. We can formulate a system of linear equations in n variables. Using interpretations (1.3) and (1.5), the system is given by:

$$\begin{cases} w_k a_{Bk} = w_B, & \forall k \neq B \\ w_k = a_{kW} w_W, & \forall k \neq W \\ w_1 + \cdots + w_n = 1 \end{cases} . \tag{1.7}$$

Since subjective judgments are often not fully rational, this linear equation system may not have a solution. Therefore, we need to use optimization methods to obtain good estimates for the weights:

$$\begin{aligned} \min_w \max_j & \{|w_j a_{Bj} - w_B|, |w_W a_{jW} - w_j|\} \\ \text{s.t.} \quad & \sum_{j=1}^{n} w_j = 1 \\ & w_j \geq 0, \quad j = 1, 2, \ldots, n, \end{aligned} \tag{1.8}$$

which can be equivalently rewritten as:

$$\begin{aligned} \min_{w,\xi} \quad & \xi \\ \text{s.t.} \quad & |w_j a_{Bj} - w_B| \leq \xi, \quad j = 1, 2, \ldots, n \\ & |w_W a_{jW} - w_j| \leq \xi, \quad j = 1, 2, \ldots, n \\ & \sum_{j=1}^{n} w_j = 1 \\ & w_j \geq 0, \quad j = 1, 2, \ldots, n \end{aligned} \tag{1.9}$$

Bayesian Best-Worst Trade-Off: A Probabilistic Group Decision-Making Model

This section presents a probabilistic model for group BWT that can be used for group decision-making problems. The elicitations for the Bayesian BWT are the same as the BWT, and the Bayesian model can merely replace Step 6 of the BWT in section "Best-Worst Trade-off". Since the Bayesian BWT is a group model, we assume that we have K Best-to-Others and Others-to-Worst vectors, shown respectively by A^k_{BO} and A^k_{OW}, $k = 1, \ldots, K$. The goal of the Bayesian BWT is to compute the optimal weight distribution for each of the DMs, shown here by w^k, $k = 1, \ldots, K$, as well as the final aggregated weight distribution w^*.

We now present the specifications of the probabilistic model for the Bayesian BWT. From a probabilistic perspective, the goal of Bayesian BWT is to estimate the following joint distribution:

$$p\big(w^*, w^{1:K} | A^{1:K}_{BO}, A^{1:K}_{OW}\big), \tag{1.10}$$

where superscript $1:K$ indicates a set of variables in the base, e.g., $w^{1:K}$ is the set of w^k's, $k = 1, \ldots, K$. Applying the Bayes rule to the above joint distribution, one can get:

$$p\big(w^*, w^{1:K} | A_{BO}^{1:K}, A_{OW}^{1:K}\big) \propto p(A_{BO}^{1:K}, A_{OW}^{1:K} | w^*, w^{1:K}). \tag{1.11}$$

We now use the following three assumptions to facilitate the right-hand side of Eq. (1.11):

- The decision-makers have expressed their preferences independently, i.e.,

$$p(A_{BO}^{1:K}, A_{OW}^{1:K} | w^*, w^{1:K}) = \prod_{k=1}^{K} p(A_{BO}^k, A_{OW}^k | w^*, w^{1:K})$$

- The Best-to-Others and Others-to-Worst vectors for each decision-maker are independent, i.e.,

$$p(A_{BO}^k, A_{OW}^k | w^*, w^{1:K}) = p(A_{BO}^k | w^*, w^{1:K}) p(A_{OW}^k | w^*, w^{1:K})$$

- Given w^k, the preferences of any decision-maker are conditionally independent of the total aggregated weight since the aggregated weight is computed based on the weights of different decision-makers. It follows:

$$p(A_{BO}^k | w^*, w^{1:K}) = p(A_{BO}^k | w^k)$$
$$p(A_{OW}^k | w^*, w^{1:K}) = p(A_{OW}^k | w^k).$$

Applying the above simplification, Eq. (1.11) can be written as:

$$p\big(w^*, w^{1:K} | A_{BO}^{1:K}, A_{OW}^{1:K}\big) \propto p(w^*) \prod_{k=1}^{K} p(A_{BO}^k | w^k) p(A_{OW}^k | w^k) p(w^k | w^*). \tag{1.12}$$

We now need to specify distributions for each element in Eq. (1.12). For distributions $p(A_{BO}^k | w^k)$ and $p(A_{OW}^k | w^k)$, we first normalize A_{OW}^k and A_{BO}^k and show them by $\hat{A}_{BO}^k$ and $\hat{A}_{OW}^k$, respectively. Now, each of $\hat{A}_{BO}^k$ and $\hat{A}_{OW}^k$ are non-negative vectors with uni-sum constraint. We now model them as:

$$\hat{A}_{BO}^k \sim Dir(\gamma^k w^k)$$
$$\hat{A}_{OW}^k \sim Dir(\gamma^k w^k), \tag{1.13}$$

where Dir is the Dirichlet distribution that is reparameterized by its mean w^r and a concentration parameter γ^k. In fact, Eq. (1.13) means that $\hat{A}_{BO}^k$ and $\hat{A}_{OW}^k$ are in the neighborhood of w^k (that is its mean), and the closeness is governed by a parameter γ^r. Also, γ^r is another parameter that needs to be tuned by the Bayesian model. Since it is a positive real number, we model it using the gamma distribution:

$$\gamma^k \sim gamma(a, b), \tag{1.14}$$

where a and b are the shape and rate parameters of the gamma distribution. To follow the maximum entropy principle, we set $a = b = 0.01$ for the prior, so the gamma distribution has a mean of one and a variance of 100. Following the same modeling principles, we use the following distributions for w and w^*:

$$\begin{aligned} &w^k \sim Dir(\gamma^* w^*), \quad k = 1, ..., K, \\ &\gamma^* \sim gamma(a^*, b^*), \\ &w^* \sim Dir(\alpha), \end{aligned}$$

where $a^* = b^* = 0.01$, and α is an n-dimensional vector with each element having a value of 0.01.

This model does not bear a closed-form solution, so we need to use the Markov-chain Monte Carlo sampling to obtain the samples from the posterior distribution. To that end, we use the JAGS (Just Another Gibbs Sampler) [9]. Given the aggregated weight distribution, we can compute the credal ranking introduced in Bayesian BWM [8].

Numerical Examples

This section presents a numerical example of using the Bayesian BWT to solve a real-world problem.The Python implementation of Bayesian BWT is also publicly available.[1] More in detail, we demonstrate the application of the proposed Bayesian BWT model to a port evaluation problem, which is essential for ports to anticipate and adapt to potential changes in port selection by shippers, freight forwarders, and carriers. Our approach is based on the work conducted by Rezaei et al. [11], who conducted a study on port performance measurement. We utilize the data from their study, specifically the information on port leg-related services and facilities (attributes, alternatives, and evaluation scores), to illustrate the Bayesian BWT procedure.

Step1. Identification of alternatives and attributes

To begin, we engaged three knowledgeable experts to evaluate the ports. This port selection study identified six attributes: *terminal handling charges, International Ship and Port Facility Security Code (ISPS), customs service, port reputation, satisfaction with terminal operations (rated on a scale of 1 to 7), and the number of container terminals*. Among these attributes, terminal handling charges and ISPS are considered cost attributes, while the rest are benefit attributes. The study examined a

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[1] https://colab.research.google.com/drive/1VDt3zCJSBgzgBeZSD8OIsoE1aPMQTH6-?usp=sharing.

Table 1.1 The recorded scores for the seven ports [11]

Ports	Attributes					
	Terminal handling charges (€/TEU)	ISPS (€/unit)	Customs service	Port reputation	Satisfaction with terminal operations	Number of container terminals
Piraeus	106	11	4.2	3.8	3.4	3
Koper	145	11	5.12	5.24	5	1
Genoa	179	13	4.2	4.4	4.4	2
Antwerp	179	12	5.44	5	5.11	4
Rotterdam	202	13	5.5	5.93	5.29	6
Hamburg	223	16	5.65	6.06	5.41	4
Gdansk	103	14	4.6	5	4.4	2

total of seven ports. Table 1.1 provides the scores of the alternative ports in relation to the attributes.

Step 2. Determination of value function for each attribute

As outlined in section "Best-Worst Trade-off", the value functions for each attribute need to be determined. This can be done, for instance, using the the mid-value splitting technique introduced by Keeney and Raiffa [6]. For detailed definitions, please refer to their study.

Step 3. Identification of best and worst attributes

According to section "Best-Worst Trade-off", all three experts agreed that attribute C_1 is the best, while attribute C_3 is considered the worst attribute.

Step 4. Comparison of best to others tradeoff

To evaluate the tradeoff between the best attribute (C_1) and the other attributes, we generated hypothetical consequences based on the method described in section "Best-Worst Trade-off". We then asked the experts to provide the undetermined values ($x_1^{1,2}, x_1^{1,3}, x_1^{1,4}, x_1^{1,5}, x_1^{1,6}$) so that the paired consequences are indifferent to each other. The specific paired consequences and their respective values are presented as follows:

$$
\begin{aligned}
x^{1,2} \sim x^2 &\Leftrightarrow (x_1^{1,2}, 16, 4.2, 3.8, 3.4, 1) \sim (223, 11, 4.2, 3.8, 3.4, 1),\\
x^{1,3} \sim x^3 &\Leftrightarrow (x_1^{1,3}, 16, 4.2, 3.8, 3.4, 1) \sim (223, 16, 5.65, 3.8, 3.4, 1),\\
x^{1,4} \sim x^4 &\Leftrightarrow (x_1^{1,4}, 16, 4.2, 3.8, 3.4, 1) \sim (223, 16, 4.2, 6.06, 3.4, 1),\\
x^{1,5} \sim x^5 &\Leftrightarrow (x_1^{1,5}, 16, 4.2, 3.8, 3.4, 1) \sim (223, 16, 4.2, 3.8, 5.41, 1),\\
x^{1,6} \sim x^6 &\Leftrightarrow (x_1^{1,6}, 16, 4.2, 3.8, 3.4, 1) \sim (223, 16, 4.2, 3.8, 3.4, 6).
\end{aligned} \tag{1.15}
$$

Following the evaluation, the three experts arrived at the following values:

$$\begin{aligned}
&\text{DM1:}(x_1^{1,1}, x_1^{1,2}, x_1^{1,3}, x_1^{1,4}, x_1^{1,5}, x_1^{1,6}) = (103, 200, 210, 180, 190, 185),\\
&\text{DM2:}(x_1^{1,1}, x_1^{1,2}, x_1^{1,3}, x_1^{1,4}, x_1^{1,5}, x_1^{1,6}) = (103, 190, 215, 175, 203, 150),\\
&\text{DM3:}(x_1^{1,1}, x_1^{1,2}, x_1^{1,3}, x_1^{1,4}, x_1^{1,5}, x_1^{1,6}) = (103, 192, 200, 153, 184, 142). \quad (1.16)
\end{aligned}$$

Step 5. Comparison of others to worst attribute tradeoff

In this step, the expert was requested to assign values $(x_1, x_2, x_3, x_4, x_5, x_6)$ according to section "Best-Worst Trade-off" in order to satisfy the following indifference relations for the generated consequences:

$$\begin{aligned}
&x^{1,3} \sim x^3 \Leftrightarrow (x_1, 16, 4.2, 3.8, 3.4, 1) \sim (223, 16, 5.65, 3.8, 3.4, 1),\\
&x^{2,3} \sim x^3 \Leftrightarrow (223, x_2, 4.2, 3.8, 3.4, 1) \sim (223, 16, 5.65, 3.8, 3.4, 1),\\
&x^{4,3} \sim x^3 \Leftrightarrow (223, 16, 4.2, x_4, 3.4, 1) \sim (223, 16, 5.65, 3.8, 3.4, 1),\\
&x^{5,3} \sim x^3 \Leftrightarrow (223, 16, 4.2, 3.8, x_5, 1) \sim (223, 16, 5.65, 3.8, 3.4, 1),\\
&x^{6,3} \sim x^3 \Leftrightarrow (223, 16, 4.2, 3.8, 3.4, x_6) \sim (223, 16, 5.65, 3.8, 3.4, 1). \quad (1.17)
\end{aligned}$$

The experts provided the following assessments:

$$\begin{aligned}
&\text{DM1: } (x_1, x_2, x_3, x_4, x_5, x_6) = (210, 15, 5.56, 5.2, 4, 3),\\
&\text{DM2: } (x_1, x_2, x_3, x_4, x_5, x_6) = (215, 13.2, 5.65, 5, 5, 3),\\
&\text{DM3: } (x_1, x_2, x_3, x_4, x_5, x_6) = (210, 13, 5.65, 4.3, 4.1, 2). \quad (1.18)
\end{aligned}$$

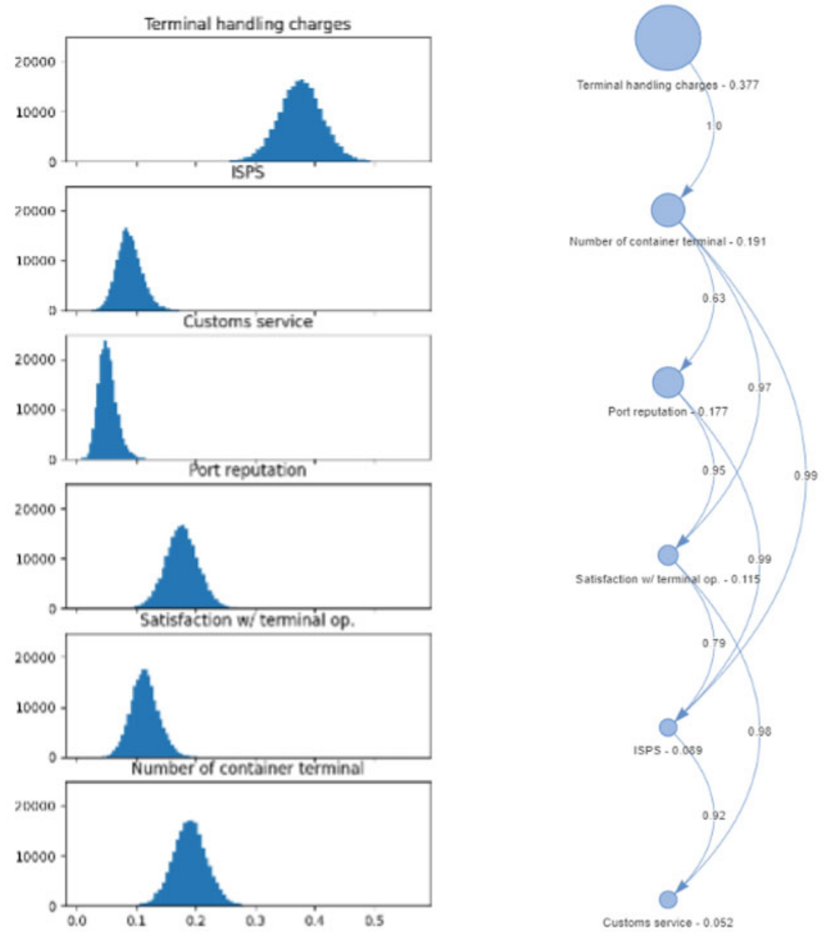
Using the value functions from Step 2, we obtain the revised vectors A^k_{BO} and A^k_{OW} as follows:

$$\begin{aligned}
&\text{DM1: } A^1_{BO} = (1, 5, 9.09, 2.70, 3.57, 3.12),\ A^1_{OW} = (9.9, 2.5, 1, 7.69, 5.55, 6.25),\\
&\text{DM2: } A^2_{BO} = (1, 3.57, 14.28, 2.5, 5.88, 1.64),\ A^2_{OW} = (14.28, 1.78, 1, 1.88, 1.25, 2.5),\\
&\text{DM3: } A^3_{BO} = (1, 3.84, 5.26, 1.72, 3, 1.47),\ A^3_{OW} = (9.09, 1.66, 1, 4.54, 2.85, 5),
\end{aligned}$$

Upon verifying the consistency, all the provided preferences exhibit both ordinal consistency and cardinal consistency. For a detailed understanding of the consistency checking procedure and the consistency thresholds, readers are referred to the original BWT paper [7].

Step 6. Finding the optimal weights attributes.

We now subject the revised vectors A_{BO} and A_{OW} to the proposed probabilistic model and obtain the aggregated weight distribution as well as the credal ranking. Figure 1.1 shows the weight distribution of the six criteria on the left panel and the outcome of the credal ranking on the right panel. According to this figure, *terminal handling charges* is the most influential criterion whose mean distribution is 0.377. This is depicted in the left panel of Fig. 1.1 by a distribution with no overlaps with the distribution of the other criteria. In the right panel, it is positioned as the highest node, meaning that it is the most important criterion, having one edge only with



(a) The weight distribution of criteria. (b) The credal ranking of criteria.

Fig. 1.1 The visualization of the credal ranking and the weight distribution of all criteria

a weight of one towards *number of container terminal*, indicating that we have a confidence level of one that it is more influential than *number of container terminal*. The edges from *terminal handling charges* to the lower nodes are also one (meaning that with a confidence level of one, it is more influential than those criteria), but they are removed to make the visualization of the credal ranking easier to be understood.

The second most influential criterion is *number of container terminal* with a mean weight distribution of 0.191. By looking at the weight distributions, it is readily seen that the distribution of this criteria overlaps with those of *Port reputation*, *Satisfaction with terminal operation*, and *ISPS*, and the corresponding confidence levels in the credal ranking to these criteria are 0.63, 0.97, and 0.99, respectively. At the other extreme, *Customs service* is deemed the least influential criterion with a mean weight distribution of 0.052, positioned at the lowest node in the credal ranking visualization.

Conclusions

In this study, the Bayesian extension of the Best-Worst Tradeoff (BWT) was proposed. The method can be used in the context of compensatory methods such as multi-attribute value/utility theory (MAVT/MAUT). The input of the proposed method is the tradeoffs among a set of decision criteria coming from a number of decision-makers or experts. The output is a set of scaling constants with their ranking order that is enriched by a confidence value. The confidence values show to what extent we could be certain about one scaling constant being greater (smaller) than the others. The proposed method has several salient features: (i) it enables us to check the consistency among the tradeoffs provided by the decision-makers and experts (the traditional Tradeoff procedure does not allow checking the consistency); (ii) it has an inherent debiasing mechanism for anchoring bias as it works based on two opposite reference points Best and Worst (the traditional Tradeoff procedure has one reference point (usually the best), which could be a source of anchoring bias; (iii) it is suitable for group decision-making situations (the original BWT is not primarily developed for group decision-making problems); (iv) the final ranking order of the criteria is enriched by extra information about the confidence we have about the relative size of the scaling constants (weights) (other aggregation methods such as geometric mean does not provide such information).

In this study we considered a traditional approach for value elicitation (mid-point technique), and we showed how this can be used together with the Bayesian BWT to rank some European seaports. As a future study, we aim to extend the Bayesian approach to the first part of the MAVT (value elicitation) and provide a full Bayesian MAVT method.

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Chapter 2
Robust Stakeholder-Based Group-Decision Making Framework: The Multi-Actor Multi-Criteria Analysis (MAMCA) with the Integration of Best-Worst Method (BWM)

He Huang

Abstract In recent years, there has been a growing recognition of the importance of stakeholder involvement in decision-making processes. To address this need, Multi-Actor Multi-Criteria Analysis (MAMCA) has emerged as a group decision-making framework that takes into account the preferences of key stakeholders. MAMCA provides a flexible structure that aims to capture the various points of view of stakeholders involved in the decision-making process. After the group evaluation, MAMCA encourages stakeholders to engage in discussions and negotiations to reach a consensus solution. However, sometimes it is challenging to reach a consensus solution as stakeholders normally hold conflict interests. Furthermore, during the evaluation, stakeholders may struggle to understand the weight elicitation methods, which can lead to elicitation results that do not reflect their preferences or expectations. Consequently, the Best-Worst Method (BWM) effectively addresses these challenges by simplifying the elicitation process and promoting consistency among judgments, ultimately enhancing the reliability and robustness of decision-making outcomes. This paper proposes a robust group decision-making framework based on MAMCA that incorporates BWM as the weight elicitation method. The proposed framework integrates elicited criteria weights and their consistency ratios from BWM into the consensus-reaching model to further increase the consistency of the results and identify consensual solutions that all stakeholders can accept. The effectiveness of the proposed framework is demonstrated through a logistics study.

Keywords BWM · MAMCA · Group decision making · Consensus reaching

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Introduction

Stakeholder involvement is a critical aspect of decision making in complex problems, particularly in the transportation sector where decisions must take into account the preferences of the related key interest groups, as well as a wide range of monetary and non-monetary factors such as transportation cost, travel time, environmental impact, etc. [1, 2]. It is essential to ensure that all relevant stakeholders are included in the decision-making process and that their preferences are taken into account in order to reach a consensual solution [3]. To address the decision-making problem in the aforementioned context, multi-criteria group decision making (MCGDM) [4–6] and multiattribute group decision making (MAGDM) [7] are often considered suitable frameworks. It is worth noting that MCGDM and MAGDM are essentially the same, as both involve decision-making processes that consider multiple criteria or attributes and involve multiple decision-makers [7, 8]. Multi-Actor Multi-Criteria Analysis (MAMCA) is a specific MCGDM framework that emphasizes stakeholder involvement [9].

MAMCA is a highly flexible MCGDM framework that derives its flexibility from the adaptable choice of elicitation methods and the ability to customize the evaluation structure. It provides a framework for involving multiple stakeholders in the decision-making process by considering the stakeholders' individual preferences, allowing them have different criteria sets, and taking these into account when evaluating alternatives [10–12]. This ensures that the final decision takes into account the needs and concerns of all relevant stakeholders, providing a more comprehensive evaluation. Furthermore, MAMCA allows for the integration of various weight elicitation methods and multi criteria decision-making (MCDM) methods [10]. This makes MAMCA an easy-to-understand framework that is straightforward to utilize, especially when stakeholders with different levels of expertise are involved.

In the social/public decision making, the selection of methods used in MAMCA becomes important, because the participants can have limited knowledge to understand the MCDM methods [13]. In addition, the ways of data collection can be survey filling, participants may have limited time to understand MCDM methods [12]. One MCDM method that is particularly suitable for use in MAMCA is the Best-Worst Method (BWM) [14]. BWM is ideal for use in MAMCA as it requires minimal input from participants from different stakeholders but still provides consistent results. This means that stakeholders can be involved in the decision-making process with a minimum of effort, making the process more accessible and efficient [15].

One challenge for MAMCA is the consensus reaching after the evaluation, given that MAMCA discourages assigning weights to stakeholders as it does not recommend aggregating the result that compensates the stakeholders' preferences [16]. It encourages negotiation and discussion among the participants in order to find the compromise solutions. However, arriving at a final solution without mathematical proof can be difficult. One possible solution is to conduct a sensitivity analysis to check the ranking of alternatives across all stakeholders [17]. In previous work, Huang et al. [16] proposed an optimization model based on weight sensitivity analysis to aid participants in reaching a consensus solution. Now, the integration of BWM can further enhance the robustness of the model output.

This study identifies two key challenges in stakeholder-based group decision-making: the challenge of non-expert stakeholders in eliciting criteria weights and the challenge of conflicting preferences among stakeholders in reaching a consensus. In order to address these challenges, we thus propose a robust group decision-making framework that combines BWM and MAMCA to assist stakeholder groups in finding consensus solutions. Specifically, the criteria weights elicited through BWM are incorporated into the consensus-reaching model as constraints to further increase the consistency of the results. The optimization model searches for the best solution that can be ranked highly by all stakeholders. Thanks to the integration of MAMCA and BWM, stakeholders can easier elicit criteria weights, ultimately leading to a more efficient and effective decision-making process. By reducing the potential for inconsistencies in criteria weight elicitation, the proposed framework not only produces robust results but also saves valuable time for stakeholders.

This paper first provides a brief literature review of MAMCA and BWM in Section "Literature Review: MAMCA Framework and the Possibility of Integration of BWM". We then present our proposed framework that combines MAMCA and BWM in Section "Robust MAMCA-BWM Framework". Next, we apply this framework to a real-life logistics study to demonstrate its effectiveness Section "Case Illustration". Finally, we draw the conclusion.

Literature Review: MAMCA Framework and the Possibility of Integration of BWM

The MAMCA framework was initially proposed to support the decision-making process in the transportation filed with the involvement of different key stakeholders [10]. It emphasizes the importance of including the perspectives and expertise of various stakeholders in process, as their support is critical for the success of the decision-making [12]. The MAMCA framework belongs to the stakeholder-based MCGDM frameworks [18, 19], as well as the participatory multi-criteria analysis (MCA) frameworks [20]. These frameworks prioritize participation and collaboration among stakeholders to achieve a common understanding and consensus. While the MAMCA framework shares many characteristics with these frameworks, it also has its unique features. One of the most significant advantages of MAMCA is its flexibility, which is reflected in its steps. The MAMCA framework is illustrated in Fig. 2.1 and the steps of MAMCA are (1) Problem identification and alternative definition; (2) Stakeholder analysis; (3) Criteria identification; (4) Criteria indicators building; (5) Stakeholder overall analyses; (6) Result discussion; (7) Implementation.

The Multi-Actor Multi-Criteria Analysis (MAMCA) framework consists of several steps that follow standard Multi-Criteria Group Decision-Making (MCGDM) frameworks [21]. However, MAMCA differs in that stakeholders are identified in the second step, so that they may be involved in subsequent steps to aid facilitators for example in identifying criteria [3]. Because MAMCA allows the stakeholders to hold different criteria, which can better help them evaluate alternatives based on their own interests and priorities. Then, criteria weights can be elicited using various methods such as SWING [22], Simos [23], or BWM [14]. In step 5, the overall analysis is conducted within stakeholders, and any MCA methods may be used to assess alternatives. Group Decision Support Methods (GDSM) [10], such as Preference Ranking Organization Method for Enrichment Evaluation (PROMETHEE) [24], Analytic Hierarchy Process (AHP) [25], or BWM [14] are well-suited for this step. In the result discussion step, facilitators can aggregate scores evaluated by different stakeholders as overall preferences or encourage stakeholders to negotiate and find compromise solutions. This approach enables different robustness analyses to help reach a consensus. As mentioned above, MAMCA can be customized in different steps and adapted to suit different decision-making contexts. This flexibility is particularly beneficial in scenarios where there are diverse stakeholders with varying interests, objectives, and preferences. Additionally, permitting the utilization and combination of various criteria weight elicitation methods and MCDM methods can promote a more thorough analysis and address the constraints of methods. For example, BWM can be used to elicit criteria weights and produce consistent results, especially in situations where stakeholders have limited expertise to understand the elicitation method or limited time to elicit weights.

The Best-Worst Method (BWM) is a widely utilized pairwise-comparison approach that is favored for its efficiency and simplicity. Unlike the conventional pairwise-comparison method AHP, which can be cumbersome and time-consuming due to the large number of pairwise comparisons required, BWM only necessitates decision-makers to compare the criteria or alternatives to the most and least important/preferred ones [14]. This streamlined approach can save significant amounts of time while still providing a consistency ratio to ensure the accuracy and reliability of the elicitation process [14]. Moreover, recent research on BWM has demonstrated that it can yield results less susceptible to anchoring bias [26]. Rezaei [27] revealed that the two-vector mechanism effectively counteracts the impact of anchoring bias, which is commonly observed in single reference point approaches, such as the Simple Multi-Attribute Rating Technique (SMART) [28] and Swing [22]. To elicit criteria weights using BWM, several steps are involved. First, evaluators (i.e., stakeholders in MAMCA) need to identify the best and worst criteria. Next, they need to assess the preferences of the best criterion over all the other criteria using a scale ranging from 1 to 9, or other scales like the Likert scale [29]. Then, the preferences of all the other criteria over the worst criterion need to be determined using the same scale. Finally, the preferences will be inputted into an optimization model to obtain the optimal weights that have maximum consistency. The comparisons can be illustrated as Fig. 2.1, where only reference comparisons are conducted, and secondary comparisons based on knowledge about the reference comparisons are not conducted [14].

Like AHP, BWM also provides the consistency ratio. This helps to avoid inconsistent that could lead to unreliable decision-making. Liang et al. [30] delves deeper into the issue of consistency in BWM and provides a more comprehensive analysis of the problem. The study explores the details of the consistency issue in BWM and

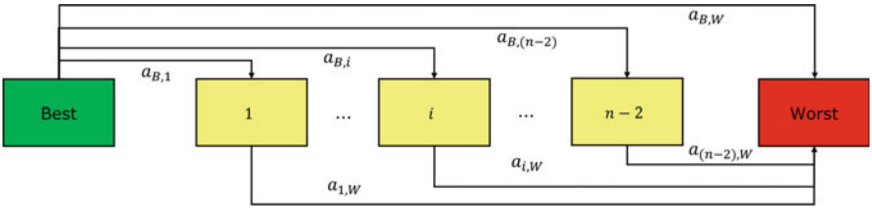

Fig. 2.1 The comparisons in the BWM [14]

provides thresholds that can be used to accept or reject inconsistency in the elicitation process. By providing such thresholds, stakeholders can have a better understanding of the consistency issue and can be confident in the reliability of the elicitation results obtained through the BWM. This further highlights the significance of BWM in ensuring consistent and reliable criteria weight elicitation for decision-making.

However, in the other side point of view, the consistency ratio in BWM also provides the possibility to help stakeholders to reach the consensus in a group decision-making context. As it is discussed previously, the consistency ratio is to check whether the stakeholders filled in consistent preference scores to different comparison. In MAMCA, when stakeholders finish the evaluation, the ranking of alternatives of stakeholders will be illustrated in step 6 [10]. Then the stakeholders need to discuss and find out compromised solutions that can be accepted by everyone. Normally, the participants and facilitators cannot identify the consensual solutions based on their rankings without any additional information [16]. Therefore, it is valuable to build a consensus reaching process (CRP) to support them [31].

In this study, CRP based on the minimization of weight modification is a feasible solution. We argue that, unlike alternative appraisal methods, which require more objective data support, the elicitation of criteria weights is subjective and inaccurate, particularly when the imprecise weight elicitation is applied [32, 33]. In this regard, we propose to apply inverse optimization based on criteria weight sensitivity analysis [34]. The weight sensitivity analysis enables the validation of the robustness of the alternative ranking of one evaluator [35]. By applying the principles of inverse optimization theory, consensual alternatives can be identified for all stakeholders through the alteration of criteria weights. Previously, Doan and De Smet [36] developed an alternative weight sensitivity analysis based on mixed integer linear programming (MILP), and Huang et al. [16] further developed it by taking the inverse optimization point of view in the context of group decision-making framework. It can be further developed by leveraging the consistency ratio of BWM to further improve its robustness. Liang et al. [30] proposed the algorithm to determine the ordinal consistent threshold of consistency ratio for different combinations in BWM. The ordinal consistency can be validated in the optimization to ensure that the solutions obtained uphold the ordinal consistency, as we argue that the weight elicitation from the BWM should at least respect the ordinal information provided by the stakeholders. In the following section, we present our robust MAMCA-BWM framework that utilize the revised consensus-reaching model.

Robust MAMCA-BWM Framework

Without loses its generality, let us define a set of alternative $A = \{a_1, a_2, \ldots, a_M\}$ need to be appraised by stakeholders $S = \{s_1, s_2, \ldots, s_K\}$ in MAMCA. For each stakeholder group k ($k = 1, 2, \ldots, K$) there is a set of criteria $C_k = \{c_1, c_2, \ldots, c_{N_k}\}$. The stakeholder will first elicit the criteria weights. For stakeholder k, best and worst criterion c_{B_k}, c_{W_k} are identified. Then the preferences of the best criterion over the other criteria are determined in a z-point scale (in this study, 9-point scale is used), which result in a Best-to-Others vector $A_{BO_k} = (a_{B_k1}, a_{B_k2}, \ldots, a_{B_kn_k})$, where $a_{B_kn_k}$ represents the preference of the best criterion c_{B_k} over c_{n_k} ($n_k = 1, 2, \ldots, N_k$). Similarly, Others-to-Worst vector is determined in the same point scale $A_{OW_k} = (a_{1W_k}, a_{2W_k}, \ldots, a_{n_kW_k})$, where $a_{n_kW_k}$ represents the preference of criterion c_{n_k} over the worst criterion c_{W_k}. Then the criteria weights $(\omega_1^*, \omega_2^*, \ldots, \omega_{n_k}^*)$ for stakeholder k can be obtained by solving the linear programming problem proposed in [37]:

$$\min \xi^L, \tag{1}$$

s.t.

$$\begin{aligned} &|\omega_{B_k} - a_{B_kn_k} \cdot \omega_{n_k}| \le \xi^L, \forall n_k \in \{1, 2, \ldots, N_k\}, \\ &|\omega_{n_k} - a_{n_kW_k} \cdot \omega_{W_k}| \le \xi^L, \forall n_k \in \{1, 2, \ldots, N_k\}, \\ &\sum_{n_k=1}^{N_k} \omega_{n_k} = 1. \end{aligned} \tag{2}$$

By utilizing this model, we can obtain a unique solution for the optimal criteria weights. Consequently, these unique criteria weights can generate a single performance score through the weighted sum of the uni-criterion scores. This approach enables us to gain an initial understanding of stakeholders' preferences, proving particularly valuable when integrating the scores of various stakeholders within the later mentioned MAMCA view On the other hand, the stakeholders need to appraise the alternative performances based on their criteria. Different MCDM methods can be used in MAMCA to appraise the alternatives. In this study, we use PROMETHEE II to appraise the alternatives. Therefore, for each stakeholder, an unweighted uni-criterion net flows can be obtained. As it is not the focus of this study, and to not lose its generality, we only define the final appraised unweighted alternative performance score matrix:

$$P_k = \begin{bmatrix} p_1^1 & \cdots & p_1^M \\ \vdots & \ddots & \vdots \\ p_{N_k}^M & \cdots & p_{N_k}^M \end{bmatrix}, \tag{3}$$

where P_k is the alternative performance score matrix appraised by stakeholder k, $p_{n_k}^m$ represents the score of alternative m based on criterion n_k. We adopt the additive model, which is the conventional form in MAMCA, to aggregate the final score of alternative for one stakeholder:

$$\phi_k^m = \sum_{n_k=1}^{N_k} p_{n_k}^m \times \omega_{n_k}, \forall n_k \in \{1, 2, \ldots, N_k\}, \tag{4}$$

where ϕ_k^m represents score of alternative m for stakeholder k. In MAMCA, the matrix of the final alternative scores can be illustrated in a so-called multi-actor view. This matrix can be expressed as:

$$\Phi = \begin{bmatrix} \phi_1^1 & \cdots & \phi_1^M \\ \vdots & \ddots & \vdots \\ \phi_K^1 & \cdots & \phi_K^M \end{bmatrix}. \tag{5}$$

As aforementioned, it is difficult to identify the consensual solution solely based on matrix (5). We applied the optimization model proposed by Huang et al. [16] to search for the solutions in a context of BWM. We formulate the optimization problem as follows: 'What would be the minimum weight modifications that should be accepted by the different stakeholders such that a common alternative would get a higher position in the different rankings, where the criteria weights still respect the ordinal consistency of BWM'. As we already have the initial criteria weights elicited by BWM $(\omega_{k,1}, \omega_{k,2}, \ldots, \omega_{k,n_k})$, the modified criteria weights of stakeholder k are denoted as $(\omega'_{k,1}, \omega'_{k,2}, \ldots, \omega'_{k,n_k})$.

We define the variables for the model. In order to linearize the absolute value, two other sets of variables for each stakeholder k are defined:

- $\mathcal{D}_{1,k} = \left\{d_{1,1,k}, d_{1,2,k}, \ldots, d_{1,N_k,k}\right\}$
- $\mathcal{D}_{2,k} = \left\{d_{2,1,k}, d_{2,2,k}, \ldots, d_{2,N_k,k}\right\}$

such that, $\forall k \in \{1, \ldots, K\}$; $\forall n_k \in \{1, 2, \ldots, N_k\}$:

$$\omega_{k,n_k} - \omega'_{k,n_k} = \begin{cases} d_{1,n_k,k} & \text{if } \omega_{k,n_k} - \omega'_{k,n_k} \geq 0 \\ -d_{2,n_k,k} & \text{otherwise} \end{cases}, d_{1,n_k,k}, d_{2,n_k,k} \geq 0 \tag{6}$$

$d_{1,n_k,k}$ (resp. $d_{2,n_k,k}$) is equal to $\omega_{k,n_k} - \omega'_{k,n_k}$ (resp. $-(w_{k,p} - w'_{k,p})$) if this difference is positive (resp. negative), and $d_{k,2,p}$ (resp. $d_{k,1,p}$) is equal to 0.

Then, we will solve the MILP for each stakeholder individually and for all the alternatives. For the sake of simplicity, let us consider the case of alternative a_m and stakeholder k, the MILP model can then be formalized as follows:

$$\min z_k^m = \sum_{n_k=1}^{N_k} |\omega_{k,n_k} - \omega'_{k,n_k}| = \sum_{n_k=1}^{N_k} (d_{1,n_k,k} + d_{2,n_k,k}), \tag{7}$$

s.t.

$$\sum_{n_k=1}^{N_k} \omega'_{k,n_k} = 1, \forall k = 1, 2, \ldots, K, \quad \text{(weights constraint)}, \tag{8}$$

$$\phi_k^{\prime m} = \sum_{n_k=1}^{N_k} p_{n_k}^m \times \omega'_{k,n_k}, \forall n_k \in \{1, 2, \ldots, N_k\}, \quad \text{(alternative scores computation)} \tag{9}$$

$$\phi_k^{\prime m} - \phi_k^{\prime m'} \leq \epsilon \, r_k^m,$$

$$\phi_k^{\prime m} - \phi_k^{\prime m'} \leq \epsilon \, (1 - r_k^m), \quad \text{(rank change of } a_m)$$

$$\sum_{m'=1, m' \neq m}^{M} r_k^m = M - g, \forall g = 1, 2, \ldots, M - 1, \tag{10}$$

$$\omega_{k,n_k}, d_{1,n_k,k}, d_{2,n_k,k} \geq 0, \;\; \forall k \in \{1, \ldots, K\}, \forall n_k \; \in \{1, 2, \ldots, N_k\}. \;\; \text{(domain)} \tag{11}$$

where ϵ in Eq. (10) is an arbitrary constant so that $Z \geq \frac{1}{d_{1,n_k,k}+d_{2,n_k,k}}$. r_k^m indicates whether alternative a_m has a higher net flow score, i.e., a better rank than alternative $a_{m'}$ in the modified ranking. We want to find the minimum weight modification that will lead alternative a_m to reach position g in the modified ranking for stakeholder k. We run the MILP model (7) to search alternatives for better ranking iteratively, each time we check if the modified criteria weights respect the ordinal consistency. As we utilize the linear BWM model, the minimum ξ^L obtained from Eq. (1) can be directly regarded as an indicator of comparison consistency. A lower ξ^L values indicating higher consistency [37]. And we define two different distances: weight distance and ranking distance. Weight distance $Z^m = \sum_{k=1}^{K} z_k^m$ represents the distance of modified criteria weights towards the original criteria weights elicited by BWM that lead the alternative m to the better position. And the ranking distance $O^m = \sum_{k=1}^{K} (K - r_k^m)$ represents the ranking positions of the alternative m towards the best position. Thus, when $O^m = 0$, all stakeholders rank alternative m as best solution. These two distances can construct a 2-D point $(Z^m, O^m) \in \mathbb{R}^2$ for each output of the model, where the ξ^L can be checked. If for one point where $O^m = 0$, ξ^L is within the threshold proposed in [30], we can conclude alternative m is a consensual solution that can be accepted by all stakeholders and still consistent. However, if ξ^L is rejected but $O^m = 0$, m is a compromised solution that is possible to be accepted by all stakeholders, but one or several stakeholders need to adapt their criteria weight elicitation. i.e., priorities. The final output can be illustrated in a line chart by connecting the points for a visual aid.

Case Illustration

To illustrate the benefits of robust MAMCA-BWM framework, we applied it in the same sustainable logistic case that is used in [16] as a didactic example. The main objectives of the case were to develop cost-effective strategies, measures, and tools for

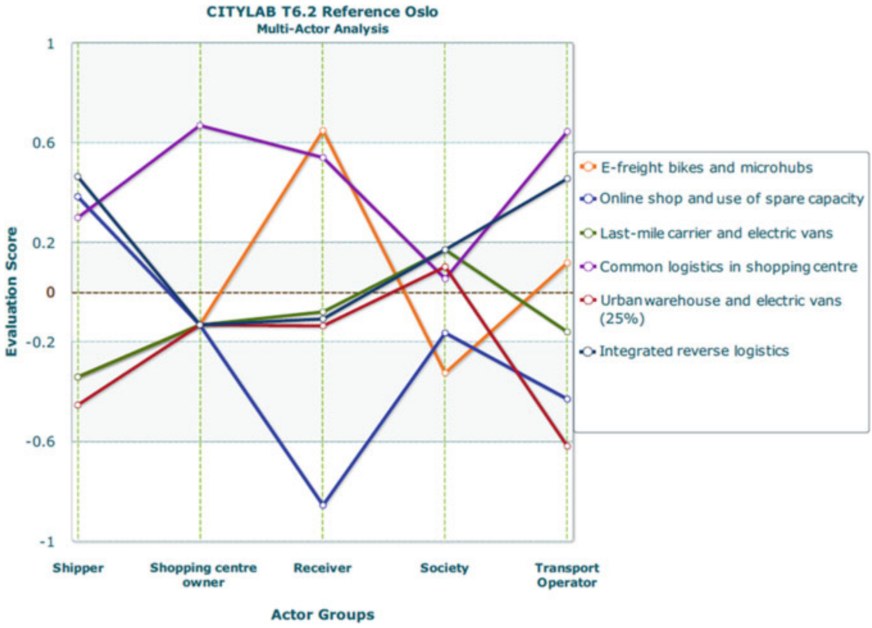

Fig. 2.2 MAMCA view of the sustainable logistic case [16]

emission-free city logistics and implement them on a larger scale. In the original case, there are six alternatives, and the MAMCA view is depicted in Fig. 2.2. The lines represent different alternatives, illustrating the aggregated performance scores for various stakeholders. It is evident that significant conflicts exist among stakeholders. To effectively demonstrate the benefits of the framework without delving too deeply into the original case, we have chosen three alternatives: (1) E-freight bikes and micro-hubs, (2) common logistics in shopping centers, and (3) integrated reverse logistics, as well as three stakeholders: shipper, receiver, and transport operator. These three alternatives exhibit relatively high scores for the three stakeholders but generate three distinct rankings (see Table 2.4). In fact, a previous study found that these three alternatives required the minimum weight distance to be ranked in the top position for all stakeholders in [16]. In other words, these alternatives are most likely to be accepted by all stakeholders as a solution. Conversely, the other three alternatives are less competitive, typically displaying negative unweighted uni-criterion net flows. Thus, we invited three researchers/experts in transport and logistics to role-play the three original stakeholders and evaluate the selected alternatives. They are asked to re-elicit the criteria weights by applying BWM. The criteria of the stakeholders are illustrated in Table 2.1.

The original BWM weights, output-based consistency ratios, unweighted PROMETHEE uni-criterion net flows, aggregated performance scores and rankings of alternatives for stakeholders are presented in Table 2.4. All numerical values

Table 2.1 Criteria of different stakeholders

Stakeholders	Criteria
Shipper	Positive effect on society, high quality deliveries, low cost for transport, high quality pick-ups
Receiver	Positive effect on society, low cost for receiving goods, high quality deliveries, attractive shopping environment
Transport operator	Viable investment, positive effect on society, satisfied employees, profitable operations, high quality service

Table 2.2 Threshold of ξ^L for different combinations using output-based consistency measurement

Number of criteria	Scale						
	3	4	5	6	7	8	9
4	0.0612	0.0820	0.1003	0.1167	0.1299	0.1420	0.1542
5	0.0497	0.0686	0.0851	0.1000	0.1129	0.1244	0.1351

are maintained to three decimal places. The scores are aggregated based on (4). It is important to note that the net flows of alternatives for each criterion do not sum to zero. This is because we have only "hided" the net flows of the other three unused alternatives, rather than deleting them. By doing so, we preserve the original outranking information of the alternatives. The pairwise comparison vectors for stakeholders' criteria can be found in the appendix for readers' reference. In the original criteria weights, the ξ^L values are validated to determine if they exhibit ordinal consistency. We employed the same method as presented in [30] to identify the approximate thresholds for the output-based consistency ratio in the linear BWM model. The corresponding thresholds of ξ^L for 4 and 5 criteria are provided in Table 2.2.

Since the linear model aims to find a unique solution instead of allowing for multi-optimality, it leads to relatively strict consistency thresholds for the ξ^L. Adjusting the weights can easily result in exceeding the approximated thresholds. Therefore, in this study, we will not only verify whether the optimized ξ^Ls fall within the threshold, but also ensure that the optimized weights preserve the same rank as the original rank, in order to provide a broader insight.

It is evident that the original rankings for stakeholders differ, highlighting the value of applying the consensus-reaching model to identify a consensus among the various stakeholder preferences. We then applied the consensus-reaching model to search for better rankings for alternatives. For example, the MILP output of alternative 'E-freight bikes and micro-hubs' are illustrated in Table 2.3.

Table 2.3 MILP model result of alternative 'E-freight bikes and micro-hubs'

MILP	z_1	z_2	z_3	o_1	o_2	o_3	Z	O	ξ^L within threshold	Preserving same rank
1	0	0	0	3	1	3	0	4	Yes	Yes
2	0	0	0.324	3	1	2	0.324	3	No	No
3	0	0	0.569	3	1	1	0.569	2	No	No
4	0.619	0	0.569	2	1	1	1.188	1	No	No
5	0.943	0	0.569	1	1	1	1.512	0	No	No

Table 2.4 Original criteria weights and uni-criterion net flows

Stakeholders	Criteria	Weight	Score of (1) E-freight bikes and micro-hubs	Score of (2) common logistics in shopping center	Score of (3) integrated reverse logistics	ξ^L	Ranking
Shipper	Positive effect on society	0.0799	0	0	1	0.090	(3) > (2) > (1)
	Low cost for receiving goods	0.0511	0.8	0	0		
	High quality deliveries	0.550	−0.6	0.6	0.2		
	Attractive shopping environment	0.319	−0.2	−0.2	1		
	Weighted sum performance score	/	−0.353	0.266	0.509		
Receiver	Positive effect on society	0.091	0	−1	0	0.076	(1) > (2)> (3)
	Low cost for receiving goods	0.066	0.8	0	0		
	High quality deliveries	0.184	−0.6	1	0.2		
	Attractive shopping environment	0.660	1	0.6	−0.2		
	Overall performance score	/	0.601	0.487	−0.095		
Transport operator	Viable investment	0.197	−0.6	0.6	0.6	0.062	(2) > (3) > (1)
	Positive effect on society	0.073	0.8	0.8	0		
	Satisfied employees	0.148	−0.6	−0.6	0.8		
	Profitable operations	0.052	0.8	0	0		
	High quality service	0.530	0.4	1	0.4		
	Overall performance score	/	0.105	0.618	0.448		

Where z_k, o_k represents the weight distance and ranking distance for stakeholder k, the MILP always search the minimum weight modification to rank alternative 'E-freight bikes and micro-hubs' to a higher position for any stakeholder. For example, from MILP 1 (original criteria weights) to MILP 2, it finds the minimum

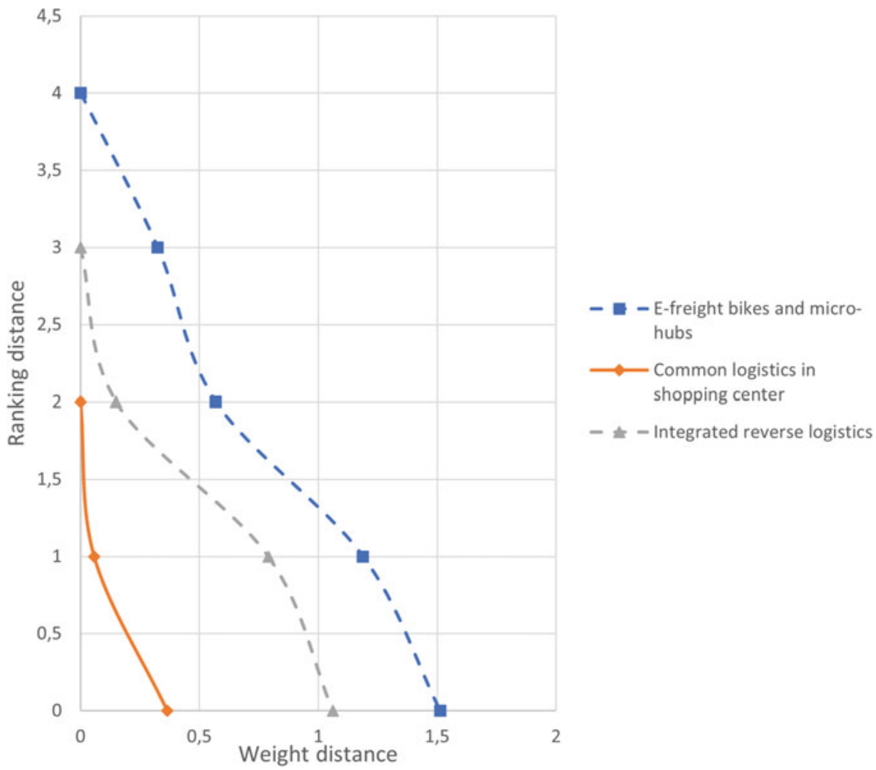

Fig. 2.3 MILP outputs

weight modification (0.324) that can help stakeholder ‘transport operator’ to rank ‘E-freight bikes and micro-hubs’ from worst position (3rd position) to a better position (2nd position). Thus, weight distance Z increases to 0.324, and ranking distance decreases to 3. However, this weight modification already results in a change of criteria rank compared to the original criteria rank information provided by the ‘transport operator’ stakeholder. Upon closer investigation, the first optimization alters the weight set elicited by ‘transport operator’ from $\{0.197, 0.073, 0.148, 0.051, 0.530\}$ to $\{0.188, 0.007, 0, 0.212, 0.53\}$. In this case, the ranks of the criteria “positive effect on society”, “low cost for receiving goods”, and “high quality deliveries” have changed. While we can still use the MILP to search for a better position, the further weight modification will always violate the ordinal consistency as illustrated in Table 2.3. Therefore, if the decision-makers want to choose the alternative ‘E-freight bikes and micro-hubs’ as the solution, they need to make a significant effort to persuade the stakeholders to reach a compromise (Table 2.4).

After conducting the MILP on all the alternatives, we can present the results in the form of a line chart, which connects the scattered points (Z^m, O^m). This visualization can provide a clear visualization of the performance of each alternative (see Fig. 2.3).

Where the Y-axis represents the ranking distances of all the alternatives; And the X-axis represents the weight distances. The lines with markers illustrate the rank changes of the alternatives with the weight modification. The dashed lines on the chart represent alternatives with weight modifications that violate rank order. It is important to note that all the ξ^Ls obtained after optimization surpass the approximated thresholds. Based on the result, we can find out 'common logistics in shopping center' is the only solution that can reach a consensus by all stakeholders, which the weight modification still preserves the same rank as the original rank. Although the alternative 'integrated reverse logistics' initially requires only a minor weight modification to improve its rank, the rank order of the criteria weights already differs from the original weights. The first optimization occurs in the stakeholder 'transport operator' by adjusting the weight of the third most important criterion, 'positive effect on society,' from 0.073 to 0, which turns it into the least important criterion. If decision-makers would like to adopt this alternative as solution, stakeholders need to make compromise. Although it is a simplified version of the decision-making process compared to the case study in [16], and the results of these two case studies are not comparable, it still addresses the limitation in the previous study. By validating ordinal consistency, the output of the MILP becomes more robust, allowing MAMCA to effectively identify both "consensual" and "compromise" alternatives in the decision-making process.

Conclusion

In the context of group decision-making framework MAMCA, stakeholders may encounter two main challenges during the decision-making process. The first challenge is related to the complexity and time-consuming nature of weight elicitation methods or MCDM methods. Stakeholders may find it difficult to comprehend the methods used for weight elicitation, resulting in elicitation results that do not reflect their preferences or expectations. Alternatively, they may not have enough time to understand and undertake the time-consuming elicitation process. The Best-Worst Method (BWM) is a possible solution to address this challenge due to its easy-to-understand and easy-to-implement process. By allowing stakeholders to compare the criteria or alternatives pairwise based on their best and worst, BWM saves time and cognitive resources compared to other complex elicitation methods. Moreover, the consistency ratio provided by BWM ensures that the elicited criteria weights are reliable and consistent, further strengthening the decision-making process.

On the other hand, due to the flexibility that MAMCA provides, allowing stakeholders to express their preferences during the decision-making process, arriving at a consensual solution can often be difficult due to conflicting interests among stakeholders. This can create significant challenges at the end of the evaluation process, leaving stakeholders struggling to find common ground. In this study, we propose a robust stakeholder-based group decision-making framework that utilizes BWM as a weight elicitation method in MAMCA to address both challenges. At the end of the evaluation, an optimization model was applied to help stakeholders find consensual solutions that could be accepted by all stakeholders while respecting the consistency in BWM. The consensus-reaching model built on top of BWM facilitates the identification of 'consensual' and 'compromise' alternatives. By allowing stakeholders to negotiate and modify the criteria weights, it fosters a collaborative decision-making process that takes into account the perspectives and preferences of all stakeholder groups involved. This promotes greater transparency, accountability, and legitimacy in the decision-making process and helps ensure that the final outcome aligns with the objectives and priorities of the stakeholder groups.

In this study, we have solely utilized the robust MAMCA-BWM framework on a didactic case, which has its inherent limitations due to the relatively simplistic nature of the problem. However, it is crucial to test its feasibility in more complex real-life decision-making problems. Therefore, in future research, we plan to apply the MAMCA-BWM framework on real-life cases to evaluate its practicality and effectiveness in addressing complex decision-making challenges faced by stakeholders in various fields. This will enable us to assess the generalizability and scalability of the proposed approach, and potentially identify opportunities for further improvements and refinements.

In conclusion, we would like to remind that the robust MAMCA-BWM framework is not the only MCGDM approach that can benefits from the advantage of BWM. In MAMCA-BWM, the linear BWM method is initially employed to quickly capture stakeholders' preferences. In contrast to the multi-stakeholder BWM presented by Liang et al. [38], which offers a range of criteria weights for stakeholders. MAMCA-BWM first attempts to identify a consensual solution. However, if a consensual solution is not found, an optimization model is applied as a post-hoc analysis. Rather than functioning as a decision-making framework, MAMCA-BWM operates more like as a decision-support framework. Its primary aim is to uncover stakeholders' perspectives and facilitate empathy-sharing during the decision-making process. The optimization model for consensus reaching serves as a mathematical proof for stakeholders to identify possible consensual solutions but is not a definitive result. Stakeholders have the autonomy to refuse to modify criteria weights, reject the proposed solution, or suggest reevaluation. The ultimate consensus should be reached through negotiation and discussion among stakeholders, with the model providing valuable support.

Appendix

The pairwise comparison vectors of stakeholders are shown in Table 2.5.

Table 2.5 Best-to-others (BO) and others-to-worst (OW) pairwise comparison vectors for three stakeholders

Shipper				
BO	Positive effect on society	Low cost for receiving goods	High quality deliveries	Attractive shopping environment
Best criterion: high quality deliveries	8	9	1	2
OW	Worst criterion: low cost for receiving goods			
Positive effect on society				2
Low cost for receiving goods				1
High quality deliveries				9
Attractive shopping environment				8
Receiver				
BO	Positive effect on society	Low cost for receiving goods	High quality deliveries	Attractive shopping environment
Best criterion: low cost for receiving goods	8	9	4	1
OW	Worst criterion: attractive shopping environment			
Positive effect on society				2
Low cost for receiving goods				1
High quality deliveries				4
Attractive shopping environment				9

Receiver					
BO	Viable investment	Positive effect on society	Satisfied employees	Profitable operations	High quality service
Best criterion: high quality service	5	8	4	9	1
OW		Worst criterion: profitable operations			
Viable investment					5
Positive effect on society					2
Satisfied employees					4
Profitable operations					1
High quality service					9

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Chapter 3
A Consistent and Consensual Best-Worst Method and Its Application to Salespersons' Performance Evaluation Problem

Nastaran Goldani and Mostafa Kazemi

Abstract It may be unrealistic to expect all experts to be specialized in all aspects of the problem and to reach full agreement in a multi-criteria group decision-making (MCGDM) process. This paper concerns obtaining solutions for a group decision-making problem, where consistency and consensus of decision-makers (DMs) are both considered. More specifically, the group decision-making (GDM) method is grounded on the best-worst method (BWM), called the consistent and consensual BWM. The method aims to minimize the inconsistencies of decision-makers' (DMs') comparisons and proposes collective weights based on the DMs' consensus. The reliability of the results is enhanced by including the reliability of the DMs' pairwise comparisons. The validity of the proposed method is indicated by conducting a case study on the salespersons' performance evaluation problem. To do so, the salespersons' performance evaluation criteria for a large selling company in Iran are identified at a particular time horizon. Then, the weights of the criteria are calculated using the proposed technique. For comparison analysis, we modify the conformity measure and total deviation to be compatible with the results of the GDM model.

Keywords Best-worst method (BWM) · Multi-criteria group decision-making (MCGDM) · Consensus · Sales · Performance evaluation

Introduction

It is challenging for a single decision maker (DM) to consider all factors of a problem due to the inevitable growing complexity of contemporary socioeconomic environments [1]. Indeed, in major industries, technical groups make significant decisions on product design, staff selection, and performance evaluation. Consequently, the

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multi-criteria group decision-making (MCGDM) concept appears to deal with these complicated decision-making problems [2]. Various DMs with varying levels of expertise and different viewpoints get together to find a common solution. The primary source of the various points of view could be uncertainty, conflict, and misunderstanding among experts [3]. There are different techniques to deal with different views, including (I) sharing, aiming to obtain a common solution by negotiating and discussing the attitudes. It goes to reduce the differences between attitudes. (II) Aggregating, achieve the final and common solution by compromising. Different attitudes are acknowledged but not reduced by negotiations or discussions in this technique. (III) Comparing, aims to reach a consensus among experts without necessarily reducing the differences between their attitudes [3].

Among these techniques, models based on sharing techniques can be very time-consuming [3]. The aggregation process, however, requires less time for a discussion and may derive rigid solutions disregarding agreements of experts [3]. Therefore, it is probable for experts to refuse to accept the obtained solutions because they believe their preferences were not adequately considered [4]. Consensus measures [5] and consensus reaching processes (CRPs) [6–8] are developed to obtain agreed solutions and to soften the inevitable part of the group decision-making (GDM) problems, which is disagreement among experts.

Mostly, DMs' evaluations suffer from some cognitive biases. The best-worst method (BWM) is one of the most recent multi-criteria decision-making (MCDM) methods established based on pairwise comparison [9]. Compared to the analytic hierarchy process (AHP), it needs less number of comparisons and produces more reliable results [10]. The comparisons are taking place regarding only two reference points, the best and the worst criteria, to determine the criteria weights. This characteristic feature of the method has captured scholars' attention [11] by reducing some cognitive biases, such as equalizing bias [12].

There exists some research that modified the BWM to be compatible with the GDM context [13–16], but they do not take consensus and consistency of evaluations into account. Therefore, this paper tries to propose a model in which not only the group consensus but also group consistency and individual consistency are considered. Indeed, the proposed BWM can deal with GDM problems by taking into account group inconsistency, and group consensus. The new MCGDM method is applied to obtain the criteria weights of salespersons' performance evaluations.

Sales organizations expect their salespeople to handle increasingly complex sales situations, persuade buyers to purchase more in increasingly competitive environments and meet overall organizational sales goals [17, 18]. Given the importance of salesperson performance, many scholars have concentrated on exploring different criteria and investigating their performance [19, 20]. In this paper, we define some key performance indicators (KPIs) to evaluate the sales persons' performances of one of the branches of a large selling company in Iran. To this aim, KPIs are determined regarding experts' opinions on the specific time of the study. Then, the proposed method is used to derive the criteria weights while aiming to reach the maximum achievable consensus among different experts involved in the decision-making and minimize their inconsistencies.

The remainder of this paper is organized as follows. Section "Literature Review" provides the literature review on the BWM and group BWM. Some background knowledge related to the paper is presented in section "Preliminaries". Section "The Proposed Method" is dedicated to the proposed method. Section "Case Study" presents the case study and discussion of the obtained results. Finally, the conclusion, future research direction, and the limitations of this work are proposed in section "Conclusion".

Literature Review

Scholars investigated the BWM from different perspectives. Some of them extended the method within different types of uncertainty theories [15, 21–23], and implemented it in different application areas [24–26]. Researchers also detected the effects of some cognitive biases that may exist within the GDM on the BWM [12, 27, 28]. There is another category of research that aims to solve GDM problems. For example, Hafezalkotoba and Hafezalkotoba [15] proposed a GDM method within the fuzzy environment. The proposed method can be applied to the problem with the hierarchical structure of DMs. Safarzadeh et al. [16] proposed a model for group BWM in which the individual and group inconsistencies are minimized. Mohammadi and Rezaei [13] presented a novel extension of the BWM, called Bayesian BWM, to calculate the criteria weight based on the distribution functions. Liang et al. [14] proposed a consensus model for GDM problems. The criteria weights are determined using the BWM. Then, alternatives are ranked based on the consensus of experts' evaluation. Benefiting from the idea of the BWM model and information granules, Qin et al. [29] proposed a new GDM model. They tried to minimize the individuals' inconsistencies using the particle swarm optimization algorithm and tried to minimize DMs' conflicts through an iterative algorithm. The main contributions of the paper are:

- We propose a new group BWM aiming to minimize group inconsistencies and reach the maximum achievable consensus among DMs.
- We modify conformity and total deviation (TD) to analyze the outputs of the proposed model.

Preliminaries

In this section, we briefly review the related concepts to the paper.

Consensus Reaching Processes

In a complex decision-making problem, when the required data are vague or imprecise, the necessity of incorporating different viewpoints and the use of a group of DMs' knowledge raises. Although having multiple DMs involved in the decision-making process has several benefits, it also leads to a significant problem: the arising of conflicts among them [30]. If conflicts fail to be appropriately handled before going for the best alternative, this alternative might not satisfy some experts, calling the process's trustworthiness into question [31]. CRPs are used to smooth out potential conflicts between expert viewpoints and arrive at an agreed-upon solution to the decision problem [32]. Therefore, to increase the degree of agreement within the group, experts converse with one another, share thoughts, and they may revise their initial viewpoints. This procedure is frequently led by a moderator, who is in charge of spotting disagreements and offering revisions to experts' viewpoints [33]. Different consensus approaches have been proposed in the literature. Some ask experts to adjust their choices through feedback methods [34]. However, other solutions offer an automatic approach in which experts are not asked to change their choices but are instead changed automatically [35].

Best-Worst Method

BWM is developed as a pairwise comparison method based on the two vectors that attempt to structure the assessment process carried out by a DM [13]. To calculate the criteria weights, two optimization models based on the multiplicative framework were proposed within the crisp environment [36]. The non-linear form of the BWM can produce multiple optimal solutions, whereas the linear form produces unique optimal solutions. In what follows, the steps and linear model of the BWM are presented.

1. Determine a set of decision criteria $C = \{c_1, c_2, c_3, \ldots, c_n\}$.
2. Specify the best or the most favorable criterion c_B and the worst or the least favorable criterion c_W.
3. Conduct the pairwise comparison using a 1–9 scale [37]. In this step, a DM expresses the preferences of the best criterion over the others to obtain the best to others (BO) vector.

$$A_{BO} = \{a_{B1}, a_{B2}, a_{B3}, \ldots, a_{Bn}\} \tag{3.1}$$

   where a_{Bi} represents the preference of the best criterion over criterion i.
4. Similar to the previous step. DM expresses the preference of criterion i over the worst criterion to obtain the others-to-worst (OW) vector.

$$A_{OW} = \{a_{1W}, a_{2W}, a_{3W}, \ldots, a_{nW}\} \tag{3.2}$$

where a_{iW} represents the preference of criterion i over the worst criterion.

5. To derive the criteria weights, the following optimization model was introduced aiming to reduce the inconsistencies of pairwise comparisons. The method was deeply discussed by Rezaei [10].

$$
\begin{aligned}
&\text{Min } \xi \\
&\text{subject to} \\
&|\, w_B - a_{Bi} \times w_i \,| \leq \xi && i = 1, 2, \ldots, n \\
&|\, w_i - a_{iW} \times w_W \,| \leq \xi && i = 1, 2, \ldots, n \\
&\sum_{i=1}^{n} w_i = 1 \\
&w_i \geq 0, && i = 1, 2, \ldots, n
\end{aligned}
\tag{3.3}
$$

where w_i is the weight of criterion i, and ξ is the inconsistency value of a DM conducting the pairwise comparisons.

The Proposed Method

In this section, the consistent and consensual BWM is presented. The proposed method tries to obtain solutions regarding the maximum achievable consensus among experts while minimizing their inconsistencies in pairwise comparisons.

Consider there is a group of m experts $DM_k(k = 1, 2, \ldots, m)$, aiming to determine the importance of the n criteria $c_i(i = 1, 2, \ldots, n)$. The steps of the proposed method are as follows:

1. Determine a set of criteria $C = \{c_1, c_2, c_3, \ldots, c_n\}$.
2. Specify the best and the worst criteria, which are indicated by c_B and c_W, respectively. In this stage, each DM_k expresses c_B and c_W from her/his perspective. The best criterion refers to the most important or the most favorable, and the worst criterion refers to the least important or the least favorable criterion regarding the DM's point of view.
3. Determine the preference of the best criterion over other criteria using a 1–9 scale [37]. In this step, each DM performs these comparisons, and the result of these comparisons is the BO vector, which is as follows:

$$A^k_{BO} = \{a^k_{B1}, a^k_{B2}, a^k_{B3}, \ldots, a^k_{Bn}\} \tag{3.4}$$

where a^k_{Bi} indicates the preference of the best criterion over the i-th criterion from DM_k point of view.

4. Determine the preference of criterion i over the worst criterion using a 1–9 scale [37]. The result of these comparisons is the OW vector regarding the DM's point

of view, which is as follows:

$$A_{OW}^{k} = \{a_{1W}^{k}, a_{2W}^{k}, a_{3W}^{k}, \ldots, a_{nW}^{k}\} \tag{3.5}$$

where a_{iW}^{k} indicates the preference of the i-th criterion over the worst criterion from DM_k's point of view.

5. Compute the input-based consistency ratio (CR_k^I) [38] regarding DM_k's evaluations, as follows:

$$CR_k^I = \max_j \{CR_{jk}^I\} \tag{3.6}$$

where

$$CR_{jk}^I = \begin{cases} \frac{|a_{Bj}^k \times a_{jW}^k - a_{BW}^k|}{a_{BW}^k \times a_{BW}^k - a_{BW}^k}, & \text{if } a_{BW}^k \geq 1 \\ 0, & \text{if } a_{BW}^k = 1 \end{cases} \tag{3.7}$$

Note: The obtained CR_k^I should be less than its corresponding threshold shown in Table 3.1. Otherwise, the pairwise comparison/s should be conducted again by the DM_k [38].

6. Calculate the criteria weights utilizing the following optimization model.

$$\begin{aligned} & \text{Min } \xi + \eta \\ & \text{subject to} \\ & \mid w_{Bk} - a_{Bi}^k \times w_{ik} \mid \leq \xi_k && i = 1, 2, \ldots, n, k = 1, 2, 3, \ldots, m \\ & \mid w_{ik} - a_{iW}^k \times w_{Wk} \mid \leq \xi_k && i = 1, 2, \ldots, n, k = 1, 2, 3, \ldots, m \\ & \xi_k \leq \xi && k = 1, 2, 3, \ldots, m \\ & \sum_{i=1}^{n} w_{ik} = 1 && k = 1, 2, 3, \ldots, m \\ & w_i^c = \frac{(\prod_{k=1}^{m} w_{ik})^{\frac{1}{m}}}{\sum_{i=1}^{n} (\prod_{k=1}^{m} w_{ik})^{\frac{1}{m}}} && i = 1, 2, \ldots, n \\ & \mid w_{ik} - w_i^c \mid \leq \eta && i = 1, 2, \ldots, n, k = 1, 2, 3, \ldots, m \\ & w_{ik} \geq 0 && i = 1, 2, \ldots, n, k = 1, 2, 3, \ldots, m \end{aligned} \tag{3.8}$$

where ξ^k is the maximum inconsistency of the DM_k. Similarly, ξ indicates the maximum value of the group inconsistency. η is a consensus variable. However, it can be considered a parameter. Since we are using Saaty multiplicative scale, the geometric mean aggregation method is utilized as an aggregation function. w_i^c is the collective weight of the criterion i derived from the geometric mean method. Since it satisfies the non-negativity and unit-sum constraint, we consider it the collective weight of criterion i. Of note, the value of ξ^k is at most one. Consequently, ξ is not greater than one. Therefore, the maximum obtained value

Table 3.1 Threshold values for CR_k^I

Scales	Criteria						
–	3	4	5	6	7	8	9
3	0.17	0.17	0.17	0.17	0.17	0.17	0.17
4	0.11	0.15	0.19	0.22	0.25	0.26	0.27
5	0.14	0.20	0.23	0.25	0.27	0.28	0.30
6	0.13	0.20	0.26	0.30	0.31	0.32	0.33
7	0.13	0.25	0.28	0.30	0.31	0.33	0.34
8	0.13	0.25	0.30	0.32	0.34	0.36	0.37
9	0.14	0.27	0.31	0.33	0.35	0.36	0.37

of the first part of the objective function is less than or equal to one. The same goes for the second part of the objective function, which shows they are truly summable.

Case Study

The performance evaluation of the salesperson mainly occurs multiple times a year, which can be monthly or even less than a month [39]. This process is based on different KPIs.

The diary company Kalleh aims to evaluate the salespersons' performance of one of its branches. The company tries to maximize its cash flow, and all salespersons are forced to minimize paper check payments, especially long-term ones. Thus, regarding the aim of the company and holding some meetings with the three experts employed by the company, the criteria are obtained as follows:

c_1 = The percentage of achieving the goals,
c_2 = The percentage of waste return,
c_3 = The percentage of sales growth,
c_4 = The percentage of paper check payments,
c_5 = The percentage of customers who bought the products.

After defining a set of evaluation criteria, regarding the steps of the proposed method explained in section "The Proposed Method", each DM determines the best and the worst criteria. Afterward, they express the BO and OW vectors to indicate their preferences. Table 3.2 shows the BO and the OW comparisons, as well as the value of CR_{jk}^I ($j = 1, 2, 3, 4, 5$; $k = 1, 2, 3$) and CR_k^I ($k = 1, 2, 3$), regarding each DMs' data. The pairwise comparisons are validated by calculating Eq. 3.6. Considering Table 3.1, since all pairwise comparisons are less than a predefined threshold, DMs are rational, and all comparisons are reliable.

Solving Eq. 3.8, the criteria weights are obtained. $w_1 = 0.186$, $w_2 = 0.042$, $w_3 = 0.254$, $w_4 = 0.451$, $w_5 = 0.067$, and the order of criteria is $c_4 > c_3 > c_1 > c_5 > c_2$.

Table 3.2 Pairwise comparisons and corresponding input-based consistency ratios

Expert		c_1	c_2	c_3	c_4	c_5	CR_k^I
DM_1	a_{Bj}^1	4	9	3	1	6	0.25
	a_{jW}^1	5	1	9	9	4	
	CR_{j1}^I	0.15	0	0.25	0	0.21	
DM_2	a_{Bj}^2	3	9	1	2	5	0.152
	a_{jW}^2	6	1	9	7	4	
	CR_{j2}^I	0.125	0	0	0.069	0.153	
DM_3	a_{Bj}^3	2	6	4	1	9	0.292
	a_{jW}^3	7	5	6	9	1	
	CR_{j3}^I	0.069	0.292	0.208	0	0	

The most important and the least important criterion are c_4 and c_2, respectively. According to Table 3.2, since c_4 and c_2 are identified as the most and the least important criterion, we can see that the derived solutions served the DMs' expectations. The obtained consensus value is $\eta = 0.219$, and the group consistency is $\xi = 0.043$, which can be regarded as consistent and agreed results.

It needs to mention that in case of inconsistent pairwise comparisons, the correspondent DM will ask to reestablish her/his decisions.

Discussion

In order to analyze the results of the proposed method, we define nine different scenarios. Each scenario is defined based on the different values of η, such that $\eta = (0.01, 0.02, 0.05, 0.1, 0.15, 0.2, 0.219, 0.5, 1)$, and the model is investigated in terms of the obtained group consistency degree, consensus values, conformity measure, and the TD value [9]. To perform the comparative analysis, we used R software and executed codes on a PC with Intel(R) Core(TM) i5-10400 CPU 2.90 GHz with 16.0 GB RAM.

Figure 3.1 shows the values of ξ and η in each scenario. The increase in ξ leads to a decrease in η. Clearly, there is a trade-off between these two values. The optimal values of ξ and η derived by solving Eq. 3.8 are 0.0434 and 0.219, respectively. According to Fig. 3.1, the approximate intersection between the different values of ξ and η can be considered at the $\xi = 0.141$ and $\eta = 0.15$ points, corresponding to scenario 5. Since we do not compute any threshold for ξ and η, we see these values as approximate thresholds. The following comparative analyses are conducted regarding different scenarios.

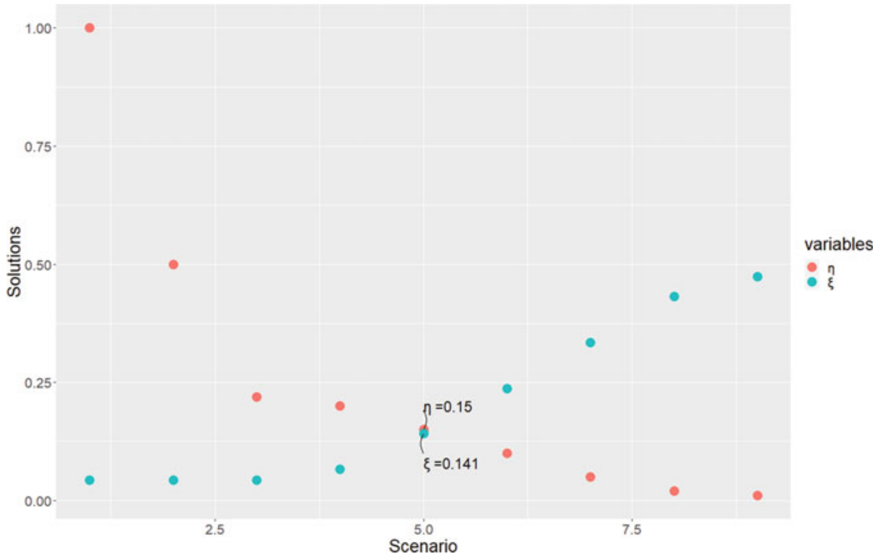

Fig. 3.1 Different values of ξ and η

Conformity

The conformity measure is the difference between the collective weights and the weights obtained from DMs' evaluations. This measure is used to determine the final appropriate criteria weights. The conformity measure is:

$$C_k = \sum_{i=1}^{n} \mid w_i^c - w_i^k \mid, k = 1, 2, 3, \ldots, m. \tag{3.9}$$

where C_k indicates the level of conformity of the obtained weights from DM's preferences to the collective weights. The closer the value to zero, indicating that the closer the preferences of DM_k to the collective preferences. Figure 3.2 shows the different values of conformity measures in defined scenarios. According to this figure, the conformity measure is approximately starting to decrease in $\xi = 0.141$ and $\eta = 0.15$, which can be a justification for determining $\xi = 0.141$ and $\eta = 0.15$ as thresholds.

Total Deviation (TD)

TD value indicates the distance between the relative preferences of the DM_k and the criteria weights. On the other hand, the TD value implies the cardinal consensus of the group. The closer the value to zero indicates the preferences of DM_k are closer to the collective weights. The TD value can be calculated as follows:

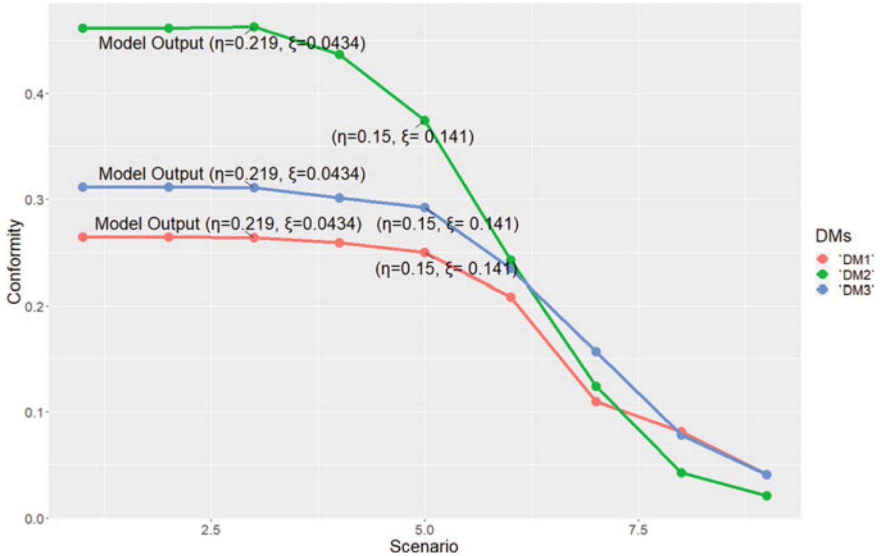

Fig. 3.2 Conformity measure

$$TD_k = \sum_{i=1}^{n}(w_B^c - a_{Bi}^k \times w_i^c)^2 + (w_i^c - a_{iw}^k \times w_W^c)^2, k = 1, 2, 3, \ldots, m. \quad (3.10)$$

where TD_k is obtained from the elicited preferences of the DM_k and the obtained collective weights. Investigating a threshold for this measure could be an interesting future research direction. However, since, no threshold is defined in this paper, we analyzed the obtained solutions in terms of different scenarios. Figure 3.3 indicates the TD values in different scenarios. Regarding Fig. 3.3 the TD values are going to increase at $\eta = 0.15$ and $\xi = 0.141$; therefore, we can consider those values as appropriate thresholds for η and ξ.

Finally, we conclude that Figs. 3.1, 3.2, and 3.3 converge to the same solutions. Indeed, approximately, all three figures show that $\eta = 0.15$ and $\xi = 0.141$ could be the threshold for η and ξ. It is evident that in the worst case where $\eta = 1$, there is no consensus among DMs, the conformity measure and TD value get the maximum value. In contrast, the group consistency reached the minimum level. In the following section, we perform Pearson correlation analysis with the generated outputs, TD value and conformity measure.

Correlation Analysis

Since in sections "Conformity" ans "Total Deviation (TD)" we stated that the graph direction of conformity measure and TD values in different scenarios can have a rela-

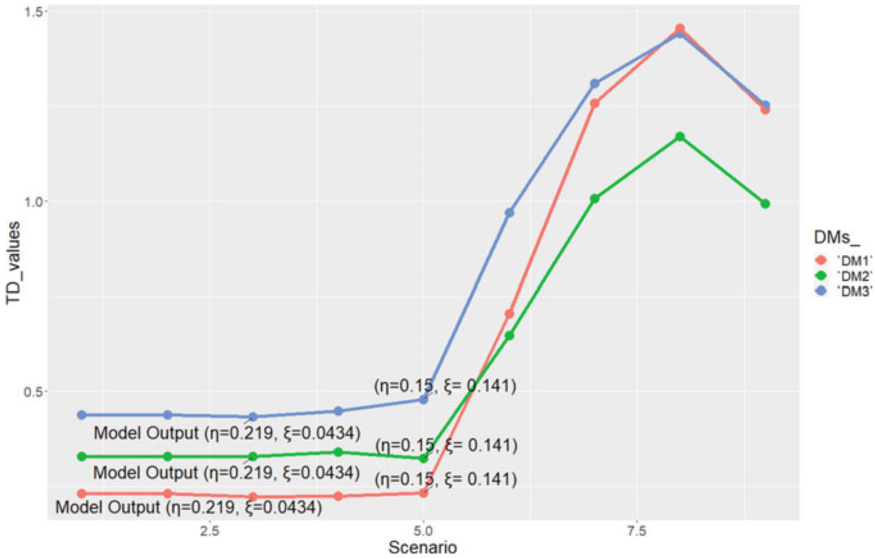

Fig. 3.3 TD values

tion with group consensus and consistency, we analyze the correlation between group consensus and consistency between conformity measure and TD values. Figure 3.4 indicates the results of execution of Pearson correlation analysis. The numbers in lower triangular squares represent the correlation between different variables and the circles in upper triangular squares are visualization of their corresponding numbers.

We can see that TD values and conformity measures have a strong correlation with group consistency. There is also a considerable correlation between group consensus, TD value and conformity measure. In this visualization negative values show the opposite behaviors of variables which can be easily found in Figs. 3.2 and 3.3. TD values have a negative correlation with group consensus and a positive correlation with group consistency, which is exactly vice versa for conformity measures. Also, there is a strong negative correlation between TD values and conformity measures. Consequently, analyzing the validity of the obtained results through conformity and TD values are logically correct.

Consequently, according to the optimal solution derived from the model and the determined threshold for η and ξ, we found that the DMs' preferences need to be modified. However, since, we do not have access to the DMs to reestablish the pairwise comparisons, we try to find the appropriate criteria weight automatically using the defined scenarios. Therefore, we consider the obtained weights corresponding to $\eta = 0.05$ as the final weights of the criteria. It needs to mention that this consideration is taken intuitively with regards to Figs. 3.2 and 3.3.

In what follows, we compare the corresponding solutions to $\eta = 0.05$ with those obtained by solving the problem through the geometric mean aggregation method.

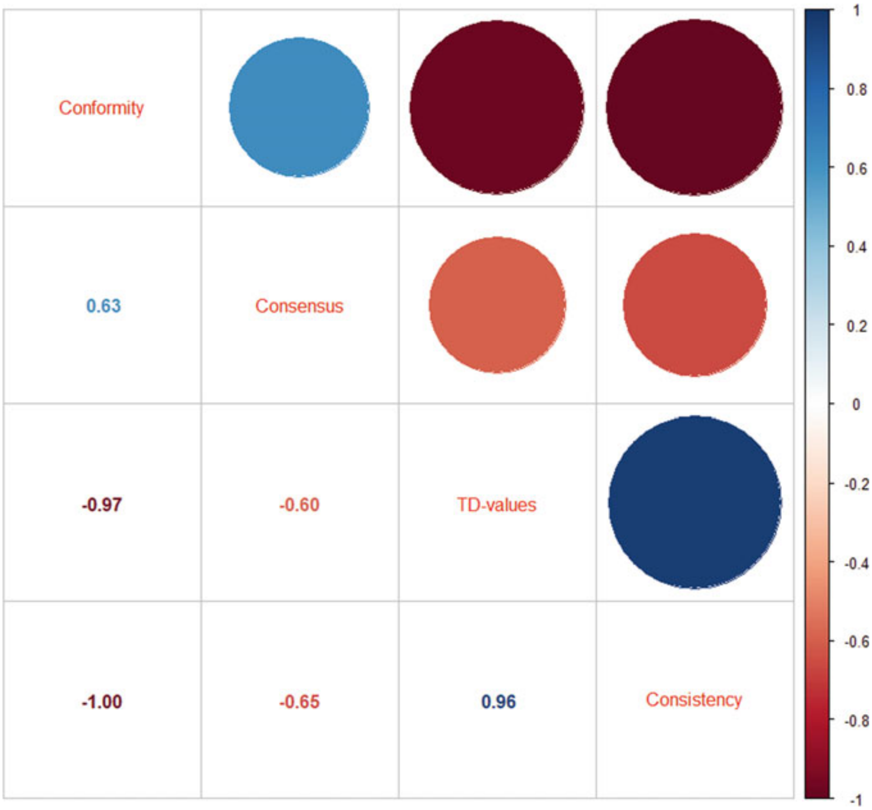

Fig. 3.4 Correlation analysis result

Comparison with the Geometric Mean

In this section, first, we discuss the philosophy of the central tendency method (geometric mean) within the concept of CRP. Then the results obtained from the geometric mean and the proposed method are compared.

There are several issues with the geometric mean as a consensus-driven strategy. Using the geometric mean, it is assumed that all experts will use the mean score as the final score. In other words, the technique does not take into account the range of values that many experts have offered. The geometric mean assumes that all group members have the same level of expertise on the issue, which is not the case in many GDM problems [40]. Because of its ease of use in mathematical computations, the geometric mean technique is used in many applications. However, the philosophy of negotiation, which is not considered in the geometric mean technique, is the cornerstone of the consensus-reaching models [40]. More specifically, since our model derives weight in a simplex environment, not in a real space applying geometric mean on priorities does not sound correct (for more detail, see [41]).

Table 3.3 Criteria weights and consistency values obtain from the different data sets

Method	c_1	c_2	c_3	c_4	c_5	ξ
Rezaei's method [10] using DM_1 data set	0.157	0.056	0.248	0.408	0.079	0.14
Rezaei's method [10] using DM_2 data set	0.169	0.040	0.435	0.253	0.101	0.073
Rezaei's method [10] using DM_3 data set	0.277	0.09	0.138	0.452	0.038	0.102
Geometric mean results	0.207	0.056	0.248	0.408	0.079	–

Table 3.4 Standard deviations of each criterion weight obtained by the proposed method and the geometric mean method

Method	c_1	c_2	c_3	c_4	c_5	ξ
The proposed method with $\eta = 0.05$	0.0235	0.0193	0.036	0.0326	0.0159	0.335
Geometric mean results	0.0541	0.0249	0.1265	0.1036	0.0303	–

Table 3.3 shows the obtained results of solving the case study by Rezaei's method [10] and the aggregated weights by the geometric mean. It is clear that obtaining the final weights using the geometric mean does not provide any information about the group's consistency. Moreover, considering Table 3.4, the standard deviations of the obtained weights using the proposed method for $\eta = 0.05$ are significantly less than the corresponding values obtained by geometric mean, which shows that the DMs' preferences must be modified and geometric mean aggregation is not the appropriate method for this problem.

Conclusion

The BWM has been used successfully to solve complex decision problems in various fields as an effective tool [42]. In this study, we proposed a modified BWM to solve MCGDM problems by taking both group consistency and consensus into account. The reliability of the DMs' pairwise comparisons was examined using the input-based consistency ratio. The proposed model respects all underlying ideas of the original BWM and it is as easy as the original method in eliciting information from DMs. The salespersons' performance evaluation problem was studied to show the validity of the proposed method. To do so, we first determined the criteria for evaluating salespersons' performance, and then the criteria weights were obtained using the proposed method. Two measures, TD value and conformity measure, were used to analyze the obtained results. A correlation analysis was conducted to investigate the relation between the group consistency, consensus, TD values, and conformity measure. The analysis indicated that there is a strong correlation between the examined outputs and measures. Finally, by comparing the results obtained from the presented model with the results obtained from the geometric mean method, we showed that the geometric mean is not a suitable method for obtaining collective weights of criteria in this problem.

Limitation and future research direction: First, In this paper, we do not examine different biases that may exist within the group of experts, and we do not investigate the probable effects of biases on the model. Consequently, no anti-biased strategy has been proposed in this paper. Therefore, detecting different biases and providing an appropriate anti-biased strategy would be an interesting future research avenue. Second, it would be of great interest to propose a consistency and consensus-improving algorithm. Regarding the mentioned limitations, it might be a place for future studies to analyze the effects of the results of the consistency and consensus-improving algorithm and the results of the anti-biased strategy on the collective weights. Third, defining group consistency and consensus threshold would benefit understanding the validity of the obtained results. So, it can be another direction for future research. Forth, since the identified criteria for evaluating salespersons' performances were defined at a particular time, future research can focus on eliciting more general subjective and objective criteria for this problem.

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Chapter 4
Which Prioritization Method Is Better for Deriving Priority from Best-Worst Preferences? A Theoretical and Experimental Analysis

Bapi Dutta, Diego García-Zamora, Álvaro Labella, and Luis Martínez

Abstract The Best-Worst Method (BWM) is a popular multi-criteria decision-making tool to prioritize alternatives or criteria via a set of subjective pairwise judgments. Deriving the priority weights from best-to-others and others-to-worst preferences is one of the key issues, and several prioritization methods have been proposed to address it. However, their behavior and performances in different situations are yet to investigate. In this study, we analyze the performance of four prioritization methods from theoretical and experimental perspectives. For this purpose, we first show that when the given preference is fully multiplicative consistent, the prioritization methods produce the same weight priority, and it can directly obtain through the analytic formulae without solving the optimization model. For inconsistent preferences, the prioritization methods are compared in terms of deviation from the original preferences and total order violation measures. Simulation experiments suggest that Euclidean distance and order violations metric based measures could lead to different choices of prioritization methods.

Keywords Best-worst method · Multicriteria decision-making · Prioritization method

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Introduction

Pairwise comparison is one of the fundamental notions to model qualitative comparative judgments by estimating the dominance in making comparisons [8, 10]. This typical method of judgment allows the decision-maker to concentrate on two objects at a time, and thus reduces the cognitive effort of the decision-maker in the preference elicitation [2]. Due to this obvious advantage, it has been adopted as a prioritization tool in the Analytic Hierarchy Process (AHP), which attempt to solve complex decision-making problem by decomposing them into a hierarchical structure and comparing the objects at different levels of the hierarchy via the pairwise fashion [7]. This simplified pairwise comparison structure in AHP was one of the key attributes of becoming the most popular and widely used multicriteria decision-making (MCDM) tool to solve decision-making problems [9, 11]. Despite its many successful applications, the number of required judgments could overwhelm the decision-maker when comparing more than five objects.

To overcome the earlier limitation, Rezaei [5] proposed Best-Worst Method (BWM) for the prioritization of objects by focusing on two specific stimuli, namely the Best and Worst objects, and comparing them with the rest of the objects. Further, it requires only $2n - 3$ judgments in comparison to $(n^2 - n)/2$ in AHP. Since its advantages over AHP, BWM has been widely used in solving a wide range of practical prioritization problems [4].

One of the important aspects of applying BWM is the choice of the prioritization method for finding priority weights from the best-to-others and others-to-worst preferences. Initially, Rezaei [5], proposed a non-linear optimization model to derive priority by minimizing the maximum deviation from the original preference. Later, a two-stage optimization model was proposed to find the interval weight, assuming that the non-linear model might have multiple solutions [6]. In addition, a relaxed linear model of the original model has been also been proposed to obtain priority [6]. Adopting a new metric, which is claimed to be more suitable than the original absolute value metric, Brunelli and Rezaei [1] proposed a linear optimization model to derive the priority weight.

Even though, there have been proposed several prioritization methods, it is not clear which one is better or how they perform under different levels of consistency in the initial judgments. Therefore, it is important to understand the proper dynamics of this prioritization method. Understanding the proper dynamics would help the DMs to choose the appropriate prioritization method based on their preference over the performance measuring aspects. With this view, this study aims at analyzing the prioritization methods from theoretical and experimental perspectives under different assumptions on the consistency of initial preference.

This study is outlined as follows. In section "Background", we briefly describe optimization models that are used to derive priority from original Best-Worst preferences. The analysis of the prioritization methods from the theoretical perspectives in the case of full multiplication preferences is described in section "Analyzing the Prioritization Methods" with an analytic formula to derive the priority weight. In addition, a simulation experiment is conducted to analyze the performance of the prioritization method under two measures, specifically, distance from original preference and total order violation in section "Analyzing the Prioritization Methods". We draw the conclusion of the study in section "Conclusions".

Background

In this section, we briefly overlay the BWM and different prioritization methods.

Best-Worst Method

Rezaei [5] proposed the BWM method to obtain priority among a set of objects $O = \{O_1, O_2, \ldots, O_n\}$ from $2n - 2$ pairwise comparisons. The process starts with the choice of the best and worst objects (say, O_B and O_W) from the set O by the decision-maker (DM). Afterward, DM compares the best object O_B and O_W to other objects in the set O in the pairwise fashion using Saaty's 1–9 numeric scale and summarizes as vectors BO and WO in the following:

$$BO = \begin{matrix} O_1 & O_2 & \cdots & O_B & \cdots & O_W & \cdots & O_n \\ (r_{B1} & r_{B2} & \cdots & r_{BB} & \cdots & r_{BW} & \cdots & r_{Bn}) \end{matrix}$$

$$OW = \begin{matrix} O_1 & O_2 & \cdots & O_B & \cdots & O_W & \cdots & O_n \\ (r_{1W} & r_{2W} & \cdots & r_{BW} & \cdots & r_{WW} & \cdots & r_{nW}) \end{matrix}$$

where $r_{Bj}, r_{jW} \in \{1, 2, \ldots, 9\}$ with $r_{BB} = 1$ and $r_{WW} = 1$. The given BO and OW preferences are said to be fully multiplicative consistent if $r_{Bj} \times r_{jW} = r_{BW}, \forall\ j = 1, 2, \ldots, n$. To obtain priority from BO and OW preference, several proposals have been put forward. In the following section, the existing optimization approaches to obtain the priority weight are described.

Prioritization Methods

Non-linear Programming Based Prioritization Method

This method was originally proposed to obtain the priority $w = (w_1, w_2, \ldots, w_n)$ from BO and OW by minimizing the maximum deviation of the weights from BO and OW preferences, and it can be put in the following non-linear optimization problem [5]:

$$\min\ \zeta$$
$$\text{s.t.}\ \begin{cases} |\frac{w_B}{w_j} - r_{Bj}| \leq \zeta, \forall\ j = 1, 2, \ldots, n \\ |\frac{w_j}{w_W} - r_{jW}| \leq \zeta, \forall\ j = 1, 2, \ldots, n \\ \sum_{j=1}^{n} w_j = 1, \\ w_j \geq 0,\ \forall\ j = 1, 2, \ldots, n. \end{cases} \tag{NLP-M}$$

Solving the (NLP-M), we obtain the priority weight w and optimal value ζ^*, which is used as an estimate of consistency for the given pairwise comparisons.

Linear Programming Based Prioritization Method

This method was developed by Rezaei [6] as a relaxation of (NLP-M) model. By replacing the non-linear term ζw_j in (NLP-M) with its upper bound ζ, the following linear optimization problem was proposed to obtain the priority w:

$$\min\ \zeta$$
$$\text{s.t.}\ \begin{cases} w_B - r_{Bj} w_j \leq \zeta,\ \forall\ j = 1, 2, \ldots, n \\ w_B - r_{Bj} w_j \geq -\zeta,\ \forall\ j = 1, 2, \ldots, n \\ w_j - r_{jW} w_W \leq \zeta,\ \forall\ j = 1, 2, \ldots, n \\ w_j - r_{jW} w_W \geq -\zeta,\ \forall\ j = 1, 2, \ldots, n \\ \sum_{j=1}^{n} w_j = 1, \\ w_j \geq 0,\ \forall\ j = 1, 2, \ldots, n. \end{cases} \tag{LP-M}$$

Interval Prioritization Method

In this approach, the interval priority weights are obtained by solving a two stages optimization problem. In the first stage, we obtain ζ^* by solving the problem (NLP-M). In the second stage, the interval weight is obtained by solving the optimization problem [6]:

$$\text{optimize}\ w_j$$
$$\text{s.t.}\ \begin{cases} |\frac{w_B}{w_j} - r_{Bj}| \leq \zeta^*,\ \forall\ j = 1, 2, \ldots, n \\ |\frac{w_j}{w_W} - r_{jW}| \leq \zeta^*,\ \forall\ j = 1, 2, \ldots, n \\ \sum_{j=1}^{n} w_j = 1, \\ w_j \geq 0,\ \forall\ j = 1, 2, \ldots, n. \end{cases} \tag{Int-M}$$

Solving the model (Int-M) for min and max for each j produce the interval priority. The mid-point of the intervals or interval comparison is used to obtain the final prioritization.

Multiplicative Prioritization Method

Rather than the distance metric used in the above prioritization models, Brunelli and Rezaei [1] adopted a new multiplicative metric to measure the deviation and proposed a linear optimization model to obtain the priority as follows:

$$\min \ \zeta$$
$$\text{s.t.} \begin{cases} l_{Bj} - (v_B - v_j) = x_{Bj}^{+} - x_{Bj}^{-}, \ \forall\ j = 1, 2, \ldots, n \\ x_{Bj}^{+} + x_{Bj}^{-} \leq \zeta, \ \forall\ j = 1, 2, \ldots, n \\ l_{jW} - (v_j - v_W) = y_{jW}^{+} - y_{jW}^{-}, \ \forall\ j = 1, 2, \ldots, n \\ y_{jW}^{+} + y_{jW}^{-} \leq \zeta, \ \forall\ j = 1, 2, \ldots, n \\ \sum_{j=1}^{n} v_j = 0, \\ x_{Bj}^{+}, x_{Bj}^{-}, y_{Bj}^{+}, y_{Bj}^{-} \geq 0, \ \forall\ j = 1, 2, \ldots, n \end{cases} \quad \text{(LMult-M)}$$

where $l_{Bj} = \ln(r_{Bj})$, $l_{jW} = \ln(r_{jW})$ and $v_j = \ln(w_j)$ for all $j = 1, 2, \ldots, n$. The priority weight is given by $w_j = \exp(v_j^*)/\sum_{k=1}^{n} \exp(v_k^*)$.

Analyzing the Prioritization Methods

This section aims at analyzing the prioritization methods from theoretical and experimental perspectives. From the theoretical perspective, we show that all methods produce the same solution when the multiplicative consistency is preserved in the given preference. In this case, the analytical solution could be found by solving a system of linear equations. From the experimental perspective, we measure the performance of the prioritization methods based on the Euclidean distance from the original preference and the violation of the total ordinal orders from the preference.

Analytic Solution

Here, we analyze the behavior of the prioritization method for full multiplicative consistent preference, which we state in the following theorems.

Theorem 4.1 *When the given BO and OW preferences are fully multiplicative consistent, i.e.,* $r_{Bj} \times r_{jW} = r_{BW}$, $\forall\ j = 1, 2, \ldots, n$, *the prioritization models (NLP-M), (LP-M), (Int-M) reduced to a system of equations and the priority weight* *is given by*

$$w_j = \frac{1}{(\sum_{k=1}^{n} \frac{r_{Bj}}{r_{Bk}})} \ \forall\ j = 1, 2, \ldots, n, \tag{4.1}$$

or

$$w_j = \frac{r_{jW}}{\sum_{k=1}^{n} r_{kW}} \ \forall\ j = 1, 2, \ldots, n. \tag{4.2}$$

Proof Since the preferences BO and OW are fully multiplicative consistent, the optimal objective value ζ^* becomes zero for the prioritization models (NLP-M), (LP-M) and (Int-M). That fact reduces the constraints sets of (NLP-M), (LP-M) and (Int-M) into the following systems of $2n - 1$ equations:

$$\begin{cases} w_B - r_{Bj} w_j = 0, \ \ j = 1, \ldots, n, \ \text{and}\ j \neq B \\ w_j - r_{jW} w_W = 0, \ \ j = 1, \ldots, n, \ \text{and}\ j \neq W \\ \sum_{j=1}^{n} w_j = 1. \end{cases} \tag{4.3}$$

Using the fact that $r_{Bj} \times r_{jW} = r_{BW}$ and $w_B/w_W = r_{BW}$, one can transform $w_j - r_{jW} w_W = 0$ into $w_B - r_{Bj} w_j = 0$. Therefore, the system of Eq. (4.3) is reduced to the following system of n equations:

$$\begin{cases} w_B - r_{Bj} w_j = 0, \ \ j = 1, \ldots, n, \ \text{and}\ j \neq B & (4.4a) \\ \sum\limits_{j=1}^{n} w_j = 1. & (4.4b) \end{cases}$$

Taking the value of w_j from Eq. (4.4a) with $w_B - r_{BB} w_B = 0$, we obtain the value of w_B from the Eq. (4.4b) as follows:

$$w_B = \frac{1}{(\sum_{k=1}^{n} \frac{1}{r_{Bk}})}. \tag{4.5}$$

Subsequently, utilizing the Eq. (4.4a), we obtain

$$w_j = \frac{1}{(\sum_{k=1}^{n} \frac{r_{Bj}}{r_{Bk}})} \ \forall\ j = 1, 2, \ldots, n. \tag{4.6}$$

Using the fact that $r_{Bk} \times r_{kW} = r_{BW}$ for all $k = 1, 2, \ldots, n$, we obtain from Eq. (4.6) as follows:

$$w_j = \frac{r_{jW}}{\sum_{k=1}^{n} r_{kW}}, \ \forall\ j = 1, 2, \ldots, n. \tag{4.7}$$

Hence the proof.

Theorem 4.2 *When the given BO and OW preferences are fully multiplicative consistent, i.e., $r_{Bj} \times r_{jW} = r_{BW}, \forall\ j = 1, 2, \ldots, n$, the prioritization model (LMult-M) produce the same priority weights given by Eqs. (4.1) and (4.2).*

Proof Since BO and OW are fully multiplicative consistent, the optimal objective of model (LMult-M) is $\zeta^* = 0$, and the optimal decision variables could be found by solving the following system of equations

$$\begin{cases} l_{Bj} - (v_B - v_j) = x^+_{Bj} - x^-_{Bj},\ \forall\ j = 1, 2, \ldots, n \text{ and } j \neq B & (4.8a) \\ x^+_{Bj} + x^-_{Bj} \leq 0,\ \forall\ j = 1, 2, \ldots, n & (4.8b) \\ l_{jW} - (v_j - v_W) = y^+_{jW} - y^-_{jW},\ \forall\ j = 1, 2, \ldots, n \text{ and } j \neq W & (4.8c) \\ y^+_{jW} + y^-_{jW} \leq 0,\ \forall\ j = 1, 2, \ldots, n & (4.8d) \\ \sum_{j=1}^{n} v_j = 0, & (4.8e) \\ x^+_{Bj}, x^-_{Bj}, y^+_{Bj}, y^-_{Bj} \geq 0,\ \forall\ j = 1, 2, \ldots, n. & (4.8f) \end{cases}$$

The inequalities in Eqs. (4.8b), (4.8d) and (4.8f) implies that the deviations variables $(x^+_{Bj}, x^-_{Bj}, y^+_{Bj}, y^-_{Bj})$ take the value zero. The system of Eqs. (4.8) reduces to the following the system:

$$\begin{cases} l_{Bj} - (v_B - v_j) = 0,\ \forall\ j = 1, 2, \ldots, n & (4.9a) \\ l_{jW} - (v_j - v_W) = 0,\ \forall\ j = 1, 2, \ldots, n & (4.9b) \\ \sum_{j=1}^{n} v_j = 0. & (4.9c) \end{cases}$$

Using the fact that $l_{Bj} + l_{jW} = l_{BW}$ and $v_B - v_W = l_{BW}$, one can transform $l_{jW} - (v_j - v_W) = 0$ into $l_{Bj} - (v_B - v_j) = 0$. Therefore, the system of Eq. (4.3) is reduced to the following system of n equations:

$$\begin{cases} l_{Bj} - (v_B - v_j) = 0\ \forall\ j = 1, \ldots, n \text{ and } j \neq B & (4.10a) \\ \sum_{j=1}^{n} v_j = 0. & (4.10b) \end{cases}$$

Taking summation on both sides of Eq. (4.10a) with $l_{BB} - (v_B - v_B) = 0$ and utilizing the Eq. (4.10b), we obtain $v_B = (\sum_{j=1}^{n} l_{Bj})/n$ and $v_j = (\sum_{j=1}^{n} l_{Bj})/n - l_{Bj}$. Since $\ln(w_j) = v_j$ and $\ln(r_{Bj}) = l_{Bj}$, we obtain the original multiplicative weights as follows:

$$w_j = \frac{(\prod_{j=1}^{n} r_{Bj})^{1/n}}{r_{Bj}},\ \forall\ j = 1, 2, \ldots, n. \quad (4.11)$$

Normalizing the weights, we have

$$w_j = \frac{\frac{(\prod_{j=1}^{n} r_{Bj})^{1/n}}{r_{Bj}}}{\sum_{k=1}^{n} \frac{(\prod_{j=1}^{n} r_{Bj})^{1/n}}{r_{Bj}}}, \ \forall\ j = 1, 2, \ldots, n$$
$$= \frac{1}{(\sum_{k=1}^{n} \frac{r_{Bj}}{r_{Bk}})}, \ \forall\ j = 1, 2, \ldots, n. \tag{4.12}$$

Thus, we obtain the weights produced by the other three prioritization methods. The representation of the weights in terms of OW elements could also be obtained by using the multiplicative relation. Hence, the proof.

Example 4.1 Consider the prioritization problem of the criteria $\{C_1, C_2\}$ with the best criteria C_1 and worst criteria C_2 and preferences $BO = (1, 3)$ and $OW = (3, 1)$. From Eq. (4.1), we have $w_1 = \frac{1}{(1/1+1/3)} = 3/4 = 0.75$ and $w_2 = \frac{1}{(3/1+3/3)} = 3/12 = 0.25$. Applying the prioritization methods (NLP-M), (LP-M), (Int-M), (LMult-M), we obtain the same weight.

Experimental Performance Measures

We have seen that in the case of fully multiplicative preferences, all the prioritization methods produce the same prioritization weights and that can be obtained via the analytic formulas given in Eqs. (4.1) and (4.2). However, it could have differed significantly in the case of not fully consistent but acceptable consistent situations. To measure how the obtained weights differ across the prioritization methods, we consider two metrics: (1) distance: how it differs from the original preferences; (2) order violation: number of violations in order from the initial preferences.

Distance Measure Criteria

Typically, we measure the deviation between the initial preferences and obtained preference from the prioritization method. For this, the priority weight $w = (w_1, \ldots, w_n)$ obtained from the prioritization is compared against the original preference BO and OW. The deviation is measured by the common symmetric Euclidean distance metric, which is defined as follows:

$$\mathcal{D}(BO, OW, w) = \sqrt{\sum_{j=1}^{n} (\frac{w_B}{w_j} - r_{Bj})^2 + (\frac{w_j}{w_W} - r_{jW})^2}. \tag{4.13}$$

Note that for the fully multiplicative preference, the distance becomes zero.

Order Violations

While the distance measure provides a view of the deviations of preference intensities of the weights from the original preferences, the order violation measure focuses on the preservation of the initial order by the prioritization methods. We define the total violations of the order by the prioritization method as follows:

$$\mathcal{V}(BO, OW, w) = \sum_{i,j=1,i<j}^{n} ov_{ij}^{B} + ov_{ij}^{W}$$

where

$$ov_{ij}^{B}(r_{Bi}, r_{Bj}, w_i, w_j) = \begin{cases} 1, & \text{if } r_{Bi} < r_{Bj} \text{ and } w_i < w_j \\ 1, & \text{if } r_{Bi} > r_{Bj} \text{ and } w_i > w_j \\ 0.5, & \text{if } r_{Bi} = r_{Bj} \text{ and } w_i \neq w_j \\ 0.5, & \text{if } r_{Bi} \neq r_{Bj} \text{ and } w_i = w_j \\ 0 & \text{otherwise} \end{cases} \tag{4.14}$$

$$ov_{ij}^{W}(r_{iW}, r_{jW}, w_i, w_j) = \begin{cases} 1, & \text{if } r_{iW} < r_{jW} \text{ and } w_i > w_j \\ 1, & \text{if } r_{iW} > r_{jW} \text{ and } w_i < w_j \\ 0.5, & \text{if } r_{iW} = r_{jW} \text{ and } w_i \neq w_j \\ 0.5, & \text{if } r_{iW} \neq r_{jW} \text{ and } w_i = w_j \\ 0 & \text{otherwise} \end{cases} \tag{4.15}$$

It is noted that when all the initial order is preserved by the prioritization method the total violation is zero, i.e., $\mathcal{V}(BO, OW, w) = 0$.

To analyze the performance of the prioritization methods, we conduct simulation-based numerical experiments. In particular, for a fixed set of objects and numerical scale, the Best-Worst preference BO and OW are generated randomly, maintaining acceptable input-based consistency suggested by the Liang et al. [3]. Then, we compute the priority weights by each of the prioritization methods. Subsequently, the distance and order violation measures are calculated. Specifically, in the experiment, we considered 4 objects that are to be compared by using the Likert scale 1–7 and set the input-based consistency threshold at 0.2457 [3, Table 3] to generate randomly Best-to-others and others-to-worst preferences. To obtain a good estimate for the distance measure and order violations, we have generated 8000 Best-Worst preferences and made subsequent computations to obtain the distance and the order violations. Note that the input-based consistency of the generated 8000 preferences can be grouped into 10 distinct values. The distance measures among the prioritization methods are depicted via box-plot in Fig. 4.1 against the input-based consistency group. It is observed from Fig. 4.1 that methods (NLP-M) and (Int-M) produce all most similar distances from original preferences, while the (LMult-M) always deviated far from original preference. The (LP-M) method produced priority deviating

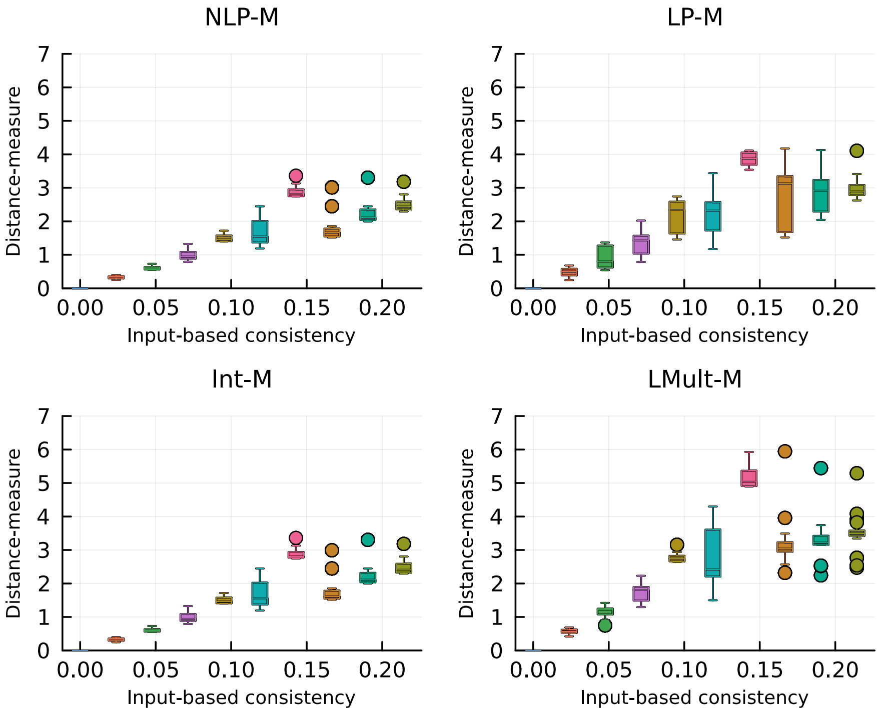

Fig. 4.1 Distance from original preferences under different input-based consistency

less from the method (LMult-M). Further, we observe that distance from the original preference increases up to the input-based consistency ratio 0.10. Afterward, their behavior becomes quite unpredictable. Overall, (NLP-M) methods perform better than other methods in terms of a distance measure from the original preference.

Now, we consider the order violation aspects for the same randomly generated preferences. For this purpose, we first compute the ordinal consistency [3, Definition 5] of earlier generated preferences. Based on the ordinal consistency, these preferences could be grouped into four categories and subsequently, the order violations measure against these categories were computed and depicted in Fig. 4.2. We found that all the methods produce similar types of violations of orders in the generated weights from original preferences. In fact, in some cases, the (LMult-M) produces fewer violations in orders. Specifically, when the input-based ordinal consistency of the preferences is 0 or 2, the priority weight generated by the (LMult-M) method made lesser violations in ordinal orders than other methods. Therefore, in terms of order violations measure (LMult-M) method performs better than others.

Although, we have presented here the results for the specific configurations of Best-Worst preferences (4 objects and 1–7 scale), the results for other configurations of the objects and scale provides similar trends in both of the measures.

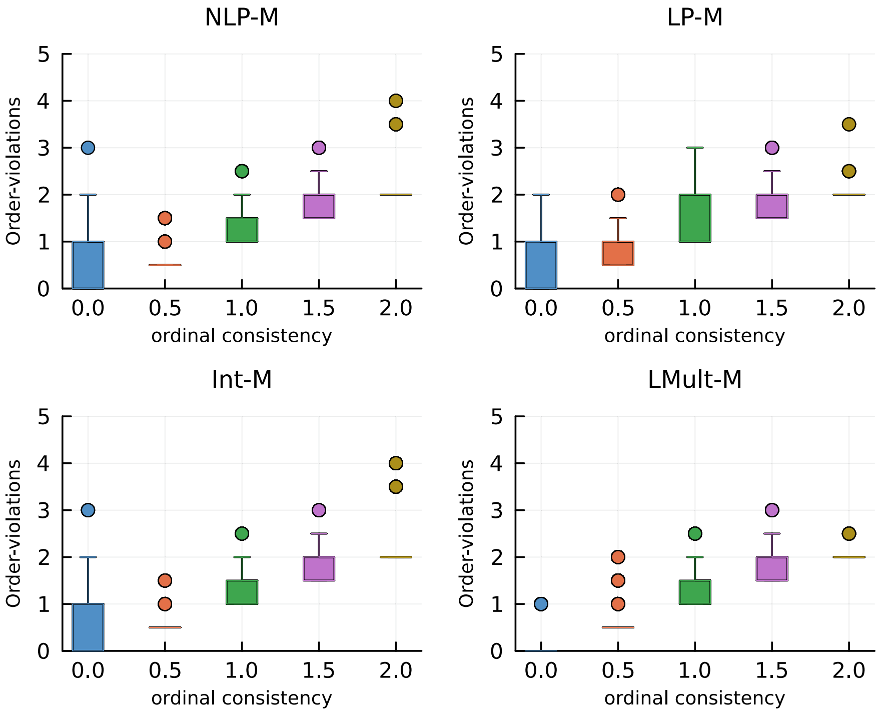

Fig. 4.2 Total order violations against the input ordinal consistency

Conclusions

In this study, we have investigated the four prioritization methods used to generate priority weight from the Best-Worst preferences. From the theoretical perspective, it has been found that all the prioritization methods produce the same weight vector when the original Best-Worst preference is fully multiplicative and consistent. Further, in this case, the priority weight can be directly obtained via the analytic formulae from best-to-other preference or others-to-worst preference. In inconsistent cases, to compare the prioritization methods, we have defined distance and order violations based measures. From the experimental perspective, we have demonstrated that the priority weight produced by the (NLP-M) method deviates less from original preferences. In terms of order violation measure, the (LMult-M) could be the better choice.

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Chapter 5
A Hesitant Multiplicative Best-Worst Method for Multiple Criteria Decision-Making

Yejun Xu and Dayong Wang

Abstract The classical Best-Worst Method (BWM) and its expansion form in the multiple criteria decision-making problem under different backgrounds are widely used to calculate the weights of criteria. The traditional BWM uses the accurate value based on Saaty's scale to describe a decision maker (DM)'s preferences. However, a DM may be unsure about his preference and may give several possible values to express his preferences. In this situation, the hesitant multiplicative elements may be truly reflected the DM's preference relation. This paper incorporates the BWM, the hesitant multiplicative preference relations (HMPR), and proposes HMBWM. Three different models are proposed to determine the weights from hesitant multiplicative best-to-others (HMBO) and hesitant multiplicative others-to-worst (HMOW) vectors. Finally, a case study of choosing commercial endowment insurance products is constructed to illustrate the practicality and correctness of the proposed model.

Keywords Best-Worst Method · Hesitant multiplicative preference relation · Pairwise comparison · Multiple criteria decision making

Introduction

Nowadays, people face to make their decision every day, and the environment is complex. In the multi-criteria decision-making (MCDM) problem, it generally has a set of n criteria, and a set of m alternatives. Generally, different criteria have different importance in the MCDM due to their nature. Thus, one of the important work is to determine the weights of criteria [1]. At present, various methods have been proposed to determine the weights for criteria. Recently, Rezaei [2] proposed the Best-Worst Method (BWM) based on multiplicative preference relation in 2015.

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Compared with the traditional analytic hierarchy process (AHP) [3], which requires $n(n-1)/2$ (n is the number of alternatives) pairwise comparisons when constructing a complete judgment matrix, BWM only needs $2n-3$ comparisons, that is, it only compares between the best criterion and all the other criteria and between all other criteria and the worst criterion to produce the best to others (BO) vector and others to worst (OW) vector, respectively. Obviously, the number of pairwise comparisons between the criteria in BWM has been greatly reduced, which makes BWM have a good performance in maintaining the logical rationality of decision makers (DMs). BWM has received a lot of attention from scholars since it was proposed, and has been extended various preference relations, such as interval preference relations [4], triangular fuzzy numbers [5], intuitionistic multiplicative preferences [6] intuitionistic fuzzy preferences [7] Z-numbers [8], interval-valued fuzzy-rough numbers [9], hesitant fuzzy preferences [10], and fuzzy preferences [11], belief BWM [12]. At the same time, BWM is applied to solve decision making problems in different fields, such as linking supplier development to supplier segmentation [13], calculating semi-human development index [14], quality assessment of airline baggage handling systems [15], and assessing organizations performance [16].

The hesitant multiplicative preference relation (HMPR) is first proposed by Xia and Xu [17] to express DM's preferences over criteria in uncertain environment. The element in hesitant multiplicative relation is used to measure the preference degree between two criteria, and is characterized by the Saaty's ratio scale [1/9, 9]. The HMPR is an extension of the traditional MPR, which allows DMs to use different values to express these preferences for alternative x_i over alternative x_j. Specifically, if the DM is not hesitant, and provide the accurate preference values when comparing two alternatives (or criteria), then the HMPR is reduced to MPR. Thus, MPR is one of specific cases of HMPR. Thus, HMPR is more flexible for DMs to express their preferences. Up to now, to the author's knowledge, there is no research about the BWM with hesitant multiplicative relation in which the elements of BO and OW vectors are represented by hesitant multiplicative set (HMS). Thus, in this paper, considering the convenience and effectiveness of HMS in describing uncertain preference information, we construct the BWM with hesitant multiplicative preference relation in which a set of possible membership values are determined by each DM in decision making process. We call it hesitant multiplicative BWM (HMBWM).

The reminder of the paper is structured as follows. Section "Preliminaries" gives basic knowledge of the paper. Section "Three Different Models of Hesitant Multiplicative BWM to Derive the Optimal Weights" proposes the HMBWM, and gives three models to determine the weights for HMBWM. Section "Illustrative Example" gives an example to show how the proposed method could be applied in real applications. Section "Conclusion" concludes the paper.

Preliminaries

In this section, the basic knowledge of the hesitant multiplicative preference relations, and the BWM are reviewed.

HMPR

The fuzzy sets is firstly proposed by Zadeh [18]. Based on this, many extensions and generalization of fuzzy sets have been proposed. Among them, a most important extension of fuzzy sets in proposed by Torra [19], called hesitant fuzzy sets (HFSs). The meaning for constructing HFSs is that it is sometimes difficult to identify the membership of an element into a set, and in some situations, this shortcoming is caused by a set of possible values. It is evident that HFSs is considered as an effective tool in expressing DM's hesitancy in decision making process. Furthermore, HFSs have been applied in different areas. According to the fuzzy preference relations and multiplicative preference relations, Xia and Xu [17] respectively defined hesitant fuzzy preference relations (HFPRs) and hesitant multiplicative preference relations (HMPRs). HMPRs are a very useful tool to show DM's preference comparison in uncertain decision-making problems. For simplicity, $N = \{1, 2, \ldots, n\}$, and let $X = \{x_1, x_2, \ldots, x_n\}$ be a set of criteria.

Definition 5.1 ([17]). Suppose that X be a set of criteria, a hesitant multiplicative set (HMS) over X is a membership function h, and the result is equal to a subset of [1/9, 9].

In short, the HMS is represented by $H = \{<x, h(x)> \mid x \in X\}$, where $h = h(x)$ is equal to a set of different values in [1/9, 9] based on Saaty [3]'s ratio scale. Furthermore, $h = h(x)$ is called hesitant multiplicative element (HME) in HMS. In particular, we call M is the set of all HMEs. Thus, the definition of hesitant multiplicative relation is shown as follows.

Definition 5.2 ([17]). Suppose that X be a set of criteria. An HMPR H over X is described as a matrix $H = \left(h_{ij}\right)_{n \times n} \subset X \times X$, where $h_{ij} = \{h_{ij}^{s}, s = 1, 2, \ldots, \#h_{ij}\}$ is an HME, representing all the possible preference values to which criteria x_i is preferred to criteria x_j. Furthermore, HME h_{ij} has the following properties.

$$h_{ij}^{\sigma(s)} h_{ji}^{\sigma(l_{h_{ij}} - s + 1)} = 1,\ h_{ii} = \{1\},\ \#h_{ij} = \#h_{ji},\ i, j = 1, 2, \ldots, n \tag{5.1}$$

where the elements in HME h_{ij} are supposed to increase from left to right, and $h_{ij}^{\sigma(s)}\ \left(s = 1, 2, 3 \ldots, \#h_{ij}\right)$ is used to represent sth smallest preference degree value in h_{ij}, and $\#h_{ij}$ is the number of values in h_{ij}.

Example 5.1 Let $X = \{x_1, x_2, x_3\}$, an organization containing some experts it authorized to provide to which x_1 is preferred to x_2, some experts provide 1/3, some provide 1/2. In such a case, the preference information h_{12} can be denoted as $h_{12} = \{1/3, 1/2\}$, and according to Eq. (5.1), $h_{21} = \{2, 3\}$. Similarly, let $h_{13} = \{3, 4\}$, $h_{23} = \{5\}$, we can obtain the HMPR is:

$$H = \begin{pmatrix} \{1\} & \{1/3, 1/2\} & \{3, 4\} \\ \{2, 3\} & \{1\} & \{5\} \\ \{1/4, 1/3\} & \{1/5\} & \{1\} \end{pmatrix}$$

Bwm

Rezaei [20] first proposed BWM. It includes the following steps:

Step 1. Determine a set of criteria for MCDM problem. In this step, according to the background and goal of MCDM problem, a set of criteria $\{c_1, c_2, \ldots, c_n\}$ is determined to describe the selected rule and standard.

Step 2. According to personal preference, each DM determines the best and the worst criteria in decision making process.

Step 3. The best-to-others (BO) vector is determined by using a number between 1 and 9, which is used to represent the preference between the best criteria and other criteria, represented as $A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$.

Step 4. The others-to-worst (OW) vector is determined by using a number between 1 and 9, which is used to represent the preference between the other criteria and worst criteria, represented as $A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$.

Step 5. A minmax model is proposed to find optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$, and the model satisfies that the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jW}\right|$ for all j is minimized.

$$\min \max_j \left\{ \left|\frac{w_B}{w_j} - a_{Bj}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right| \right\}$$
$$\text{s.t.} \begin{cases} \sum_{j=1}^{n} w_j = 1 \\ w_j \geq 0, \text{ for all } j \in N \end{cases} \tag{5.2}$$

At the same time, model (5.2) can be transformed into the following model.

$$\min \xi$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi,\ j \in N \\ \left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi,\ j \in N \\ \sum_{j=1}^{n} w_j = 1 \\ w_j \geq 0,\ j \in N \end{cases} \tag{5.3}$$

Three Different Models of Hesitant Multiplicative BWM to Derive the Optimal Weights

In this section, we extend the traditional BWM to accommodate HMPR. The first two steps are same. Then, the hesitant multiplicative best-to-others (HMBO) vector and hesitant multiplicative others-to-worst (HMOW) vector are determined by the DM. As the pairwise comparisons are HMSs, then, three different optimization models are proposed to obtain the weights of criteria in the framework of the original BWM to adapt to different situations.

In the HMBWM, the BO vector and OW vector are replaced by the HMBO, and HMOW, respectively. Similarly, h_{Bj} and h_{jW} are used to represent the hesitant preference values between the best criterion c_B and criteria c_j, and the hesitant preference values between the criteria c_j and worst criterion c_W, respectively. Thus, we can obtain

$$HMBO = \left(h_{B1}, h_{B2}, \ldots, h_{Bj}, \ldots, h_{Bn}\right),\ HMOW = \left(h_{1W}, h_{2W}, \ldots, h_{jW}, \ldots, h_{nW}\right)^T \tag{5.4}$$

where $h_{BB} = h_{WW} = \{1\}$.

(1) **the weight-determining model of HMBWM based on geometric mean**

In the HMPR, each pairwise comparison is an HME, and it may have multiple values. We propose the geometric mean to fuse these different values in to one value as follows:

Definition 5.3 Let $h = \{h^s | s = 1, 2, \ldots, \#h\}$ be an HFE, then we call

$$g(h) = \sqrt[\#h]{\prod_{s=1}^{\#h} h^s} \tag{5.5}$$

geometric mean of h.

For example, let $h = \{1, 2, 3\}$ be an HMS. Then, the geometric mean of h is $g(h) = \sqrt[3]{1 \times 2 \times 3} \approx 1.8063$.

In the HMBWM, the DM provides the HMBO and HMOW vectors. To derive the criteria weights, we use Eq. (5.5) to transform the HMBO and HMOW vectors into the Saaty's comparisons as follows:

$$g(HMBO) = (g(h_{B1}), g(h_{B2}), \ldots, g(h_{Bj}), \ldots, g(h_{Bn})) \tag{5.6}$$

$$g(HMOW) = (g(h_{1W}), g(h_{2W}), \ldots, g(h_{jW}), \ldots, g(h_{nW}))^T \tag{5.7}$$

Based on the traditional BWM, for each pair of w_B/w_j and w_j/w_W, we have $w_B/w_j = g(h_{Bj})$, $w_j/w_W = g(h_{jW})$. To satisfy these conditions for all j, we should find a solution where the maximum absolute differences $\left|\frac{w_B}{w_j} - g(h_{Bj})\right|$ and $\left|\frac{w_j}{w_W} - g(h_{jW})\right|$ for all j is minimized. Then, we establish the following model:

(M-1)

$$\begin{aligned} &\min \max_j \left\{ \left| \frac{w_B}{w_j} - g(h_{Bj}) \right|, \left| \frac{w_j}{w_W} - g(h_{jW}) \right| \right\} \\ &\text{s.t.} \begin{cases} \sum_{j=1}^{n} w_j = 1 \\ w_j \geq 0,\ j \in N \end{cases} \end{aligned} \tag{5.8}$$

Problem (5.8) can be transformed into the following model:

(M-2)

$$\begin{aligned} &\min\ \xi_g \\ &\text{s.t.} \begin{cases} \left| \frac{w_B}{w_j} - g\left(h_{Bj}\right) \right| \leq \xi_g,\ j \in N \\ \left| \frac{w_j}{w_W} - g\left(h_{jW}\right) \right| \leq \xi_g,\ j \in N \\ \sum_{j=1}^{n} w_j = 1 \\ w_j \geq 0,\ j \in N \end{cases} \end{aligned} \tag{5.9}$$

According to model (5.9), the optimal weights of criteria can be directly obtained.

(2) **the weight-determining model of hesitant multiplicative best-worst method based on β-normalization**

In the HMPR, each pairwise comparison is an HME, and it may have different values. For two different hesitant fuzzy sets, Zhu et al. [21] proposed a method called

β-normalization to add some values into the shorter one until all the hesitant fuzzy sets have the same number of values. In particular, in β-normalization method, Xu and Xia [22] fully considered the attitude of DMs, called optimism and pessimism rules, and then extended the components of each hesitant multiplicative preference with equal lengths. However, there are some limitations in both and Zhu et al. [21] and Xu and Xia [22] methods. Specifically, the added value in Xu and Xia [22] method is only the minimum or maximum value in the original HME, and the added value in Zhu et al. [21] is between the minimum and maximum value, this will distort the DM's original judgment. However, in the real decision-making process, there are three DMs, who provide the preferences over alternative x_i over alternative x_j using Saaty's scale. One DM provides his preference is 1, and two DMs provide their preferences are 2. Thus, their hesitant preferences set is {1, 2}. However, as two DMs' preferences are 2, and only one is reflected in the set {1, 2}. Thus, the original hesitant preferences of the DMs should be {1, 2, 2}. In this situation, the omitted value should be one of the values in the original set {1, 2}. To overcome above described limitations of Zhu et al. [21] and Xu and Xia [22] and methods, Xu et al. [23] thought the added value should be one of the original values. In this paper, we adopt Xu et al. [23] method to add values.

Definition 5.4 Let $h = \{h^s \mid s = 1, 2, \ldots, \#h\}$ be an HME, $\overline{h}$ be the direct added value, which satisfy $\overline{h} \in h$, and the elements are added after the existing values.

Based on the above normalization method, we extend the BWM to the HMPR. Suppose that the maximum length of HME is equal to l, where $l = \max_{ij}(h_{ij})$, and then we use Definition 5.4 to normalize each h_{ij} until the length of all the values in h_{ij} is l, that is, we obtain $h_{Bj}^{(1)}, h_{Bj}^{(2)}, \ldots, h_{Bj}^{(l)}$, and $h_{jW}^{(1)}, h_{jW}^{(2)}, \ldots, h_{jW}^{(l)}$. The weight of criterion c_j is a hesitant fuzzy element, i.e., $w_j = w_j^{(1)}, w_j^{(2)}, \ldots, w_j^{(l)}), j \in N$. Then, the relation between each component of hesitant multiplicative preferences and its corresponding hesitant weights is determined as follows.

$$w_B^{(1)}/w_j^{(1)} = h_{Bj}^{(1)}, w_B^{(2)}/w_j^{(2)} = h_{Bj}^{(2)}, \ldots, w_B^{(l)}/w_j^{(l)} = h_{Bj}^{(l)} \tag{5.10}$$

And

$$w_j^{(1)}/w_W^{(1)} = h_{jW}^{(1)}, \ w_j^{(2)}/w_W^{(2)} = h_{jW}^{(2)}, \ldots, \ w_j^{(l)}/w_W^{(l)} = h_{jW}^{(l)} \tag{5.11}$$

Furthermore, various slack variables are used to measure the consistency of normalized hesitant multiplicative vectors, represented as $\left|w_B^{(1)}/w_j^{(1)} - h_{Bj}^{(1)}\right| \leq \xi^{(1)}$, $\left|w_B^{(2)}/w_j^{(2)} - h_{Bj}^{(2)}\right| \leq \xi^{(2)}$, $\ldots$, $\left|w_B^{(l}/w_j^{(l)} - h_{Bj}^{(l)}\right| \leq \xi^{(l)}$, $\left|w_j^{(1)}/w_W^{(1)} - h_{jW}^{(1)}\right| \leq \xi^{(1)}$, $\left|w_j^{(2)}/w_W^{(2)} - h_{jW}^{(2)}\right| \leq \xi^{(2)}, \ldots$, and $\left|w_j^{(l)}/w_W^{(l)} - h_{jW}^{(l)}\right| \leq \xi^{(l)}$.

Below, a new optimization model in hesitant multiplicative best-worst method is proposed based on normalization conditions to calculate the hesitant multiplicative weights.

(M-3)

$$\min \xi^{(s)}$$
$$\text{s.t.}\begin{cases} \left|\dfrac{w_B^{(s)}}{w_j^{(s)}} - h_{Bj}^{(s)}\right| \le \xi^{(s)}, s = 1, 2, ..., l, j \in N \\ \left|\dfrac{w_j^{(s)}}{w_W^{(s)}} - h_{jW}^{(s)}\right| \le \xi^{(s)}, s = 1, 2, ..., l, j \in N \\ \sum_{j=1}^{n} w_j^{(s)} = 1 \\ w_j^{(s)} \ge 0, j \in N, s = 1, 2, ..., l \end{cases} \tag{5.12}$$

(3) **the weight-determining model of hesitant multiplicative best-worst method Based on α-normalization**

In the β-normalization, it needs to add some values into the original HME. There is another normalization method, called α-normalization, which is to remove some elements of HME or, it is natural to abstract the most reasonable preferences from the DMs' hesitant information. For example, a doctor wanted to diagnose the disease of a patient, and asked how the patient felt, and the patient gave several feelings or symptoms. After some days or some hours, the doctor asked the patient again, and patient gave his several feelings again. In these situations, it is preferred to use the hesitant preferences to describe his symptoms or feelings, and it is natural that the doctor should abstract the most possible preferences from the DMs' hesitant preferences to determine what is the patient's really disease. Therefore, the weight and the HME should satisfy:

$$w_B/w_j = h_{Bj}^{(1)} \text{ or } \dots \text{ or } h_{Bj}^{(\# h_{Bj})}, w_j/w_W = h_{jW}^{(1)} \text{ or } \dots \text{ or } h_{jW}^{(\# h_{jW})} \tag{5.13}$$

where $\# h_{Bj}$ and $\# h_{jW}$ represents the number of values in h_{Bj} and h_{jW}, respectively.

Let $S(h_{Bj})= h_{Bj}^{(1)}$ or … or $h_{Bj}^{(\# h_{Bj})}$, $S(h_{jW}) = h_{jW}^{(1)}$ or … or $h_{jW}^{(\# h_{jW})}$, according model (M-1), we construct the following model:

(M-4)

$$\min \max_j \left\{ \left| \frac{w_B}{w_j} - S(h_{Bj}) \right|, \left| \frac{w_j}{w_W} - S(h_{jW}) \right| \right\}$$
$$\text{s.t.}\begin{cases} \sum_{j=1}^{n} w_j = 1 \\ w_j \ge 0, j \in N \end{cases} \tag{5.14}$$

(M-4) can be transformed into the following problem:

(M-5)

$$\min \xi$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B}{w_j} - S(h_{Bj})\right| \le \xi,\ j \in N \\ \left|\frac{w_j}{w_W} - S(h_{jW})\right| \le \xi,\ j \in N \\ \sum_{j=1}^{n} w_j = 1 \\ w_j \ge 0,\ j \in N \end{cases} \tag{5.15}$$

(M-5) can be transformed into the following (M-6):

(M-6)

$$\min \xi$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B}{w_j} - \sum_{s=1}^{\#h_{Bj}} z_{Bj}^{(s)} h_{Bj}^{(s)}\right| \le \xi,\ j \in N \\ \left|\frac{w_j}{w_W} - \sum_{s=1}^{\#h_{jW}} z_{jW}^{(s)} h_{jW}^{(s)}\right| \le \xi,\ j \in N \\ \sum_{j=1}^{n} w_j = 1 \\ w_j \ge 0,\ j \in N \\ \sum_{s=1}^{\#h_{Bj}} z_{Bj}^{(s)} = 1,\ j \in N \\ \sum_{s=1}^{\#h_{jW}} z_{jW}^{(s)} = 1,\ j \in N \\ z_{Bj}^{(s)} = 0 \text{ or } 1,\ s = 1, 2, \ldots, \#h_{Bj},\ j \in N \\ z_{jW}^{(s)} = 0 \text{ or } 1,\ s = 1, 2, \ldots, \#h_{jW},\ j \in N \end{cases} \tag{5.16}$$

Illustrative Example

In this section, an example is illustrated to show the practicality and correctness of the proposed model. Recall that the case of choosing commercial endowment insurance products is first proposed in paper [10]. With the continuous development of science and technology and continuous improvement of the quality of life, the aging problem of China's population is very serious and the pressure of old-age care is huge. Up to now, there are three major security systems in today's society: social endowment insurance, enterprise supplement endowment insurance, and commercial endowment insurance. Among them, commercial endowment insurance plays an indispensable role in China's development process, and more and more adults begin to purchase commercial endowment insurance plans for their future life. However, many people show hesitation and uncertainty when choosing commercial endowment insurance products. A series of reliable standards and options need to be developed. Guarantee period (c_1), payment method (c_2), scope of security (c_3), cost return ratio (c_4), and evaluation results of China Insurance Industry Association (c_5) are five different criteria for selecting commercial endowment insurance products.

Step 1. Determine a set of decision criteria, including five criteria $\{c_1, c_2, c_3, c_4, c_5\}$.

Step 2. According to the investigation, the focus DM selects the guarantee period (c_1) as the best criteria and the payment method (c_2) is the worst criteria at the same time.

Step 3. The HMBO vector is determined by using HMEs, which represent the reference comparison between the best criteria (c_2) and other criteria.

$$HMBO = (\{1, 2\}, \{1\}, \{7, 8\}, \{2, 3\}, \{3\})$$

Step 4. The HMOW vector is determined by using HMEs, which represent the reference comparison between the other criteria and worst criteria (c_3).

$$HMOW = (\{4\}, \{7, 8\}, \{1\}, \{4\}, \{3\})^T$$

Step 5.

(1) Geometric mean-based weight determination model.
First, calculate the geometric mean of HME. Using Eq. (5.5), we have:

$$g(HMBO) = (1.4142, 1, 7.4833, 2.4495, 3),$$
$$g(HMOW) = (4, 7.4833, 1, 4, 3)^T$$

Based on model (5.9), we can construct the following model:

$$\min \xi_g$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B}{w_1} - 1.4142\right| \le \xi_g \\ \left|\frac{w_B}{w_3} - 7.4833\right| \le \xi_g \\ \left|\frac{w_B}{w_4} - 2.4495\right| \le \xi_g \\ \left|\frac{w_B}{w_5} - 3\right| \le \xi_g \\ \left|\frac{w_1}{w_W} - 4\right| \le \xi_g \\ \left|\frac{w_2}{w_W} - 7.4833\right| \le \xi_g \\ \left|\frac{w_4}{w_W} - 4\right| \le \xi_g \\ \left|\frac{w_5}{w_W} - 3\right| \le \xi_g \\ w_1 + w_2 + w_3 + w_4 + w_5 = 1 \\ w_j \ge 0, j = 1, 2, ..., 5 \end{cases}$$

Solving the model, we obtain: $w = (0.2250, 0.3967, 0.0517, 0.1888, 0.1378)$, $\xi_g = 0.3491$, which means that $c_2 \succ c_1 \succ c_4 \succ c_5 \succ c_3$. The symbol $\succ$ means 'more important than' or 'preferred to'.

(2) The β-normalization based model.
First, we use Definition 5.4 to add some values into the HME, and all the HME have the number of values. Then,

$$HMBO = (\{1, 2\}, \{1\}, \{7, 8\}, \{2, 3\}, \{3, 3\})$$
$$HMOW = (\{4, 4\}, \{7, 8\}, \{1\}, \{4, 4\}, \{3, 3\})^T$$

Based on Eq. (5.12), we can construct the following models:

$$\min \xi^{(1)} \qquad\qquad \min \xi^{(2)}$$

$$\text{s.t.}\begin{cases}\left|\frac{w_B^{(1)}}{w_1^{(1)}}-1\right|\le \xi^{(1)}\\ \left|\frac{w_B^{(1)}}{w_3^{(1)}}-7\right|\le \xi^{(1)}\\ \left|\frac{w_B^{(1)}}{w_4^{(1)}}-2\right|\le \xi^{(1)}\\ \left|\frac{w_B^{(1)}}{w_5^{(1)}}-3\right|\le \xi^{(1)}\\ \left|\frac{w_1^{(1)}}{w_W^{(1)}}-4\right|\le \xi^{(1)}\\ \left|\frac{w_2^{(1)}}{w_W^{(1)}}-7\right|\le \xi^{(1)}\\ \left|\frac{w_4^{(1)}}{w_W^{(1)}}-4\right|\le \xi^{(1)}\\ \left|\frac{w_5^{(1)}}{w_W^{(1)}}-3\right|\le \xi^{(1)}\\ w_1^{(1)}+w_2^{(1)}+w_3^{(1)}+w_4^{(1)}+w_5^{(1)}=1\\ w_j^{(1)}\ge 0,\ j=1,2,\ldots,5\end{cases} \qquad \text{s.t.}\begin{cases}\left|\frac{w_B^{(2)}}{w_1^{(2)}}-2\right|\le \xi^{(2)}\\ \left|\frac{w_B^{(2)}}{w_3^{(2)}}-8\right|\le \xi^{(2)}\\ \left|\frac{w_B^{(2)}}{w_4^{(2)}}-3\right|\le \xi^{(2)}\\ \left|\frac{w_B^{(2)}}{w_5^{(2)}}-3\right|\le \xi^{(2)}\\ \left|\frac{w_1^{(2)}}{w_W^{(2)}}-4\right|\le \xi^{(2)}\\ \left|\frac{w_2^{(2)}}{w_W^{(2)}}-8\right|\le \xi^{(2)}\\ \left|\frac{w_4^{(2)}}{w_W^{(2)}}-4\right|\le \xi^{(2)}\\ \left|\frac{w_5^{(2)}}{w_W^{(2)}}-3\right|\le \xi^{(2)}\\ w_1^{(2)}+w_2^{(2)}+w_3^{(2)}+w_4^{(2)}+w_5^{(2)}=1\\ w_j^{(2)}\ge 0,\ j=1,2,\ldots,5\end{cases}.$$

Solving the two models, we have: $\xi^{(1)} = 0.4641$, $\xi^{(2)} = 0.5359$, $w = (\{0.2465, 0.2235\}, \{0.3608, 0.4208\}, \{0.0552, 0.0493\}, \{0.1952, 0.1708\}, \{0.1422, 0.1356\})$, which means that $c_2 \succ c_1 \succ c_4 \succ c_5 \succ c_3$.

(3) The α-normalization based model.

The DM provides the HMBO and HMOW are same as in Steps 4 and 5, they are:

$$HMBO = (\{1, 2\}\{1\}, \{7, 8\}, \{2, 3\}, \{3\}),\ HMOW = (\{4\}\{7, 8\}, \{1\}, \{4\}, \{3\})^T$$

Based on Eq. (5.16), we can construct the following models:

$$\min \xi^{(1)}$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B^{(1)}}{w_1^{(1)}} - 1\right| \le \xi^{(1)} \\ \left|\frac{w_B^{(1)}}{w_3^{(1)}} - 7\right| \le \xi^{(1)} \\ \left|\frac{w_B^{(1)}}{w_4^{(1)}} - 2\right| \le \xi^{(1)} \\ \left|\frac{w_B^{(1)}}{w_5^{(1)}} - 3\right| \le \xi^{(1)} \\ \left|\frac{w_1^{(1)}}{w_W^{(1)}} - 4\right| \le \xi^{(1)} \\ \left|\frac{w_2^{(1)}}{w_W^{(1)}} - 7\right| \le \xi^{(1)} \\ \left|\frac{w_4^{(1)}}{w_W^{(1)}} - 4\right| \le \xi^{(1)} \\ \left|\frac{w_5^{(1)}}{w_W^{(1)}} - 3\right| \le \xi^{(1)} \\ w_1^{(1)} + w_2^{(1)} + w_3^{(1)} + w_4^{(1)} + w_5^{(1)} = 1 \\ w_j^{(1)} \ge 0, j \in N \end{cases}$$

$$\min \xi^{(2)}$$
$$\text{s.t.}\begin{cases} \left|\frac{w_B^{(2)}}{w_1^{(2)}} - 2\right| \le \xi^{(2)} \\ \left|\frac{w_B^{(2)}}{w_3^{(2)}} - 8\right| \le \xi^{(2)} \\ \left|\frac{w_B^{(2)}}{w_4^{(2)}} - 3\right| \le \xi^{(2)} \\ \left|\frac{w_B^{(2)}}{w_5^{(2)}} - 3\right| \le \xi^{(2)} \\ \left|\frac{w_1^{(2)}}{w_W^{(2)}} - 4\right| \le \xi^{(2)} \\ \left|\frac{w_2^{(2)}}{w_W^{(2)}} - 8\right| \le \xi^{(2)} \\ \left|\frac{w_4^{(2)}}{w_W^{(2)}} - 4\right| \le \xi^{(2)} \\ \left|\frac{w_5^{(2)}}{w_W^{(2)}} - 3\right| \le \xi^{(2)} \\ w_1^{(2)} + w_2^{(2)} + w_3^{(2)} + w_4^{(2)} + w_5^{(2)} = 1 \\ w_j^{(2)} \ge 0, j \in N \end{cases}$$

Solving the model, we obtain: $w_1 = 0.2000$, $w_2 = 0.4081$, $w_3 = 0.0500$, $w_4 = 0.1989$, $w_5 = 0.1430$, which means that $c_2 \succ c_1 \succ c_4 \succ c_5 \succ c_3$.

Discussion

Comparisons with the Existing Methods

At present, various BWM are proposed. The traditional BWM proposed by Rezaei [2] only uses the accurate preferences, and can not express DMs' hesitant information. Thus, the proposed HMBWM is more flexible than the traditional BWM. Liang et al. [24] proposed Best-Worst Tradeoff method (BWTM), which integrates the BWM and tradeoff method. Although the BWTM can check the consistency, it is very complicated. To deal with uncertainty, Liang et al. [12] introduced a belief structure in the BWM, where the level of belief in preferences being expressed is taken into account. However, the belief is difficult to be determined.

Anchoring Bias Analysis

Anchoring bias is one of the main cognitive biases. Many methods in multiple attribute decision-making have anchoring bias. Recently, Rezaei [1] studied the anchoring bias of two methods, SMART and Swing. His study showed that the existence of anchoring bias in the two methods. As there is only one single anchor like SMART, Swing, the bias always exists. For the BWM, there are two anchors, the BO and OW, thus, the potential anchoring bias is mitigated, this is also for the proposed HMBWM.

Conclusions

This paper extends the classical BWM to the hesitant multiplicative environment, which is called HMBWM method. First, the HMBO vector, HMOW vector are given by the decision maker. Three different models are proposed to determine the weights from HMBO and HMOW vectors. Specifically, the first model is constructed according to the geometric average function of hesitant multiplicative element (HME). The second one uses the β-normalization method to add some values until all the HMEs have the same length, and then introduces normalization method to obtain more reliable hesitant weights. The third one uses the α-normalization method to reduce some values, aiming to determine the crisp weights which is closest to the original hesitant multiplicative values. Finally, a case study of choosing commercial endowment insurance products is constructed to illustrate the practicality and correctness of the proposed model. The HMBWM has the ability to deal with a set of possible uncertain preference values in preference comparison process, which enrich the application fields of the BWM.

Consistency check [25] is an important problem for pairwise comparisons. In this paper, this part is not involved. Another important problem is anchoring bias. Although the HMBWM also uses two anchors (best and worst), however, what extent the bias is for HMBWM? All of these will be our future studies.

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Chapter 6
Industry 4.0 and Green Entrepreneurship for Environmental Sustainability: Exploring Barriers from an Indian SME Perspective

Himanshu Gupta, Sourav Mondal, Saumya Singh, and Manjeet Kharub

Abstract Industry 4.0 has been considered a significant conduit for sustainable goods and processes, and green entrepreneurship are being held up as a solution for many social and environmental challenges. However, green entrepreneurs face certain challenges and uncertainty in incorporating digitisation (such as Industry 4.0) in sustainability activities. This article discusses the role and barriers that industry 4.0 and green entrepreneurs confront for environmental sustainability in Small and Medium Enterprises (SMEs). Therefore, we begin with a study identifying barriers based on a case study of SMEs and outline recent contributions exploring this role. Theoretical supports (Resource-Based View (RBV), Natural Resource-Based View (NRBV), and Stakeholder Theory (ST)) are used to support this case study. With expert opinion, multi-criteria decision-making modelling (MCDM), such as the "Best-Worst Method" (BWM), is used to assess and rank the barriers. The findings show that among the main category of barriers are "technology-related barriers", whereas in the sub-category, "minimal technological resources and lack of technological infrastructure and facilities" are the top barriers to Industry 4.0 and green entrepreneurship on environmental sustainability. We then summarise the papers and conclude with suggestions for further research.

Keywords Industry 4.0 · Green entrepreneurship · Environmental sustainability · Barriers · Best-Worst methods

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Introduction

In recent years, the rapid industrialization of small and medium enterprises has played a noteworthy role in economic as well as financial development and negatively impacted the environment. Due to rising negative global environmental issues, many entrepreneurs and existing businesses have been forced to give priority to environmental protection over economic development [44]. In this regard, stakeholders such as the government, top management, and start-ups focus on and give importance to sustainable industrial development. The goal of sustainability has begun to alter the competitive environment, compelling organisations to embrace or employ digital technologies such as Industry 4.0 (I4.0) or the fourth industrial revolution, which play an important role in allowing industries to operate effectively and efficiently [45]. The growing body of research shows that I4.0 has become crucial for a company's performance, sustainable production and manufacturing development, and economic and competitive advantages at the national and global level. Further, this I4.0 helps advance the process, increases efficiency and profitability, and helps sustainability practises such as green practises. On the other side, Green Entrepreneurship (GE) involves creating new firms or modifying existing ones with an emphasis on environmental sustainability and social responsibility [21]. Green entrepreneurs strive to create and deploy innovative technology, goods, and services that have a positive environmental effect while making a profit. GE and I4.0 are closely related in that I4.0 technology may be utilised to assist GE and environmental sustainability [37]. For example, integrating IoT sensors and big data analytics may assist businesses in optimising energy and resource consumption, reducing waste, and lower greenhouse gas emissions. By boosting energy efficiency, lowering waste, and improving product quality, robotics, and automation may lessen the environmental impact of industrial operations. Moreover, I4.0 technology may foster GE by providing new possibilities for enterprises to produce and sell environmentally friendly goods and services and by helping in environmental sustainability. Companies, for example, may use sophisticated analytics and machine learning to create more sustainable goods across their entire life cycle, from manufacture to disposal.

Lots of research has been investigated in the areas of I4.0, GE, and sustainability. Leona Niemeyer et al. [32] and Yin et al. [61] studied I4.0 to improve and develop sustainable production and manufacturing in business. Schröder [51] shows the challenges of I4.0 for SMEs, whereas [34] studied and evaluated the barriers of I4.0 in supply chain sustainability contexts. Another study [22] shows the interrelationship between I4.0, digitalization, and opportunities with sustainability. In their study, [50] show the challenges and opportunities of I4.0. Polas et al. [43], in their study, show the relationship between blockchain technology and GE,here, they slightly discuss the importance of I4.0. Some studies [17] perform systematic literature reviews on I4.0 and environmental sustainability. This study tries to link I4.0 and sustainability. Castelo-Branco et al. [10] assess I4.0 from a developed country perspective in their study. Further, [37] studied barriers to GE and green initiatives from financial market perspectives.

Meanwhile, green entrepreneurs play a vital role in developing and incorporating I4.0 into manufacturing operations for environmental sustainability. Over the past several decades, the use of I4.0 has also aided sustainability in many ways. For example, this helps entrepreneurs develop smart manufacturing systems [61]. These further assist in monitoring and controlling energy consumption, water usage, and material waste, enabling businesses to improve resource efficiency and reduce carbon emissions. It also supports GEs transition to a "circular economy", "waste management," and maximum utilisation of waste. This enables businesses to develop and implement new sustainable products, services, and business models. Therefore, GE is critical to the growth of I4.0 and environmental sustainability. Several studies on GE, I4.0, and sustainability have been conducted (for example, [32, 61]). Nevertheless, most of the present research in this field is focused on establishing the role of I4.0 in sustainability, with no studies examining its relationships with GE in relation to environmental sustainability. Although green entrepreneurs try to develop I4.0 activities focused on sustainability, there are certain barriers faced by MSMEs. Some earlier research [34] examined the hurdle to I4.0. Therefore, there needs to be more research on the barriers to adopting I4.0 on green entrepreneurship and environmental sustainability in developed nations like Indian MSMEs. Experts have emphasised that studies in the area will help with I4.0, GE, and environmental sustainability. However, it is crucial to comprehend these barriers in depth before attempting to address them. Thus, the purpose of the study is to address the following research objectives (RO):

RO1 To study the relationship between I4.0 and GE in manufacturing SMEs.
RO2 To identify the barriers that may hinder I4.0 and GE on environmental sustainability.
RO3 To rank the identified I4.0 and GE on environmental sustainability.

The remainder of the research is structured as follows: The second portion contains a review of the literature, and the third section describes the research methods utilised in this research, the fourth section provides an analysis of the case study and results; the fifth section discusses the results, the sixth section presents conclusions, and the final section presents implications, limitations, and future research directions.

Literature Review

This section discusses I4.0, GE, and environmental sustainability. The first part of the literature review examines the theoretical views (RBV, NRBV, and ST) employed in this research, followed by literature on I4.0, GE, and environmental sustainability and their relationship. This study contextualises and operationalizes these theories by identifying influencing barriers (i.e., internal, external, and organisational barriers) that industry 4.0 and green entrepreneurs confront for environmental sustainability. These theories provide a new perspective and logical basis for identifying the relevant barriers from the literature that are potentially represented in the context.

Theoretical Framework

Resource-Based View (RBV)

Resource-Based View (RBV) is a theoretical framework used in strategic management to analyse a firm's internal resources and capabilities and how they can be leveraged to achieve a competitive advantage in the marketplace [6, 36]. The RBV suggests that a firm's unique resources and capabilities are the primary drivers of its competitive advantage, rather than the industry or market in which it operates. According to the RBV, capabilities refer to a firm's ability to use its resources to achieve its goals effectively, and this can be developed through internal processes, such as using I4.0 to develop effective and efficient production [6]. The RBV emphasises the importance of developing unique capabilities that are difficult for competitors to replicate. For example, firms that adopt I4.0 technologies to increase efficiency can reduce their carbon footprint and environmental impact. RBV can help firms identify and leverage their internal resources and capabilities to create sustainable competitive advantages. Moreover, GE can drive innovation and create new opportunities for sustainable growth [36]. By developing new products and services that prioritise environmental sustainability, green entrepreneurs can help address alarming environmental issues like climate change, resource depletion, and pollution. RBV, I4.0, and GE can be powerful tools for promoting environmental sustainability. Hence, this theory aids in identifying and categorising the technical, financial, strategic, and institutional-related resources required in SMEs and, without this, creates obstacles for them to encounter while attempting to embrace and develop I4.0 and GE practises for environmental sustainability.

Natural Resource-Based View (NRBV)

The Natural Resource-Based View (NRBV) is a strategic management theory that suggests that a firm's sustainable competitive advantage is derived from the unique resources and capabilities that are rooted in the natural environment [20]. This is because natural resources are typically characterised by high barriers to entry and are difficult to replicate or substitute. The NRBV highlights the importance of resource identification, assessment, and development in achieving competitive advantage [39]. It also emphasises the need for sustainable resource management practises that balance economic, social, and environmental objectives. Further, SMEs can use I4.0 technologies to improve resource efficiency and reduce environmental impact while identifying new sources of natural resources that can be used in manufacturing [36]. For example, some manufacturers are using renewable energy sources, such as solar and wind power, to power their factories and reduce their carbon footprint. Similarly, GE can also be viewed through the lens of the NRBV. Green entrepreneurs aim to create new products and services that are environmentally sustainable, such as eco-friendly packaging, energy-efficient lighting systems, and waste-reduction technologies. These entrepreneurs are innovatively leveraging natural resources to create value for their customers while promoting environmental sustainability [36]. In this case, NRBV provides a valuable framework for understanding and identifying the natural resource constraints and capabilities that manufacturing SMEs face while trying to adopt I4.0 and GE to achieve sustainable competitive advantage and promote environmental sustainability.

Stakeholder Theory (ST)

This stakeholder theory (ST) is a management and organisational theory that suggests that a company's success is not only determined by its financial performance but also by its ability to create value for a wide range of stakeholders, including employees, customers, suppliers, communities, and the environment [59]. According to this theory, a company should strive to create a balance between the interests of its various stakeholders rather than focusing solely on maximising profits for shareholders. By doing so, a company can build long-term, sustainable relationships with its stakeholders, enhance its reputation, and improve its financial performance [7]. Stakeholder theory suggests that companies have ethical and social responsibilities to their stakeholders beyond their legal obligations. This can be achieved through various mechanisms, such as stakeholder consultation, engagement, and collaboration. Further, with I4.0, stakeholders like employees, customers, suppliers, and the environment are impacted by the integration of advanced technologies. Further, GE also involves a wide range of stakeholders, such as investors, employees, customers, suppliers, and the environment [60]. Stakeholder theory suggests that companies should consider the interests of all these stakeholders when developing and implementing sustainable products and services [59]. This can include sourcing sustainable materials, reducing waste, and minimising environmental impact. In addition, stakeholder theory provides a valuable framework for understanding how companies can adopt I4.0 and GE to achieve environmental sustainability. By considering all stakeholders' interests, companies can create long-term sustainable value and build stronger relationships, leading to greater success in the long run. While developing I4.0 and GE initiatives for environmental sustainability, ST can assist in identifying the various barriers related to or affecting stakeholders and their divergent interests, concerns, and expectations of SMEs.

Industry 4.0 (I4.0) in SMEs

I4.0 can significantly impact SMEs in terms of opportunities and challenges. One of the key benefits of I4.0 for SMEs is the potential for increased productivity and efficiency [27]. By integrating advanced technologies, such as the Internet of Things (IoT), artificial intelligence (AI), and big data analytics, SMEs can streamline their operations and improve their overall performance [25]. For example, businesses or start-ups can use IoT-enabled sensors to monitor their equipment and optimise their production processes or use AI algorithms to automate routine tasks and reduce errors. I4.0 can also provide SMEs with new opportunities for growth and innovation. By leveraging advanced technologies, SMEs can develop new products and services, enter new markets, and establish partnerships with other companies. For example, they can use digital platforms to reach new customers and markets or collaborate with other SMEs to develop innovative solutions. However, there are also several challenges that SMEs may face when adopting I4.0 [40]. One of the main challenges is the cost of implementing these advanced technologies, which can be prohibitively expensive for some SMEs. Additionally, challenges may be related to the skills and expertise needed to implement and manage these technologies. To address these challenges, SMEs can consider partnering with other companies or collaborating with research institutions to share the costs and expertise needed to adopt I4.0. Additionally, they can invest in training and development programmes to build the necessary skills and knowledge within their organisation. Overall, I4.0 presents both opportunities and challenges for SMEs. By adopting advanced technologies and leveraging new opportunities for growth and innovation, SMEs can achieve long-term success and remain competitive in the global market.

Green Entrepreneurship (GE) in SMEs

GE in SMEs refers to starting and running businesses that are environmentally sustainable, socially responsible, and economically viable [42]. Green MSMEs are those businesses that create products and services that help reduce environmental impact, conserve natural resources, and promote sustainable practises. In addition, GE in SMEs allows businesses to create value while promoting environmental sustainability and social responsibility [53]. It can also help businesses differentiate themselves in the marketplace and appeal to consumers who are increasingly concerned about sustainability. GE differentiates itself from other types of entrepreneurship because it focuses on creating businesses that generate profits and positively impact the environment and society. While traditional entrepreneurship is primarily concerned with maximising profits, GE seeks to balance economic, social, and environmental sustainability [56]. Green entrepreneurs are motivated by a desire to address environmental and social challenges such as climate change, resource depletion, and social inequality, and they see business as a means to create positive change. They are committed to sustainable practises, and their businesses often use eco-friendly technologies, reduce waste, and minimise their carbon footprint. Green practises in SMEs can face several challenges that can hinder their adoption and implementation [60]. Here are some of the common problems faced by SMEs when adopting green practises: a lack of resources, limited awareness and knowledge, resistance to change among the employees, a lack of supportive policies, and limited market demand, which can make it problematic for SMEs to justify the investment in green practises and products.

Relationship of I4.0 with GE

Industry 4.0 (I4.0), the Fourth Industrial Revolution, refers to integrating advanced technologies such as artificial intelligence, the Internet of Things (IoT), cloud computing, and robotics in manufacturing [49]. This new wave of technological transformation significantly impacts various aspects of business, including sustainability and environmental management. In contrast, GE refers to businesses that are designed to provide sustainable solutions to environmental problems [19]. The role of I4.0 in promoting GE and environmental sustainability and this technology can help businesses optimise resource use, reduce waste, and improve energy efficiency [49]. For example, IoT sensors can monitor energy consumption in real-time, allowing businesses to identify areas where energy can be saved. In addition, I4.0 technologies can enable businesses to adopt circular business models, which aim to reduce waste and promote resource reuse. Further, IoT-enabled tracking systems can help businesses track the lifecycle of products and materials, allowing them to identify opportunities for reuse and recycling [19]. Although I4.0 technologies can enable businesses to create more innovative and sustainable supply chains, for example, blockchain technology can be used to track the origin of raw materials and ensure that they are ethically and sustainably sourced. I4.0 technologies can facilitate the adoption of renewable energy sources, such as solar and wind power. IoT-enabled sensors can monitor energy production from renewable sources and help businesses optimise their use of these resources. In conclusion, I4.0 has the potential to play a significant role in promoting GE and environmental sustainability. By leveraging advanced technologies, businesses can optimise resource use, adopt circular business models, create smarter and more sustainable supply chains, and adopt renewable energy sources. It can lead to a more sustainable future where businesses can thrive while promoting environmental sustainability.

Research Gap and Existing Problems

Several studies on I4.0, GE, and environmental sustainability have been conducted separately. Although prior research has successfully shown the importance of I4.0 and GE in manufacturing SMEs, comparatively few studies have highlighted its importance for sustainable development. There are minimal studies on the impact of technologies on GE, and they are limited to specific areas. Balachandran and Sakthivelan [8] show the importance of technology on entrepreneurship, while [22] shows the importance of I4.0 on sustainability. Numerous businesses have integrated sustainability into their I4.0 to improve environmental sustainability. However, the literature lacks studies that examine the impact of technologies on the sustainability of manufacturing SMEs. Moreover, more research needs to be conducted on identifying challenges, barriers, fundamental difficulties, and problems adapting digital technologies (i.e., I4.0) in manufacturing SMEs. For instance, [34] provide a list of barriers to I4.0 in the other sector in a developed country [51], and Ghobakhloo et al. [23] present the barriers to technology applications; however, their suggestion that future studies are still pending. In addition, [43] also show the relationship between blockchain technology and GE. However, to the best of our knowledge, no prior study has shown the relationship between I4.0 with GE and environmental sustainability. Moreover, no study identified barriers or challenges impeding I4.0 and GE activity. None have explicitly integrated I4.0 and GE for environmental sustainability studies, as this study does. The details steps followed in this research have been provided in Fig. 6.1.

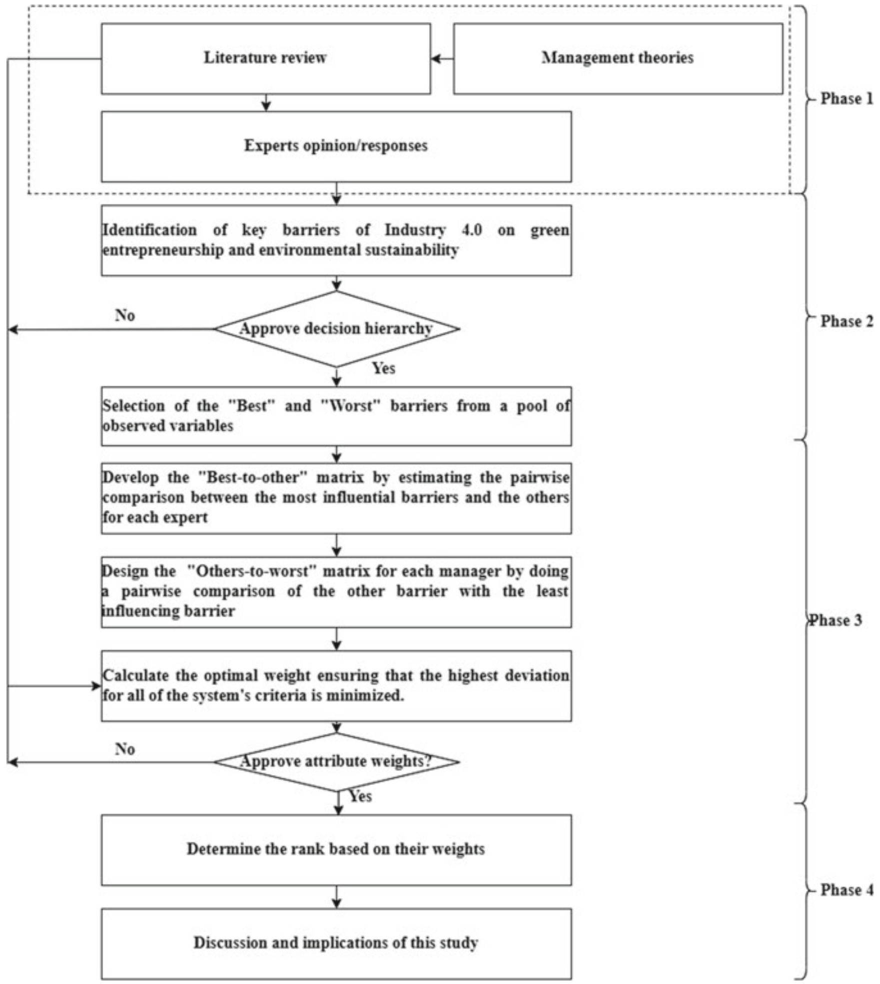

Fig. 6.1 Flow chart for carrying out research methodology

Methodology

This study applied a four-phase multi-case methodology (see Fig. 6.1) to analyse and rank the barriers. In the first phase of the research, barriers were identified; in the second phase, they were classified; in the third phase, expert responses were taken; and in the fourth phase, weight and rank were calculated. For weight and rank calculation [47] were used. The "Best-Worst Method" (BWM) is a "Multi-Criteria Decision-Making" (MCDM) technique used to evaluate items or alternatives based on their relative importance or value. BWM is preferred in comparison to other MCDM techniques because it requires fewer pairwise comparisons, improves consistency in the ranking, considers only integer values, reduces the computational burden, and can easily be combined with their methodologies'. In addition, this methodology is flexible, solves the inconsistency problems during pairwise comparison, is robust, provides an intuitive result, and produces valid and reliable results [47, 55]. Furthermore, consistency judgement is an important step in BWM to ensure the reliability of the results and should be performed before interpreting the rankings obtained from the participants. Consistency judgement involves checking whether the participants have responded consistently to the questions presented to them. Experts are asked to rank a set of items based on their relative importance. The ranking is done by choosing the best and worst items from a set of items. To ensure consistency, the same set of items is presented to the participants multiple times, and the rankings are compared across the different sets. In addition, consistency judgement in BWM involves calculating the consistency ratio (CR), which is a measure of how consistent the participants' rankings are across the different sets. The consistency ratio (CR) is used to evaluate the reliability and consistency of the obtained weights (a lower CR value indicates more consistency in ranking). The CR is calculated from the consistency index, and the value of CR varies between 0 and 1 (Table 6.7 in appendix shows the output of the CR). Here, a close value of 0 shows more consistency, whereas a close value of 1 shows less consistency [47]. Therefore, it has been used in different fields of research, for example, operations research, healthcare, tourism management, finance, energy management, marketing research fields, etc. Hence, in order to evaluate different barriers of I4.0 and GE in Indian MSMEs. The following are the detailed implementation and inference steps of BWM [47].

Step 1 Identify the set of relevant barriers (n) for the research and set of relevant barriers $\{c_1, c_2, \ldots, c_n\}$.

Step 2 Experts determine the Best (e.g., most desirable or most important) and Worst (e.g., least desirable or least important).

Step 3 The next step is to rank the best criterion above all other criteria. On a scale from 1 (equally significant) to 9 (extremely significant), an expert builds the best-to-others vector. This yields vector $A_{Bj} = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ where a_{Bj} denotes the preference value of the "best criteria" B in relation to criterion j. It is clear that $a_{BB} = 1$.

Step 4 Similarly, experts use a 1–9 scale to generate the others-to-worst (OW) vector. 1 shows equally significant preference amongst the criteria, while 9 implies extremely significant preference. This will also produce the vector $A_{jW} = (a_{1W}, a_{2W}, \ldots, a_{nW})^T$, where a_{jW} denotes the relevance value of criteria j over the "worst criterion" (W). It is clear that $a_{ww} = 1$.

Step 5 Then compute the optimised weights (w_1^*, w_2^*, …, w_n^*) for each criterion.

In other words, we obtain the weights of criteria such that the highest absolute variations for every j can be minimised for $\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jW}w_W\right|\right\}$. Therefore, the minimax model is constructed as follows:

$$\begin{aligned} &\min\max\left\{\left|w_B - a_{Bj}w_j\right|, \left|w_j - a_{jW}w_W\right|\right\} \\ &\text{s.t. } \Sigma_j w_j = 1 \\ &w_j \geq 0, \text{ for all j} \end{aligned} \tag{6.1}$$

While Model (6.1) is converted into a linear model, the results are improved, as shown in the model below.

$$\begin{aligned} &\min.\ \xi^L \\ &\text{s.t.} \\ &\left|w_B - a_{Bj}w_j\right| \leq \xi^L, \text{ for all j} \\ &\left|w_j - a_{jW}w_W\right| \leq \xi^L, \text{ for all j} \\ &\Sigma_j w_j = 1;\ \text{wj} \geq 0, \text{ for all j} \end{aligned} \tag{6.2}$$

Model (6.2) can be solved to get "optimal weights" (w_1*, w_2*,…, w_n*) and "optimal value" ξ^L. The consistency (ξ^L) of attribute comparisons near "0" is required.

Further, for the pairwise comparison of vector A_{BO}, and A_{OW} the "cardinal consistency" is considered [30]. Here the pairwise comparison is assumed cardinal-consistent if

$$a_{Bj} \times a_{jW} = a_{BW}, \text{ for all the value of j} \tag{6.3}$$

Here, a_{BW} is the "best criteria's" preference over the "worst criterion".

To assess the level of inconsistency in a pairwise comparison, a CR is necessary. The original BWM method uses an "output-based consistency measurement" that relies on the optimal objective value of the optimization model. However, an alternative approach is called "input-based consistency" measurement, which is easy to calculate and has a clear algebraic interpretation [30]. The "input-based consistency" can quickly determine the level of consistency in a decision maker by using the input the expert offers without the need for the entire optimization process; it is also called an "Input-Based Consistency Ratio" (CR^I) and is formulated as follows.

$$CR^I = \max_j CR_j^I \quad (6.4)$$

where,

$$CR_j^I = \begin{cases} \frac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & \mathrm{a_{BW}} > 1 \\ 0 & \mathrm{a_{BW}} = 1 \end{cases} \quad (6.5)$$

Here, CR_j^I is the local "input-based consistency ratio" for all criteria related with CR_j. Here "input-based consistency ratio" is used over the "output-based consistency ratio" because it may give immediate feedback, is simple to comprehend, is model-independent, and can provide decision-makers with a clear guideline for revising inconsistent judgment(s) [30]. In the Appendix, Table 6.6 provides the different threshold values and it is adopted from [30]. Further, Table 6.7 provides the obtained "input input-based consistency ratio" of different experts for different barriers.

Experts' Background and Case Analysis

Case Details and Experts' Background

In order to achieve the objectives, thirteen experts from ten different firms and academia were chosen. The experts are considered and chosen from diverse manufacturing SMEs with different work experiences (at least ten years), and they practise I4.0 and GE. For this study, participants were intentionally chosen from various functional areas in order to achieve more generalised outcomes. Experts with insufficient experience and no upper management roles were also disqualified. The further expert considered here is from the top management of that organisation, and having a specialised team, they have sufficient knowledge and experts. The details of the thirteen selected experts are presented in Table 6.1. Delphi techniques were used for data collection to identify the barriers. The Delphi technique is a structured communication method used to gather expert opinions from a group of individuals, typically to make informed decisions or predictions about a particular topic or issue [3]. The technique involves a series of questionnaires or surveys distributed to a panel of experts who anonymously provide their opinions and feedback. Experts from SMEs are selected here because they have a significant role in the Indian economy and are regarded as the country's backbone since they contribute considerably to job creation, GDP growth, and industrial output. In the Delphi method, instead of starting with an open question about what is most important to the subject under consideration, experts create individual models that are then combined, averaged, and analysed to draw a final conclusion, and it allows experts to work independently but on the same model until that model can be accepted without major additional modifications. Here, arithmetic mean aggregation and a threshold technique are employed to select the most important experts' responses. The Delphi method was then used in this research, which employs the same group of experts in each round to help define, analyse, and come up with useful evidence about the barriers. Furthermore, through the use of literature, expert feedback, and management theories, this method assists in obtaining a final list of obstacles, which are then classified into six main categories and twenty-eight sub-category impediments (as shown in Table 6.2). Then, using the BWM methodology, each of the experts (Table 6.1) was requested to individually identify the "best" as well as "worst" barriers among the "main category" as well as the "sub-category" barriers. The experts were then asked to rate the " Best-to-Others" (BO) and "Other-to-Worst" (OW) for all the main categories as well as the "sub-category" barriers, respectively, using a 1–9 scale. The pairwise comparison for main category barriers for all experts is presented in Table 6.3. Next, using Eq. (6.2) and the pairwise ratings obtained for all the "main category" barriers as well as the "sub-category" barriers, the weights of each of the main category and sub-category barriers are calculated. The detailed weights as well as the rankings for sub-category barriers, are presented in Table 6.4. Here Table 6.4 the obtained ranking using the arithmetic mean, whereas Table 6.5 in Appendix A shows the ranking calculation obtained from the geometric mean (for further analysis, we consider Table 6.4, which is obtained from the arithmetic mean). Table 6.3 provides a summary of the responses received from experts. Next, the weight of each "main-category" and "sub-category" barrier is calculated using Eq. (6.2), and "pairwise ratings" are obtained from all the barriers. After getting the "local weight" of each "sub-category" barrier, we calculate the global weight by multiplying each sub-category weight with its parent category weight (see the plot of Fig. 6.2). Based on the obtained weight, we provided the rank of each barrier. The detailed weights and rankings are presented in Table 6.4 as a plot of global weight (see Fig. 6.2).

Discussions

The research identified and finalised the barriers to I4.0 and GE on environmental sustainability using a mix of literature reviews, management theories, and many round discussions ("Delphi Techniques") with experts from Indian manufacturing SMEs. The identified barriers are then classified into six "main barriers" and twenty-eight "sub-barriers". According to the results, among the main categories of barriers, technology-related hurdles (TB) were identified as the most pressing challenges facing Indian SMEs in adopting and implementing I4.0 activities through green entrepreneurship to enhance environmental sustainability (see Table 6.4). One of the essential aspects of implementing I4.0 and GE in a manufacturing operation in an SME is technological support. This shows that the absence of technical know-how among manufacturing SMEs in developing countries like India causes impediments to the implementation, acceptance, and development of I4.0 and GE for sustainable development. In addition, these SMEs face severe challenges in acquiring and developing technologies, capabilities, knowledge, and infrastructure [29], for example,

Table 6.1 Information about experts involved in case analysis

Expert	Expertise	Experience	Experts academic background	Type of SMEs/ organisations
Expert-1	Head engineering	18	MBA	Textile Manufacturing
Expert-2	Senior operation manager	15	MTech	Steel manufacturing
Expert-3	Senior production manager	11	MTech	Electrical and electronics
Expert-4	Technical manager	15	MBA	Plastic manufacturing and processing
Expert-5	General manager	12	MBA	Automotive industry
Expert-6	Asst. Manager-Process Control	17	B.Tech	Agro based products
Expert-7	Manager-Operations	11	MBA	Metal and fabrication
Expert-8	Senior production manager	12	MTech	Automobile company
Expert-9	Senior operation manager	11	BE	Automotive industry
Expert-10	Senior Manager-Procurement	13	B.Tech	Automobile parts manufacturing company
Expert-11	Academician	12	PHD	Professor
Expert-12	Academician	10	PHD	Associate professor
Expert-13	Academician	15	PHD	Professor

implementing I4.0 on flexible production and manufacturing, monitoring and developing "waste management", recycling, regenerating, and reusing waste components. Lack of technical support creates enormous barriers to developing sustainability activities or achieving UNDP's sustainable development goals [38]. Certain technological factors, such as a lack of technological infrastructure in the I4.0 era, stifle the development of technological capabilities for green entrepreneurs and SMEs. The next pressing issue is the institutional or institutional-organisational barriers (IB) that create barriers to I4.0 and GE (see Table 6.4). These barriers, like technological barriers, are important impediments to I4.0 and GE. They include resistance to change, a lack of investment, a regulatory environment, a lack of skilled labour, and a lack of awareness and education. These barriers are also affected by the SMEs' external as well as internal factors [2]. To overcome these barriers, organisations may need to take proactive steps to educate stakeholders, invest in new technologies and

Table 6.2 Barriers to I4.0 and GE on environmental sustainability

Main barriers	Sub-barriers	Description	Code	References
Technology impediments (TB)	Minimal technological resources and lack of technological infrastructure and facility	Minimal technological resources and a lack of technological infrastructure and facilities can be significant barriers for green businesses adopting new technologies (such as I4.0) and digitising their operations	TB1	Fatimah et al. [18]
	Lack of technological collaboration between firm, industry and academia	Collaboration is essential for sharing knowledge, expertise, and resources to optimise technology use (i.e., I4.0) to increase efficiency, profit, competitive advantage and sustainability. The lack of these creates barriers to GEs developing environmental sustainability	TB2	Tseng et al. [58]
	Gap between I4.0 design and implementation	This creates barriers such as misalignment between GE and its strategic goals and the technology implementation strategy, cost overruns, reluctance to change, and opportunity limitations	TB3	Çınar et al. [12]
	Lack of focus on innovation and R&D capabilities	A lack of attention to innovation and R&D skills provides impediments to knowledge enhancement, process development, efficiency, and overall entrepreneur performance	TB4	Wu et al. (2020)

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
Institutional and administrative barriers (IB)	Lack of commitment and communication from top management	Without top management commitment or engagement in I4.0 adoption, SMEs face challenges	IB1	de Sousa Jabbour [14]
	Lack of proper decision-making related to how to develop I4.0 activity for sustainability	The absence of adequate decision-making creates a barrier to sustainable activities, such as a clear understanding of the objectives, poor decision-making and planning, and added cost. This creates barriers GEs to developing and adopting I4.0 activities for long-term sustainability	IB2	Dwivedi et al. [16]
	Lack of use I4.0 for waste management and recycling facilities	The lack of use of I4.0 for waste management and recycling facilities can create several barriers, including inefficient waste management, lower recycling rates, as manual sorting and processing methods can be slow and inaccurate, increased negative environmental impacts, and barriers to sustainability and value creation	IB3	Chiarini [11]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
	Lack of understanding of customer requirements and market demand	These barriers created obstacles for GE to integrate I4.0 activities due to inefficient resource utilisation, wasted opportunities, low adoption rates, and a lack of meaningful value on return on investment	IB4	Lin et al. [33]
	Lack of government policies and regulations	The absence of government laws and regulations may provide a number of challenges for GEs seeking to develop and execute I4.0 operations. Inconsistent standards may cause interoperability challenges across various I4.0 systems and technologies, reducing their efficacy and acceptance	IB5	Kumar et al. [29]
Socio-cultural barriers (SCB)	Lack of social and stakeholder pressure	This reduces the transparency of stakeholders, trust between stakeholders and companies, innovation in I4.0 technologies and sustainability practices, and the company's reputation	SCB1	D'Souza et al. [13]
	Habit of use of traditional technologies	Habit of use of traditional technologies resists GEs from developing I4.0 activities and development practices that help in sustainable development	SCB2	Cai et al. [9]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
	Stereotyping and bias	Stereotyping and bias can lead to discrimination and prejudice, which can create a toxic work environment and hinder diversity and inclusion efforts	SCB3	Interview
	Lack of cultural awareness	Employees and leaders may lack awareness or understanding of other cultures, which can lead to cultural insensitivity and misunderstandings	SCB4	Tripathi and Gupta [57]
	Resistance to change	Cultural norms and values can sometimes resist change, making it difficult for organisations to implement new processes, and technologies, i.e., related to I4.0. Implementing new technologies can be disruptive and require changes to existing workflows and processes. Some employees may be resistant to change, which can slow down the adoption of I4.0 and other digital technologies	SCB5	Raj et al. [45]
Finance and economic barriers (FB)	High initial investment in developing I4.0 activities	Because of the substantial investment, this creates hurdles for GEs to develop I4.0 activities in their businesses, as well as impediments to developing environmental sustainability	FB1	Awan et al. [6]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
	Insufficient income and lack of clarity of financial benefit	The starting expenses of introducing new technologies (I4.0) or innovation may be substantial, and firms may be unwilling to invest unless they have a clear knowledge of the prospective financial rewards	FB2	Habib et al. [24]
	Lack of financial support by the government, banks and from investors	This creates barriers to GE to incorporating and practising I4.0 activities	FB3	He et al. [26]
	Lack of capital to carry out I4.0 activities	Adopting I4.0 technologies often requires considerable upfront expenditures in hardware, software, training, and maintenance, which may be prohibitively costly for many firms. A GE without adequate money causes challenges to the development of environmental sustainability	FB4	Shet and Pereira [52]
Knowledge and attitudinal barriers (KB)	Lack of proper technological know-how training of managers and businesses	Without adequate training, SME struggle to grasp the efficient use of I4.0 (i.e., automation, flexible production systems) or embrace new technology trends	KB1	Rizos et al. [48]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
	Lack of proper education level among employees	Employees at businesses and start-ups with insufficient education levels may lack the necessary skills and knowledge to fulfil their job functions successfully. This may lead to decreased productivity, worse work quality, and decreased job satisfaction and motivation	KB2	Struckell et al. [54]
	Lack of entrepreneurial skills and innovative thinking	This creates constraints for GEs associated with I4.0 activity, novel possibilities for expansion, efficiency difficulties, and overall sustainability-related activity	KB3	Moktadir et al. [41]
	Perceived lack of competency and fear of failure	This barrier has an impact on employee productivity, confidence, start-up success, and the integration of new technology, all of which hamper environmental sustainability	KB4	Kumar et al. [29]
	Entrepreneurial role and intentions	The negative attitude of green entrepreneurs creates barriers to incorporating I4.0 activity, which further helps in environmental sustainability	KB5	Abbasianchavari and Moritz [1]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
Strategic barriers (SB)	Lack of green manufacturing and operational capabilities development	This creates challenges and resistance for GE to expand I4.0 activities for increased production, effectiveness, and environmental sustainability	SB1	Karuppiah [28]
	Lack of standardisation	I4.0 technologies are still evolving, and there are currently no industry standards for many of these technologies. This can make it difficult for SMEs to choose the right technologies and ensure compatibility with existing systems	SB2	Tripathi and Gupta [57]
	Less intention towards the sustainability concepts	Medium and small manufacturing enterprises struggle to implement I4.0 activities for improved production and operational activity for sustainable development because of a lack of attention to sustainability on the part of the business, and they are more focused on profit	SB3	Lau and Hashini [31]
	Fierce competitive pressure	This barrier causes issues with thinking, investment in innovation, teamwork, and the general efficiency of a green entrepreneur in developing I4.0 practices for environmentally sustainable development	SB4	Alsaad et al. [5]

(continued)

Table 6.2 (continued)

Main barriers	Sub-barriers	Description	Code	References
	Unclear and complex organisational dynamic orientations	This barrier affects GE's use of I4.0 for environmental sustainability in ways such as a lack of clarity on aim and strategy, which causes problems in decision-making and reluctance to change in SMEs	SB5	Randhawa [46]

training, and work with policymakers to create a more supportive regulatory environment [35]. Third, another important barrier related to I4.0 and GE on environmental sustainability is financial and economic barriers (FB) (see Table 6.4). These hurdles include the cost of integrating new technologies and processes, investing in renewable energy sources, or upgrading to more energy-efficient equipment [15]. Moreover, SMEs may face severe competition from bigger firms with the means to engage in these practises, or they may struggle to find consumers willing to pay more for environmentally friendly goods and services. The following important barriers are related to strategic barriers (SB) and socio-cultural barriers (SCB), and the last and most important barriers are related to knowledge- and behaviour-based barriers (KB), which hinder the adoption and development of I4.0 and GE activities on environmental sustainability. Among the sub-category barriers, minimal technological resources and lack of technological infrastructure and facilities (TB1) are the most important issues related to I4.0 and GE, which hinder progress towards environmental sustainability (see Table 6.4). The absence of technical infrastructure creates impediments to the growth of I4.0, and activities connected to sustainability are a difficult challenge [45]. Manufacturing firms in India often lack critical technological infrastructure. These constraints are exacerbated by hurdles such as a lack of access to data and analytics,developing and deploying new technologies such as the Internet of Things (IoT), Artificial Intelligence (AI), and robots need significant investment in infrastructure and facilities [38]. Businesses that do not have access to this technology may struggle to keep up with rivals that do. This may limit their potential to enhance efficiency, eliminate waste, and boost output, which are critical for environmental sustainability. Moreover, they may be hampered in minimising their carbon footprint and environmental sustainability. The next sub-category barrier is the "gap between the design and implementation of I4.0" (TB3). This creates barriers without proper design and implementation, such as increased energy consumption, no control over waste, and increased cost and complexity for developing I4.0 activities, particularly in SMEs in developing countries [27]. The third most important sub-category barrier

Table 6.3 Identification of "Best" and "Worst" I4.0 barriers and sub-barriers

I4.0 category and sub-category barriers obtained from BWM	Identified as "Best" by experts	Identified as "Worst" by experts
Main-category barriers		
TB	2, 4, 7, 12	6
IB	1, 10, 13	12
SCB	11	5,7,9,13
FB	5, 8	3,10
KB	9	1,4,11
SB	3, 6	2,8
Sub-barriers of technology impediments		
TB1	3, 6, 9, 11	5,7
TB2	7, 8, 10	2,4,11,13
TB3	1, 5, 12, 13	3,8,10
TB4	2, 4	1,6,9,12
Sub-barriers of institutional and administrative barriers		
IB1	10	3,8,13
IB2	1, 3, 6, 12	7
IB3	2, 5, 8, 11	4,10
IB4	4	1,6,9,12
IB5	7, 9, 13	2,5,11
Sub-barriers of socio-cultural barriers		
SCB1	4, 9	3, 6, 10
SCB2	1, 3, 8, 12	7
SCB3	7	1, 2, 5, 9, 11
SCB4	2, 5, 6, 13	8, 12
SCB5	10, 11	4,13
Sub-barriers of finance and economic barriers		
FB1	7, 11	4, 6, 9, 12
FB2	2, 3, 5, 8	10, 11
FB3	1, 4, 9, 13	2, 5, 8
FB4	6, 10, 12	1, 3, 7, 13
Sub-barriers of knowledge and attitudinal barriers		
KB1	4, 8, 12	3, 11
KB2	11	1, 5, 8, 10, 13
KB3	3, 13	2, 6, 7
KB4	2, 5, 7, 10	9
KB5	1, 6, 9	4, 12

(continued)

Table 6.3 (continued)

I4.0 category and sub-category barriers obtained from BWM	Identified as "Best" by experts	Identified as "Worst" by experts
Sub-barriers of strategic barriers		
SB1	2, 5, 7, 9, 11	10
SB2	13	1, 4, 5, 8, 11
SB3	1, 6, 8, 12	3,7
SB4	4	6, 9, 13
SB5	3, 10	2, 12

Table 6.4 Ranking of barriers

Main barriers	Local weight	Sub barriers	Weight of sub-barriers	Global weight	Rank
TB	0.247	TB1	0.309	0.076	1
		TB2	0.230	0.057	4
		TB3	0.265	0.065	2
		TB4	0.195	0.048	7
IB	0.206	IB1	0.132	0.027	19
		IB2	0.291	0.060	3
		IB3	0.238	0.049	6
		IB4	0.140	0.029	17
		IB5	0.199	0.041	10
SCB	0.119	SCB1	0.173	0.021	22
		SCB2	0.279	0.033	12
		SCB3	0.119	0.014	27
		SCB4	0.262	0.031	15
		SCB5	0.168	0.020	24
FB	0.165	FB1	0.185	0.030	16
		FB2	0.342	0.056	5
		FB3	0.274	0.045	9
		FB4	0.199	0.033	13
KB	0.117	KB1	0.214	0.025	21
		KB2	0.108	0.013	28
		KB3	0.174	0.020	23
		KB4	0.274	0.032	14
		KB5	0.230	0.027	20
SB	0.146	SB1	0.324	0.047	8
		SB2	0.126	0.018	25
		SB3	0.234	0.034	11
		SB4	0.122	0.018	26
		SB5	0.194	0.028	18

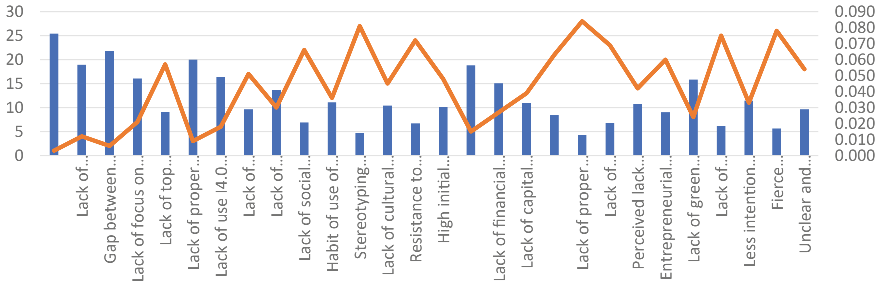

Fig. 6.2 Plot of global weight and global rank

is the "lack of proper decision-making related to developing I4.0 activity for sustainability" (IB2). These constraints impact I4.0, such as SMEs investing in I4.0 technology and processes that do not emphasise environmental sustainability. This might lead to needless expenditure, which can harm the SME's financial viability. It may also hinder SMEs' capacity to engage in GE methods, which may require substantial financial resources. Therefore, businesses may be unable to maximise their I4.0 investments to enhance environmental sustainability without thorough study and planning. This can reduce the environmental and financial sustainability advantages of I4.0 [4].

Conclusion

Sustainability is a worldwide critical issue, and India and other developing nations face several obstacles associated with political issues, finances, and technology, among other things. In addition, manufacturing SMEs are a sector that significantly contributes to the developing global economy but also faces several challenges. To cope with this challenging and rising global sustainability problem, industrial organisations and entrepreneurs must create a new innovative way that helps in coping with these challenges. There are several ways to solve this issue; however, the incorporation of digital technologies (such as I4.0) and GE plays a significant role. Further, to implement these, SMEs face several challenges, and it is necessary to identify the barriers. Therefore, this study identified a list of barriers that hampers the adoption, development and make the operation of I4.0 and GE on environmental sustainability in the manufacturing SMEs. This study further helps to rank these barriers based on obtained weight. This study identifies the technology barrier (in the sub-category "minimal technological resources and lack of technological infrastructure and facilities"), the institutional barrier (in the sub-category "lack of proper decision-making related to how to develop I4.0 activity for sustainability"), in financial, economic barrier (in the sub-category "insufficient income and lack of clarity of financial benefit"), in strategic barrier (among sub-category "lack of green manufacturing and operational capabilities development"), in socio-cultural barrier (among sub-category "habit of the use of traditional technologies"), and among attitudinal and knowledge-based barrier (among sub-category "perceived lack of competency and fear of failure") are the most important I4.0 and GE barriers on environmental sustainability. As a result, this interdisciplinary research integrates three streams of literature, namely I4.0, GE, and sustainability. It builds on prior studies that either focused only on the application of I4.0 or GE on sustainability or addressed the hurdles in separate research.

Implications, Limitations and Future Recommendations

Implications

This research finding has significant implications for manufacturing SME managers, entrepreneurs, the government, policymakers, and academicians. This interdisciplinary study combined theoretical and empirical approaches to better understand the challenges that SMEs encounter during the development and implementation of Industry 4.0 and GE for sustainability. Because of their significant harmful impact (such as the creation of more pollution and waste generation) on the environment, the industrial sector is constantly in the news when policymakers and scholars examine environmental degradation. Manufacturing SMEs must accept and innovate long-term solutions to environmental problems caused by their operations. But given the size and complication of the procedures, the green entrepreneurs or green entrepreneurs of manufacturing SMEs face several challenges to implementing innovative solutions, such as the adoption, development, and implementation of Industry 4.0 activities. The present study provides a framework for manufacturing SMEs by identifying six "main-category" and twenty-eight "sub-category" barriers to Industry 4.0 and green entrepreneurship on environmental sustainability in the context of manufacturing SMEs. Overall, the "lack of proper decision-making" related to developing Industry 4.0 activities for sustainability can significantly affect the development or adoption of Industry 4.0 and green entrepreneurship on environmental sustainability in SMEs in India. To address these challenges, SMEs can focus on building awareness and understanding of the environmental benefits of I4.0 and work with experts to design and implement Industry 4.0 solutions that prioritise environmental sustainability. Governments can also support SMEs by providing funding and incentives to promote the adoption of Industry 4.0 solutions that prioritise environmental sustainability, as well as by promoting awareness of the environmental benefits of Industry 4.0. Policymakers and regulatory authorities in developing nations might also benefit from this study by testing the present framework in several other industries to better understand the underlying constraints. Policymakers should also concentrate on capacity development for the manufacturing sector by providing technology engagement assistance and skill improvement training to employers of manufacturing SMEs. Moreover, managers and business owners may design customised training seminars and programmes to improve their employees' technical abilities and competencies. Managers may use this study as motivation to invest more in research infrastructure for their businesses, empowering their teams to engage in Industry 4.0 and green practises. According to the findings of this study, managers and regulatory bodies need to take action on a macro level by formulating strategies, drafting policies, and allocating subsidies and funds to support activities that enhance research and technological capability in order to achieve sustainable development. Further, the results might be used by the government to implement reforms in areas like taxation, policymaking, workforce development, technical assistance, and incentive schemes.

Limitations and Future Recommendations

As every study has some limitations, this research also has some of them. This study, through literature and expert advice, identifies barriers to Industry 4.0 and green entrepreneurship for environmental sustainability. Future studies can focus on identifying a few more Industry 4.0 barriers, which can be explored more with a more comprehensive literature review. This study used MCDM techniques to evaluate the barriers. Future studies can use techniques such as structural equation modelling (SEM) to determine the relationship among barriers. Future studies can use larger data sets, as this study's techniques only used a few limited experts to conclude the results. Further future studies can use other Multi-Criteria Decision Making (MCDM) techniques such as the Bayesian or "Fuzzy Best-Worst Method" (BBWM or FBWM), which gives real-world situations by considering decision-makers' confusion. Further. This technique used thirteen experts, which can be increased with experts from more diverse fields. Undoubtedly, this preliminary study opens more opportunities for future work to be carried out.

Appendix

See Tables 6.5, 6.6 and 6.7.

Table 6.5 Ranking of barriers (when considering geometric mean)

Main barriers	Local weight		Sub barriers	Weight of sub-barriers		Global weight	Rank
	Geometric mean	Normalized weight		Geometric mean	Normalized weight	Normalized weight	
TB	0.202	0.254	TB1	0.239	0.335	0.085	1
			TB2	0.151	0.212	0.054	5
			TB3	0.185	0.260	0.066	3
			TB4	0.137	0.193	0.049	7
IB	0.173	0.218	IB1	0.105	0.138	0.030	14
			IB2	0.235	0.309	0.067	2
			IB3	0.178	0.234	0.051	6
			IB4	0.105	0.138	0.030	15
			IB5	0.137	0.181	0.039	10
SCB	0.089	0.112	SCB1	0.131	0.172	0.019	23
			SCB2	0.220	0.291	0.032	11
			SCB3	0.088	0.116	0.013	28
			SCB4	0.190	0.250	0.028	17
			SCB5	0.129	0.170	0.019	24
FB	0.125	0.158	FB1	0.127	0.176	0.028	18
			FB2	0.261	0.360	0.057	4
			FB3	0.202	0.280	0.044	9
			FB4	0.133	0.184	0.029	16
KB	0.091	0.115	KB1	0.160	0.212	0.024	21
			KB2	0.087	0.115	0.013	27
			KB3	0.127	0.169	0.019	22
			KB4	0.205	0.272	0.031	13
			KB5	0.174	0.232	0.027	20
SB	0.115	0.144	SB1	0.262	0.337	0.049	8
			SB2	0.096	0.123	0.018	26
			SB3	0.173	0.223	0.032	12
			SB4	0.099	0.128	0.018	25
			SB5	0.147	0.190	0.027	19

Table 6.6 Thresholds values for different combinations using "input-based consistency measurement"

Scales	3	4	5	6	7	8	9
3	0.167	0.167	0.167	0.167	0.167	0.167	0.167
4	0.112	0.153	0.190	0.221	0.253	0.258	0.268
5	0.135	0.199	0.231	0.255	0.272	0.284	0.296
6	0.133	0.199	0.264	0.304	0.314	0.322	0.326
7	0.129	0.246	0.282	0.303	0.314	0.325	0.340
8	0.131	0.252	0.296	0.315	0.341	0.362	0.366
9	0.136	0.268	0.306	0.334	0.352	0.362	0.366

* Adopted from [30]

Table 6.7 CR table of expert's response

Expert	Input-based consistency ratio						
	Main-category barriers	Sub-barriers					
		Technological	Institutional and administrative	Socio-cultural	Finance and economic	Knowledge and attitudinal	Strategic
Expert 1	0.125	0.153	0.097	0.153	0.153	0.153	0.153
Expert 2	0.083	0.214	0.153	0.214	0.153	0.153	0.083
Expert 3	0.153	0.083	0.153	0.153	0.125	0.153	0.153
Expert 4	0.153	0.125	0.214	0.153	0.153	0.153	0.153
Expert 5	0.153	0.125	0.083	0.125	0.083	0.153	0.125
Expert 6	0.083	0.153	0.153	0.153	0.153	0.153	0.153
Expert 7	0.097	0.179	0.153	0.153	0.125	0.214	0.179
Expert 8	0.153	0.125	0.153	0.153	0.153	0.153	0.153
Expert 9	0.153	0.153	0.153	0.125	0.069	0.153	0.153
Expert 10	0.153	0.153	0.153	0.179	0.153	0.153	0.153
Expert 11	0.153	0.097	0.083	0.153	0.179	0.153	0.153
Expert 12	0.153	0.125	0.083	0.153	0.125	0.153	0.097
Expert 13	0.153	0.083	0.153	0.153	0.153	0.153	0.125

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Chapter 7
Supplier Selection for the Oil Industry Using a Combined BWM & F-VIKOR, Case Study: National Iranian South Oil Company

Hamzeh Amin-Tahmasbi, Abbas Ayaran, and Mahdi Zarepoor

Abstract Supplier selection is one of the most important strategic activities that has a significant impact on the output quality of any company, as it involves multiple criteria for the evaluation and selection of suppliers. The goal of this research is to evaluate and select suppliers for the National Iranian South Oil Company. The opinions of company experts and managers were used for evaluations. The weighting of criteria was done using the Best and Worst method, and the suppliers were ranked using the fuzzy VIKOR. Fuzzy preference relations were used to incorporate the ambiguities and uncertainties that existed in experts' judgments about the priority of each supplier considering research criteria. The results of using BWM to prioritize contributing factors in supplier selection indicate that the Financial System criterion "production price" is the most important factor in supplier selection. Finally, some practical strategies for managers are provided.

Keywords Best-worst method · Supplier selection · Supply chain · Oil industry · Fuzzy VIKOR

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Introduction

The notion that supplier selection is a critical step in developing a competitive supply chain has been a mainstay since the early days of supply chain thinking. This importance is rooted in the critical nature of purchasing and procurement decisions. In industrial organizations, raw material purchasing ranges from 50 to 90% of the total organizational turnover. Not only there is a concern with the high costs of purchasing and procurement, but the appropriate form of a supply base is necessary for effective and efficient materials and product logistics. Thus, this selection will directly influence an organization's business continuity [1]. The supply chain is a cycle that encompasses all activities related to the flow of goods from the conversion of raw materials to the stage of delivery of the final product to the consumer [2]. Supply chain management is the set of approaches that effectively integrate suppliers, manufacturers, warehouses, and distributors to produce and distribute the required goods in the correct place and time to minimize the costs of the system for the desired level of service [3].

The supplier selection decision, as a strategically focused decision, is not trivial. Supplier selection decisions play a significant role in the production and supply management of companies. Multiple criteria are needed to consider different aspects of selection. Producers spend 60% of their time on supplying raw materials, and 70% of production costs are related to purchasing of goods and services [4]. As a result, incorrect decisions on supplier selection would lead to negative consequences and losses for the company [5]. Reduction of the supply chain risk, reduction of production costs, increasing the revenue, improvement of customer service, optimization of inventory levels and business processes, and cycle time, and as the result enhancing the competition and customer satisfaction and profitability are the main objectives of supply chain management [6]. Assessment, ranking, and selection of suppliers are important components of supply chain management. Issues related to supplier selection are complex and may include many concerns.

The conventional techniques in this area deal with quantitative criteria, yet there are many qualitative criteria in the supply chain, so a technique is necessary that includes both the quantitative and qualitative criteria. Considering the multi-criteria nature of supplier selection, multi-criteria decision-making techniques can be very useful. In this study, a combined method of the BWM (Best and Worst Method) and FVIKOR (fuzzy Vlse Kriterijumsk Optimizacija Kompromisno Resenje) technique is proposed to evaluate and rank suppliers. First BWM is used to calculate the relative weights of criteria. Then, by using the decision matrix developed based on BWM weights, suppliers are ranked using the fuzzy VIKOR technique. The proposed method increases the efficiency of the evaluation and ranking process by employing BWM to obtain criteria weights which reduces the number of pairwise comparisons substantially and simultaneously provides more consistent weights. Additionally, this model proposes a compromise solution that decreases the level of conflict among decision-makers. In this paper, we used the concept of fuzzy set theory and linguistic values to determine the uncertainty in qualitative factors. The proposed model is capable of taking into account both data and experts' opinions in an integrated manner which leads to a more effective decision-making process.

The BWM is characterized by some salient features such as (i) it provides a very structured pairwise comparison, which results in highly consistent and reliable results; (ii) it uses only two vectors instead of a full pairwise comparison matrix. This implies fewer data collection efforts, taking less time from the analyst and the decision-maker.

The primary contributions of this study are summarized as follows: (1) employing BWM to obtain criteria weights that reduce the number of pairwise comparisons substantially, and simultaneously provide more consistent weights; (2) combining the merits of both subjective and objective weighting methods, a combination weighting method is proposed to define criteria weights in solving the supplier selection problem; and (3) to identify the most appropriate supplier, an extended fuzzy VIKOR method is developed for the ranking of the considered alternatives. Furthermore, NISOC's (the National Iranian South Oil Company) supplier selection is provided to illustrate the applicability and effectiveness of our proposed combined method.

Literature Review

The goal of supplier selection in the supply chain is to find suitable suppliers at a reasonable price and at the right time, with the appropriate quality and quantity. Previously, several criteria were used to select suppliers in the supply chain, and it is stated that supplier selection risk assessment is critical in the selection process [6]. In addition, different researchers used a variety of criteria [5]. Molataifeh and Talebi [7] attempted to select the best supplier in the Bahman Engine Center by establishing the significant criteria in supplier selection as well as determining the importance of each in terms of an expert's opinion using fuzzy AHP (Analytical Hierarchy Process) approach. Irajpour et al. [8] used DEMATEL (Decision-Making Trial and Evaluation) to identify and evaluate the most effective criteria in the selection of a green supplier. They presented a multi-criteria approach to supplier selection and evaluation with thirteen criteria. Pouya and Alizadeh [9] used the combined fuzzy Delphi-VIKOR model to tackle the supplier selection problem at the Snowflake mineral water company. According to the findings, the most essential criteria for supplier selection are as follows: quality, timely delivery, facilities and production capacity, industry position, and flexibility. Shafiei et al. [4] used a fuzzy DEA (Data Envelopment Analysis) model and two-step analysis to examine 23 criteria for selecting Daiti Company's suppliers. Daneshvar and Saputro [10] sought to develop a new perspective on multi-criteria decision-making methods and multi-objective planning to address pressing issues. For supplier selection and optimization, they used TOPSIS and fuzzy goal-programming techniques. Amin-Tahmasbi and Alfi [11] introduced a fuzzy optimization multi-criteria decision-making model for selecting suppliers and allocating orders in the green supply chain. Considering the uncertainty in supplier capacity and consumer demand, they developed their model in the form of fuzzy multi-objective linear programming.

On the other hand, the Best and Worst method has been used in solving the supplier selection problem in previous studies, either alone or together with other methods. Haeri and Rezaei [12] proposed a comprehensive grey-based green supplier selection model that incorporates both economic and environmental criteria. A novel weight assignment model is proposed by combining BWM and fuzzy grey cognitive maps to capture the interdependencies among the criteria. Zolfani et al. [13] created a structured framework for sustainable supplier selection by combining the BWM and another MCDM methods in the steel industry. Ecer and Pamucar [14] used the fuzzy BWM to extract the relative weights of SSCM (Sustainable supply chain management practices) and the CoCoSo method to select the most appropriate suppliers. Javad et al. [15] studied green supplier selection for a steel industry company using BWM and fuzzy TOPSIS. In their research, the company's alternative suppliers are identified, and the most effective criteria for supplier selection based on the supplier's green innovation abilities are determined. Masoomi et al. [16] applied the fuzzy BWM and two another approach to strategic supplier selection for the renewable energy supply chain under green capabilities. Shang et al. [17] applied the integrated BWM and two other techniques for sustainable supplier selection. Paul et al. [18] attempt to integrate BWM and two other methods to solve a supplier selection problem for the textile industry based on the six most significant criteria. Asadabadi et al. [19] developed a novel criteria-based decision framework for suppliers' assessment by integrating BWM with fuzzy grey cognitive maps to capture the interdependencies among the criteria.

Kurniawan and Puspitasari [20] evaluated supplier selection factors in a small medium scale paper manufacturer in Indonesia is demonstrated using the fuzzy BWM.

Meksavang et al. [21] aimed to develop a modified VIKOR technique for sustainable supplier evaluation that uses ordered weighted distance operators in the aggregation of picture fuzzy information. Kannan et al. [22] combined the fuzzy BWM and the interval VIKOR technique to prioritize sustainable suppliers in circular supply chain.

Garg and Sharma [23] proposed a combined model based on BWM and VIKOR for the selection of partner in a electronics company of India. Kusi-Sarpong et al. [24] proposed a multi-criteria decision-making support tool composed of the BWM and VIKOR was applied to aid in the evaluation and selection of a sustainable supplier in Pakistan's textile manufacturing company. Wei and Zhou [25] provides insights into electric vehicle supplier selection from the perspective of government agencies and public bodies using an integrated multi-criteria decision-making (MCDM) framework based BWM and fuzzy VIKOR.

According to the research in this area, the majority of the researchers conducted their own research using similar methods, with little innovation. In addition, there is currently no research on the selection of suppliers for the NISOC. In this research, a compilation model of the BWM and fuzzy VIKOR has been used for investigating the selection of suppliers in the supply chain of the NISOC.

Methodology

This research is in the category of applied research in terms of purpose. The statistical population of this research is the National Iranian South Oil Company (NISOC) and the method of collecting research data is a survey and library. In the term of superior supplier selection, the first step is to provide a complete and comprehensive list of criteria related to the selection of options and the definition of these criteria is one of the most important stages of designing the model. Reviewing the research literature and the criteria used in the research literature, the criteria of the research model have been adapted from Avila et al. [26]. According to experts, most of the criteria used were exactly in agreement with the conditions of the research question. Therefore, it seems reasonable to use the same criteria in the current research. The research method includes three steps. The first step includes developing a model, and the criteria and sub-criteria are evaluated by experts. The criteria and sub-criteria that scored less than 70% are removed from the model. Then BWM technique is used to determine the weight of each of the criteria and sub-criteria. In the third step, different options (suppliers) are compared and ranked using approved criteria and the fuzzy VIKOR technique.

The BWM Technique

The BWM technique was proposed by Rezaei [27]. It is one of the most effective multi-criteria decision-making techniques based on paired comparisons which has less comparison and higher reliability compared to other paired comparison methods [27]. For example, the Best and Worst method requires $2n - 3$ comparisons, but the hierarchical analysis method, which is the most widely used multi-criteria decision-making method, requires $\frac{n(n-1)}{2}$ comparisons. Some features such as greater stability and consistency of the weights determined at the end of the decision-making problem, the possibility of using them together with other methods, the use of integers to make comparisons, and the simplicity of use, are recommended as an efficient and reliable method in solving multi-criteria decision-making problems.

The steps of the linear BWM technique are as follows [28]:

Step 1. Determining a set of decision criteria: In this step, a set of criteria, which should be considered in the decision is determined as follows: $\{C_1, C_2, \ldots, C_n\}$.

Step 2. Determining the best (the most important/the most appropriate) and Worst (the least important/least appropriate) criterion: In this step, the decision maker will determine the most important and least important criterion;

Step 3. Determining the priority of the best/most important criterion compared to other criteria using 1 through 9: The priority vector is the best criterion compared to other criteria that are shown as follows:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}). \tag{7.1}$$

In this vector, a_{Bj} indicates the superiority of the best criterion (B) to the jth criterion. It is clear that: $a_{BB} = 1$;

Step 4. The expert panel juxtaposes the worst criteria with the other criteria in a pairwise approach.

The priorities of other criteria to the worst criteria were then given between numbers one to nine by the expert panel. The worst factor likely to lead to others will be:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T \tag{7.2}$$

The choice of "criteria j over the worst criteria W" is indicated here by $a_{\mathrm{j}W}$. The definition of $a_{\mathrm{WW}} = 1$ is evident.

Step 5: Find optimized weights $\left(w_1^*, w_2^*, \ldots, w_n^*\right)$ and ξ^{L^*} by solving the following linear model:

$$\begin{aligned} &\min\ \xi^L \\ &\text{s. t.} \\ &\left|w_B - a_{Bj} w_j\right| \le \xi^L \\ &\left|w_j - a_{jW} w_W\right| \le \xi^L \\ &\sum_{j=1} w_j = 1, \\ &w_j \ge 0,\ \text{for all } j \end{aligned} \tag{7.3}$$

in the linear model of the BWM, ξ^{L^*} is considered as an indicator of pairwise comparisons' consistency: a value nearer to zero is a sign of high level of consistency. However, as an effective way to address the consistency problem in this model, Liang et al. [29] recently proposed a method based on input data, known as input-based method. In this method, after determining the preferences of the criteria by a decision maker in the form of best-to-others and others-to-worst vectors, an I mediate feedback on the consistency of her/his data is provided. It is required the preferences to be corrected before going on the implementation of the model, if the consistency ratios are not in the allowable threshold.

Input-based consistency ratio is defined as: $CR^I = \max CR_j^I$.

Where,

$$CR_j^I = \left\{ \begin{matrix} \frac{\left|a_{Bj\times} a_{jW-} a_{BW}\right|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1 \\ 0 & a_{BW} = 1 \end{matrix} \right\} \tag{7.4}$$

In the above relations, CR^I is the global input-based consistency ratio for all criteria and CR_j^I is the indicator of local consistency level for the criterion C_j. Allowable thresholds of input-based consistency ratio are obtained from Table 7.1 with respect to the number of criteria and the scale used in the BWM [29].

Table 7.1 Allowable thresholds for input-based consistency ratio

Scale	Criteria number						
	3	4	5	6	7	8	9
3	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667	0.1667
4	0.1121	0.1529	0.1898	0.2206	0.2527	0.2577	0.2683
5	0.1354	0.1994	0.2306	0.2546	0.2716	0.2844	0.2960
6	0.1330	0.1990	0.2643	0.3044	0.3144	0.3221	0.3262
7	0.1294	0.2457	0.2819	0.3029	0.3144	0.3251	0.3403
8	0.1309	0.2521	0.2958	0.3154	0.3408	0.3620	0.3657
9	0.1359	0.2681	0.3062	0.3337	0.3517	0.3620	0.3662

The Fuzzy VIKOR Technique

The VIKOR method was first proposed by Opricovic [30] for multi-criteria optimization of complex systems, which can determine compromise solutions for a problem with conflicting criteria and help the decision makers to reach a final decision. Since the selection of suppliers of parts, especially High-Tech parts of the oil industry, is very important for the company, therefore, a method should be used to select the closest option to the ideal option. VIKOR method is developed based on the collective consensus method for complex systems. This method focuses on categorizing and choosing from a set of options and determines compromise solutions for a problem with conflicting criteria. So that it can help decision-makers to reach a final decision. Here, the compromise solution is the closest justified solution to the ideal solution and the farthest solution from the anti-ideal solution [31]. Also, since the criteria are mostly qualitative and it is not possible to determine exact numbers for the performance of suppliers in each of the criteria based on the opinion of experts in the form of a definite number, therefore, after determining the weight of the sub-criterion, to determine the ideal option of the fuzzy VIKOR method was used. In the following, ranking the options using the FVIKOR method is explained step by step by Opricovic:

Step 1. Formation of the Fuzzy Decision Matrix: The fuzzy decision matrix is developed based on experts' opinions and using verbal expressions and equivalent fuzzy numbers. The verbal expressions and the equivalent fuzzy numbers used in the present study are presented in Table 7.2.

Step 2. Descaling the Decision Matrix: In this step, the decision-making fuzzy matrix is descaled based on the following steps and equations.

The best and the worst values are identified for each criterion and are named respectively as $\tilde{f}_j^*$ and $\tilde{f}_j^0$. If the jth criterion is positive, $\tilde{f}_j^*$ and $\tilde{f}_j^0$ can be obtained from Eqs. (7.5) and (7.6).

$$\tilde{f}_j^* = \max_i \tilde{f}_{ij} \quad i = 1, 2, \ldots, n \quad \text{for } j \in j^b \tag{7.5}$$

Table 7.2 Verbal expressions and fuzzy equivalents

Verbal expression	Fuzzy equivalents
Very weak	(0, 0, 1)
Weak	(0, 1, 3)
Almost weak	(1, 3, 5)
Average	(3, 5, 7)
Almost good	(5, 7, 9)
Good	(7, 9, 10)
Very good	(9, 10, 10)

$$\tilde{f}_j^0 = {}_i^{Min} \tilde{f}_{ij} \quad i = 1, 2, \ldots, n \quad \text{for } j \in j^b \tag{7.6}$$

If the j_{th} criterion is negative, $\tilde{f}_j^*$ and $\tilde{f}_j^0$ can be obtained from Eqs. (7.7) and (7.8).

$$\tilde{f}_j^* = {}_i^{Min} \tilde{f}_{ij} \quad i = 1, 2, \ldots, n \quad \text{for } j \in j^c \tag{7.7}$$

$$\tilde{f}_j^0 = {}_i^{Max} \tilde{f}_{ij} \quad i = 1, 2, \ldots, n \quad \text{for } j \in j^c \tag{7.8}$$

After determining the best and the worst value of each criterion $\tilde{f}_j^* = \left(l_j^*, m_j^*, u_j^*\right)$ and $\tilde{f}_j^0 = \left(l_j^0, m_j^0, u_j^0\right)$, fuzzy distance from ideal $\left(\tilde{d}_{ij}\right)$, can be obtained using Eqs. (7.9) and (7.10).

$$\tilde{d}_{ij} = \frac{\tilde{f}_j^* \ominus \tilde{f}_{ij}}{u_j^* - l_j^0} \quad \text{for } j \in j^b \text{ (profit)} \tag{7.9}$$

$$\tilde{d}_{ij} = \frac{\tilde{f}_{ij} \ominus \tilde{f}_j^*}{u_j^0 - l_j^*} \quad \text{for } j \in j^c \text{ (cost)} \tag{7.10}$$

Step 3. Determining the utility value $\tilde{S}_i$ and the regret of each option $\tilde{R}_i$: the utility value $\tilde{S}_i$ represents the relative distance of the ith option from the ideal point and the regret $\tilde{S}_i$ is the maximum discomfort of the ith option due to the distance from the ideal point that is calculated using Eqs. (7.11) and (7.12). If $\tilde{S}_i = \left(S_i^l, S_i^m, S_i^u\right)$ and $\tilde{R}_i = \left(R_i^l, R_i^m, R_i^u\right)$, then:

$$\tilde{S}_i = \sum_{j=1}^{J} \left(w_j \times \tilde{d}_{ij}\right) \tag{7.11}$$

$$\tilde{R}_i = max_j\left(w_j \times \tilde{d}_{ij}\right) \tag{7.12}$$

Here $\tilde{S}$ denotes a fuzzy weighted sum and $\tilde{R}$ denotes a fuzzy operator max, and w_j are criterion weights calculated with BWM, respectively.

Step 4. Calculation of the VIKOR Index $\tilde{Q}_i$: In this step, the VIKOR index $\tilde{Q}_i$ is calculated for each of the options using Eqs. (7.13) and (7.14). If $\tilde{Q}_i = \left(Q_i^l, Q_i^m, Q_i^u\right)$ then:

$$\tilde{Q}_I = v\frac{\left(\tilde{S}_i \ominus \tilde{S}^*\right)}{S^{0u} - S^{*l}} \oplus (1 - v)\frac{\left(\tilde{R}_i \ominus \tilde{R}^*\right)}{R^{0u} - R^{*l}} \tag{7.13}$$

Here:

$$\tilde{S}^* = min_i\tilde{S}_i;\ \tilde{S}^{0u} = max_i S_i^u;\ \tilde{R}^* = min_i\tilde{R}_i;\ \tilde{R}^{0u} = max_i R_i^u. \tag{7.14}$$

$\tilde{S}^*$ and $\tilde{R}^*$ are of distance from ideal. Therefore, the optimal value of $\tilde{S}^*$ and $\tilde{R}^*$ is the smallest value of S and R. (The lower the values of S and R, the better.)

The parameter v is the weight of the maximal desirability of a group whose value can be between 0 and 1, which in the present study according to the experts' opinion is considered to be 0.5. In the current study, Eq. (7.15) is used to change the fuzzy values of S, R, and Q to crisp ones. If $\tilde{N} = (l, m, u)$ is a triangular fuzzy number, then:

$$Crisp\left(\tilde{N}\right) = \frac{l + 2m + u}{4} \tag{7.15}$$

Step 5. Ranking the options based on S, R, and Q values: In this step, based on S, R, and Q values the options are ranked into three groups.

Step 6: Determining the final solution and final ranking of options. In this step, two conditions are emphasized for decision making and there are three modes based on these two conditions on which the final decision will be made based on.

First condition: Acceptable Advantage Condition: If A(1), A(2) and A(I) are respectively the first, second, and worst options based on the Q value, and n was the number of options, then Eq. (7.16) must be true.

$$\frac{\left[Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right)\right]}{\left[Q\left(A^{(I)}\right) - Q\left(A^{(1)}\right)\right]} \geq \frac{1}{n - 1} \tag{7.16}$$

Second condition: Acceptable Stability in Decision Making: Option A(1) must rank first at least in one of the S or R groups. The modes that may arise under these two conditions are:

The first mode: When the first condition is not satisfied, a set of options is selected as the top options = A(1), A(2), …, A(M). The maximum value of M is calculated using Eq. (7.17).

$$Q\left(A^{(2)}\right) - Q\left(A^{(1)}\right) < \frac{1}{n - 1} \tag{7.17}$$

Second mode: When the first condition is satisfied, but the second condition is not, A(1) and A(2) are selected as the top.

Third mode: If both conditions were met, A(1) is selected as the top.

Case Study

The goal of this study is to rank NISOC suppliers for the supply of the "12 ¼" Poly Crystal Diamond (PCD) drill bit". Relying on the scientific and executive capabilities of artisans, the company is responsible for the planning, production, and optimal development of oil and gas fields in four provinces based on scientific methods and new technologies. It has defined its organizational policy to meet its missions and duties and to achieve the goals announced by the South Oil National Corporation with a commitment to sustainable development, laws, regulations, and the regulatory requirements and regulations of the oil industry. The drill is the most important component of a drilling machine because it is the primary tool for cutting and rubbing rocks; it is erodible and has a short lifetime compared to other equipment because it becomes dull after a while and its replacement necessitates stopping the drilling operation. Therefore, by choosing the correct supplier for this part, operational delays during the work process can be minimized and the drilling process can be optimized.

5 American, European and Chinese companies produce this technological component ("12 ¼" PCD drill bit) and due to the sanctions against Iran, these companies do not have direct business exchanges with Iranian oil companies; so these technological components are supplied by joint venture or intermediary companies. Therefore, the list of these companies can be seen in Table 7.3. The views of 10 senior staff members of the NISOC have been used to evaluate the suppliers.

Table 7.3 List of suppliers

No.	Supplier	Symbol
1	PAM Co. with Varel Co, France	A_1
2	Dana Engineering Co. with Best Co, China	A_2
3	Arvand Saman Kish Company with Kingdream Co, China	A_3
4	RTC Co. with Chuanke Co, China	A_4
5	TFTI Co. with Halliburton Co, The U.S.	A_5

Results and Discussion

Criterion Localization

A localization questionnaire was provided to experts to localize the conceptual framework at the NISOC. The experts were then asked to rate the relevance of the proposed main and sub-criterion to the research topic on a scale of 1–10. Finally, with an mean of 7, all of the main and sub-criterion were chosen. According to the experts' initial views on the criterion and sub-criterion presented in Table 7.4, it can be seen that the total quality management (TQM) system from the quality system criterion, employment contracts from the financial system criterion, training costs from the cost system criterion, and environmental issues from the production system criterion could not attain the minimum score and were thus eliminated. Also, the synergy system's main criterion, along with all its sub-criteria, was therefore eliminated from the model. Table 7.4 displays the experts' mean opinions on each of the main and sub-criterion.

Data Analysis

As mentioned earlier, BWM and FVIKOR have been used to analyze the data. First, the significance of each of the criteria involved in the selection of suppliers was calculated using the BWM technique; then, the priority of each of the options (suppliers) was determined using the FVIKOR technique according to the weights of the results obtained at the previous stage. It should be noted that, given the literature of the study and the large number of studies conducted on the significance of the criterion involved in the evaluation and selection of suppliers, most experts expressed their ideas regarding the importance of each of the suppliers' assessment and selection criteria. Therefore, it was required to use an efficient technique such as BWM in certain conditions.

On the other hand, ambiguity and uncertainty among experts regarding the performance and status of each supplier for each of the research criterion justify the necessity of using the VIKOR technique in fuzzy conditions.

Data Analysis: BWM Technique

In this part of the research, to explain the BWM technique step by step, we have determined the weights of the main criteria of the research.

Step 1. Determining a set of decision criterion: The criterion and sub-criterion of the current research are presented in Table 7.4. As can be seen, the criterion of the quality system, financial system, production system, and cost system are the four main criteria of the research.

Table 7.4 Mean of opinions of experts in terms of the relevance of criterion

Criterion	Mean	Sub-criterion	Mean	Selection status
Quality system	7.72	Quality control system	8.9	Selected
		Warranty	7.7	Selected
		Service level	7.8	Selected
		Target market	7.4	Selected
		TQM system	6.8	Not selected
Financial system	7.12	Economic ratios	7.3	Selected
		Value-added ratios	7.1	Selected
		Financial stability	7.1	Selected
		Production price	8.6	Selected
		Employment contracts	5.5	Not selected
Synergy system	4.06	Potential synergy	4.5	Not selected
		Position	4.4	Not selected
		Strategic aspects	5.9	Not selected
		Intra-organizational relations	4	Not selected
		Cultural aspects	1.5	Not selected
Cost system	7.76	Production cost	9.3	Selected
		Transport cost	7.2	Selected
		Flexibility of payments	8.2	Selected
		After-sales services cost	8.3	Selected
		Training cost	5.8	Not selected
Production system	7.02	Environmental issues	5.5	Not selected
		Product features	8.1	Selected
		Innovation	7.2	Selected
		Number of product lines	7.2	Selected
		Production capacity	7.1	Selected

Step 2. Determining the best (the most important or most desirable) and the worst (the least important or least desirable) criterion based on the opinion of each expert. For example, the most important criterion is the financial system and the least important criterion is the production system based on the opinion of expert No. 1.

Step 3. Determining the preference of the best or most important criterion for other criteria using numbers 1 to 9 by each expert (Table 7.5).

Step 4. Determining the preference of other criteria compared to the worst or least significant criterion using numbers 1 to 9 by each expert (Table 7.6).

Step 5: The weight of all four main criterion of the research was calculated by applying the linear model (3) and the consistency ratio of all the comparisons calculated by Eq. (7.4) for each expert (Table 7.7). As seen in this table, The consistency ratio of all the comparisons is smaller than Threshold. This approved the proper

Table 7.5 The preference level of the most important criterion

Expert	Best	Quality system (QS)	Financial system (FS)	Production system (PS)	Cost system (CS)
Expert 1	(FS)	5	1	8	2
Expert 2	(FS)	5	1	7	2
Expert 3	(CS)	7	3	5	1
Expert 4	(CS)	4	2	6	1
Expert 5	(FS)	8	1	4	2
Expert 6	(FS)	7	1	4	2
Expert 7	(FS)	5	1	8	3
Expert 8	(FS)	5	1	7	2
Expert 9	(FS)	8	1	4	2
Expert 10	(FS)	9	1	6	2

Table 7.6 The preference of criterion compared to the least important criterion

Expert	Worst	Quality system (QS)	Financial system (FS)	Production system (PS)	Cost system (CS)
Expert 1	(PS)	2	8	1	6
Expert 2	(PS)	2	7	1	6
Expert 3	(QS)	1	2	3	7
Expert 4	(PS)	2	5	1	6
Expert 5	(QS)	1	8	2	5
Expert 6	(QS)	1	7	3	6
Expert 7	(PS)	3	8	1	5
Expert 8	(PS)	2	7	1	5
Expert 9	(QS)	1	8	3	6
Expert 10	(QS)	1	9	2	7

consistency and, therefore, high reliability of the results. Then, to conclude the experts' opinions, the Geometric mean of the calculated weights was normalized and used for each main criterion. The mean weights are available in the last row of Table 7.7.

Finally, these five steps are done to find the mean weight of all sub-criteria. The final results after aggregation of the experts' results are shown in Table 7.8. According to the results, production price, economic ratios, and production cost with a weight of 0.1937, 0.1647, and 0.1464 are respectively in the first and third places.

Table 7.7 The weight of the main criteria and CR according to the opinion of experts

Expert	Quality system (QS)	Financial system (FS)	Production system (PS)	Cost system (CS)	CR	Threshold
Expert 1	0.118	0.529	0.059	0.294	0.071	0.2521
Expert 2	0.119	0.519	0.063	0.299	0.119	0.2457
Expert 3	0.071	0.220	0.132	0.578	0.191	0.2457
Expert 4	0.143	0.286	0.071	0.50	0.133	0.199
Expert 5	0.062	0.523	0.138	0.277	0.036	0.2521
Expert 6	0.061	0.504	0.145	0.290	0.119	0.2457
Expert 7	0.138	0.575	0.057	0.230	0.179	0.2521
Expert 8	0.123	0.512	0.058	0.307	0.167	0.2457
Expert 9	0.06	0.520	0.14	0.280	0.071	0.2521
Expert 10	0.073	0.530	0.067	0.329	0.250	0.2681
Mean	**0.092**	**0.476**	**0.095**	**0.338**		

Table 7.8 Weight of criterion and sub-criterion

Criterion	Mean weight	Sub-criterion	Weight	Mean weight
Quality system	0.092	Quality control system	0.183	0.0168
		Warranty	0.189	0.0174
		Service level	0.603	0.0555
		Target market	0.025	0.0023
Financial system	0.476	Economic ratios	0.346	0.1647
		Value-added ratios	0.058	0.0276
		Financial stability	0.187	0.0890
		Production price	0.407	0.1937
Production system	0.095	Product Features	0.115	0.0109
		Innovation	0.339	0.0322
		Number of production lines	0.113	0.0107
		Production capacity	0.433	0.0411
Cost system	0.338	Production cost	0.433	0.1464
		Transportation cost	0.339	0.1146
		Flexibility of payments	0.113	0.0382
		After-sales services cost	0.115	0.0389

Data Analysis: Fuzzy VIKOR Technique

After determining the mean weight of the criterion, it is needed to rank the suppliers using the FVIKOR method. The evaluation of options is presented in Table 7.8 based on the criterion according to the fuzzy numbers and the verbal expressions given in

Table 7.1. The numbers in Table 7.9 are the fuzzy mean of the opinions of experts. The signs of the production price (C24), production cost (C41), transportation cost (C42), and after-sales services cost (C44) are negative (−). The first column of Table 7.9 indicates 16 sub-criterion of research; the second column includes the weight of each criterion, which was obtained using the BWM technique; the third to seventh columns include the five companies that are considered suppliers; and the two final columns indicates $\tilde{f}_j^*$ and $\tilde{f}_j^0$ for each sub-criterion.

The matrix of the fuzzy distance from ideal $\left(\tilde{d}_{ij}\right)$ is obtained based on Eqs. (7.11) and (7.12), which can be seen in Table 7.10. Then the fuzzy weighted sum $\tilde{S}_i$ and the fuzzy operator max $\tilde{R}_i$ for each company obtain by Eqs. (7.12) and (7.13) and the VIKOR Index $\tilde{Q}_i$ calculated using Eq. (7.14). Results shown in Table 7.11.

Finally using by Eq. (7.16), the crisp values of S, R, and Q obtained that shown in Table 7.12.

Table 7.12 indicates that Dana Engineering from Best Co., China (A_2) ranked first, PAM Co. from Varel, France (A_1) ranked 2nd, Arvand Saman Kish Co. from Kingdream, China (A_3) ranked 3rd, RTC Co. from Chuanke, China (A_4) ranked 4th, and finally, TFTI Co. from the U.S. (A_5) ranked last in terms of research criterion.

Conclusion and Future Research

Iran's oil industry is an important factor, contributing 25% of its GDP, 85% of its foreign exchange earnings, and 65% of its government revenue. NISOC is the largest oil producer in Iran, accounting for 85% of crude oil production. As sanctions became more severe in recent years, the issue of NISOC supplier selection drew the attention of managers and statesmen more than ever before. This is even though few studies have been conducted on supplier selection with a multi-criterion decision-making approach at NISOC. In the present research, a combined approach has been adopted, and using two techniques, BWM and FVIKOR, suppliers have been ranked.

According to the text, the criteria such as "quality system, financial system, cost system, and production system" were considered the main criteria, and "quality control system, warranty, service level, target market, economic ratios, value-added ratios, financial stability, production price, production cost, transportation cost, the flexibility of payments, after-sales services cost, product features, innovation, number of production lines, and production capacity" were considered sub-criterion for the model. Considering the mean weights obtained from the BWM technique, the main criteria and sub-criteria were ranked in terms of the mean weight, respectively; the weights were used as input for the FVIKOR technique. The financial system was first, with a weight of 0.476, followed by the cost system, production system, and quality system criterion, with mean weights of 0.338, 0.095, and 0.092, respectively. In addition, sub-criterion were ranked to achieve the main objective of the research. The sub-criterion of the production price, economic ratios, and production cost had

Table 7.9 Fuzzy decision matrix scores of alternatives evaluation

Sub-criterion	Weight	A1	A2	A3	A4	A5	$\tilde{f}_j^*$	$\tilde{f}_j^o$
C11(+)	0.0168	(0, 1, 3)	(1.1, 3, 5)	(0, 1, 3)	(3.6, 5.6, 7.6)	(3.6, 5.6, 7.6)	(3.6, 5.6, 7.6)	(0, 1, 3)
C12(+)	0.0174	(0, 0.2, 1.3)	(3, 5, 7)	(0.1, 1.3, 3.3)	(5.6, 7.6, 9.3)	(5.3, 7.3, 9.1)	(5.6, 7.6, 9.3)	(0, 0.2, 1.3)
C13(+)	0.0555	(0, 1, 3)	(2, 4, 6)	(8.3, 9.5, 9.9)	(7.3, 9.1, 10)	(7, 9, 10)	(8.3, 9.5, 10)	(0, 1, 3)
C14(+)	0.0023	(0, 1, 2)	(3.6, 5.6, 7.6)	(2.8, 4.5, 6.3)	(8.3, 9.5, 9.9)	(4.3, 6.1, 7.8)	(8.3, 9.5, 9.9)	(0, 0.2, 1.3)
C21(+)	0.1647	(0, 1, 3)	(1.3, 3.3, 3.5)	(0, 1, 3)	(3.6, 5.6, 7.6)	(5.3, 7.3, 9.1)	(5.3, 7.3, 9.1)	(0, 1, 3)
C22(+)	0.0276	(0, 0.3, 1.6)	(7.6, 8.8, 9.1)	(0.1, 1.3, 3.3)	(5.6, 7.6, 9.3)	(0, 1, 2)	(7.6,8.8,9.3)	(0,0.3,1.6)
C23(+)	0.0890	(1.1, 3, 5)	(2, 4, 6)	(2, 4, 6)	(7.3, 9.1, 10)	(4, 6, 7.8)	(7.3,9.1,10)	(1.1,3,5)
C24(−)	0.1937	(0, 1, 3)	(3.6, 5.6, 7.6)	(3, 5, 7)	(9, 10, 10)	(5.3, 7.3, 9.1)	(0,1,3)	(9,10,10)
C31(+)	0.0109	(7.5, 8.5, 8.8)	(0.1, 0.6, 2)	(0, 1, 3)	(3.6, 5.6, 7.6)	(0, 1, 3)	(7.5,8.5,8.8)	(0,0.6,2)
C32(+)	0.0322	(0, 0.8, 2.6)	(0.1, 1.3, 3.3)	(0, 1, 3)	(5.6, 7.6, 9.3)	(4, 6, 7.8)	(5.6,7.6,9.3)	(0,0.8,2.6)
C33(+)	0.0107	(0.1, 0.6, 2)	(1.3, 3.3, 3.5)	(1.3, 3.3, 3.5)	(7.3, 9.1, 10)	(5.3, 7.3, 9.1)	(7.3,9.1,10)	(0.1,0.6,2)
C34(+)	0.0411	(0, 1, 3)	(3, 5, 7)	(2.7, 4.6, 6.6)	(7.6, 8.8, 9.1)	(6.6, 8.6, 8.9)	(7.6,8.8,9.1)	(0, 1,3)
C41(−)	0.1464	(0.1, 0.6, 2)	(3, 5, 7)	(0, 1, 2)	(3.6, 5.6, 7.6)	(0, 1, 2)	(0,0.6,2)	(3.6,5.6,7.6)
C42(−)	0.1146	(0, 1, 3)	(1.1, 2.8, 4.6)	(0.8, 2, 4)	(5.3, 7.3, 9.1)	(3.6, 5.6, 7.6)	(0,1,3)	(5.3,7.3,9.1)

(continued)

Table 7.9 (continued)

Sub-criterion	Weight	A1	A2	A3	A4	A5	$\tilde{f}_j^*$	$\tilde{f}_j^o$
C43(+)	0.0382	(0.8, 2, 4)	(1.1, 3, 5)	(1.3, 3.3, 3.5)	(7, 9, 10)	(5.3, 7.3, 9.1)	(7,9,10)	(0.8,2,3.5)
C44(−)	0.0389	(0, 1, 3)	(2.8, 4.5, 6.3)	(2.8, 4.5, 6.8)	(9, 10, 10)	(7, 9, 10)	(0,1,3)	(9,10,10)

weights of 0.1937, 0.1647, and 0.1464, respectively. By applying the FVIKOR technique, the best suppliers of the NISOC for 12 ¼" PCD drill bit were determined according to the identified criterion and their degree of importance as follows: Dana Engineering from Best Co., China (A_2) ranked first in terms of research criterion, followed by PAM Co. from Varel, France (A_1), Arvand Saman Kish Co. from Kingdream, China (A_3), RTC Co. from Chuanke, China (A_4), and finally Halliburton Co. from the United States (A_5).

Therefore, the Chinese company is in a better position in this sense, and as it is clear, the Chinese company ranked higher, and the results are justifiable in reality as well. Iran has been under sanctions for many years, and from the perspective of experts, it is not likely that American and European companies rank highly as the suppliers of the NISOC. But after the "Comprehensive Plan of Action" between the Islamic Republic of Iran and Group 5+1, some European countries have begun limited economic and financial relationships with Iran, and France was one of them. Because of the technical abilities of European companies, Iranian companies have always been enthusiastic to deal with them, and since the "PAM Co. from Varel" has attained a good position in this term, the experts gave it a good score, and it could take second place in the ranking among other companies. Considering the results of weighting the criterion and positioning "product prices" at the forefront of importance, it is suggested that managers use long-term contracts with selected suppliers to reduce the problem of rising prices. Also, registering long-term contracts could prevent suppliers from abusing Iran's sanctions and proposing unfair prices. It is also recommended to identify and sign contracts with more suppliers to unlock the market from monopolies, and through this, indirectly, suppliers will be forced to adjust the price of the products.

It is suggested that in future research, by applying the soft thinking approach and structuring methods to the problem, such as Soft Systems Methodology (SSM), first, it will identify the problem-oriented position and structure it, then pay more attention to the selection and implementation of the appropriate techniques for hard OR. The simultaneous use of hard and soft techniques, while covering the weaknesses of each of them, will increase the reliability of the research results.

Table 7.10 Fuzzy distance from ideal ($\tilde{d}_{ij}$)

Sub-criterion	A1	A2	A3	A4	A5
C11(+)	(1, 1, 1)	(0.565, 0.565, 0.694)	(1, 1, 1)	(0, 0, 0)	(0, 0, 0)
C12(+)	(1, 1, 1)	(0.288, 0.351, 0.464)	(0.750, 0.851, 0.982)	(0, 0, 0)	(0.025, 0.041, 0.054)
C13(+)	(1, 1, 1)	(0.571, 0.647, 0.759)	(0, 0, 0.14)	(0, 0.047, 0.120)	(0, 0.059, 0.054)
C14(+)	(1, 1, 1)	(0.267, 0.419, 0.566)	(0.419, 0.538, 0.663)	(0, 0, 0)	(0, 0.059, 0.157)
C21(+)	(1, 1, 1)	(0.755, 0.635, 0.918)	(1, 1, 1)	(0.246, 0.70, 0.321)	(0.244, 0.366, 0.482)
C22(+)	(1, 1, 1)	(0, 0, 0.026)	(0.770, 0.882, 0.987)	(0, 0.141, 0.263)	(0.918, 0.948, 1)
C23(+)	(1, 1, 1)	(0.800, 0.836, 0.855)	(0.800, 0.836, 0.855)	(0, 0, 0)	(0, 0, 0.079)
C24(-)	(0, 0, 0)	(0.400, 0.511, 0.657)	(0.333, 0.444, 0.571)	(1, 1, 1)	(0.440, 0.508, 0.532)
C31(+)	(0, 0, 0)	(0.987, 1, 1)	(0.853, 0.949,1)	(0.176, 0.375, 0.520)	(0.0.853, 0.0.949, 1)
C32(+)	(1, 1, 1)	(0.896, 0.926, 0.982)	(0.940, 0.971,)	(0, 0, 0)	(0, 0, 0.120)
C33(+)	(1, 1, 1)	(0.813, 0.682, 0.833)	(0.813, 0.682, 0.833)	(0, 0, 0)	(0.224, 0.235, 0.286)
C34(+)	(1, 1, 1)	(0.344, 0.487, 0.605)	(0.410, 0.538, 0.645)	(0, 0, 0)	(0.033, 0.026, 0.132)
C41(−)	(0, 0, 0.028)	(0.521, 0.710, 0.833)	(0, 0, 0.065)	(0.583, 0.806, 1)	(0, 0, 0.65)
C42(−)	(0, 0, 0)	(0.132, 0.217, 0.208)	(0.083, 0.120, 0.151)	(0.504, 0.759, 1)	(0.667, 0.882, 0.679)
C43(+)	(0.923, 1, 1)	(0.769, 0.857, 0.952)	(0.814, 0.919, 1)	(0, 0, 0)	(0.138, 0.243, 0.274)
C44(−)	(0, 0, 0)	(0.254, 0.318, 0.311)	(0.292, 0.318, 0.311)	(0.538, 0.818, 1)	(0.538, 0.727, 0.778)

Table 7.11 The fuzzy set S, R, and Q for each company

Company	$\tilde{S}_i$	$\tilde{R}_i$	$\tilde{Q}_i$
PAM Co.	(0.185, 0.236, 0.251)	(0.141, 0.167, 0.191)	(0.225, 0.301, 0.341)
Dana Engineering Co.	(0.525, 0.591, 0.647)	(0.079, 0.110, 0.142)	(0, 0.067, 0.082)
Arvand Saman Kish Co.	(0.318, 0.461, 0.518)	(0.170, 0.189, 0.210)	(0.588, 0.640, 0.69)
RTC Co.	(0.244, 0.335, 0.478)	(0.156, 0.168, 0.185)	(0.345, 0.401, 0.445)
TFTI Co.	(0.321, 0.540, 0.703)	(0.160, 0.185, 0.211)	(0.56, 0.80, 0.995)

Table 7.12 The final ranking of options based on S, R, and Q values

Company	S		R		Q		Final rank
	Value	Rank	Value	Rank	Value	Rank	
PAM Co	0.228	1	0.167	2	0.292	2	2
Dana Engineering Co	0.589	5	0.110	1	0.054	1	1
Arvand Saman Kish Co	0.435	3	0.190	4	0.640	4	4
RTC Co	0.348	2	0.169	3	0.398	3	3
TFTI Co	0.527	4	0.185	5	0.789	5	5

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Chapter 8
Assessing Smartness of Automotive Industry: An Importance-Performance Analysis

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Abstract The automotive industry, like other industries, has been affected by the fourth industrial revolution. The intelligentization of manufacturing systems in the automotive industry is one of the achievements of this industrial revolution. Implementing a new manufacturing system requires continuous attention to the variables and conditions called Critical Success Factors (CSF). To successfully implement smart manufacturing, first, it is essential to assess the smartness level of an industry to have a better picture of that. To do this assessment, the importance of CSFs should be determined. Then the industry's current performance should be evaluated based on CSFs. This assessment provides managers with a clear understanding of the condition of the industry, which can influence the effectiveness of their decisions. Therefore, this research aims to identify CSFs and evaluate the automotive industry's performance. One approach to study this is using an importance-performance analysis (IPA). This approach is applied to the case of Iran's two largest car manufacturers automotive industry. When studying importance, the Best-Worst Method is used. Due to incomplete information and uncertainty in the field of smart manufacturing, interval numbers have been used for more detailed analysis. Our results showed that although the two car manufacturers have performed relatively well in some factors, they have not performed well in important ones, such as customization and digitization of products and required technological infrastructure for using Industry 4.0. So, it seems these need to change the priority of these two care manufacturers' attention to CSFs of smart manufacturing implementation. The results of this research can be suitable and useful for the managers of car manufacturers in Iran and other countries similar to Iran in terms of economic, political, and social conditions.

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Keywords Smart manufacturing · Critical success factors (CSFs) · Interval importance-performance analysis (IIPA) · Non-linear best-worst method · Interval analysis

Introduction

Manufacturing systems are essential to any country's economy [1]. Nowadays, manufacturing systems are influenced by Industry 4.0 [2]. Using Industry 4.0 technologies such as Internet of Things (IoT), Big Data (BD), Artificial Intelligence, and Cloud Computing (CC) has transferred manufacturing systems to smart manufacturing systems [3]. Manufacturing organizations are encouraged to move towards smart manufacturing due to several benefits, such as increasing productivity, improving the quality of operations, and having optimal scheduling [3, 4]. The successful implementation of this new manufacturing system requires the identification of critical success factors because these factors will affect the outputs and performance of the manufacturing system [5]. CSFs include areas an organization must continuously pay attention to have the highest performance [5].

Like the other organizations, automotive industry manufacturers must move towards smart manufacturing. The rules of sustainability, changing consumer choices, and increasing connectivity between things force the automotive industry to follow Industry 4.0 technologies [6]. Large manufacturers such as Audi, Volkswagen, and Tesla have used robots and implemented self-control and automation in assembly [7]. According to many studies in the field of Industry 4.0, it can be highlighted that implementing Industry 4.0 has been started in developed countries (see, for instance, [8, 9]). However, developing countries need to follow this industrial revolution and use the benefits of smart manufacturing in their global economy [9]. Many developing countries have only brought up the implementation of Industry 4.0 in their policies.

In contrast, the organizations of developed countries have already become smart, and their processes are adopted Industry 4.0 technologies [9]. Therefore, it is vital for the automotive industry in developing countries to start studying Industry 4.0 and look into whether they are ready for it. There are several studies on the readiness of the automotive industry in developing countries like India [3, 10], and Malaysia [11]. Iran is another developing country that needs to evaluate the readiness of its automotive industry to identify weaknesses and improve them for successful performance. Iran's automotive industry is the third most active industry in the country, after its oil and gas industry. Iran's automotive industry includes car manufacturers, car parts manufacturers, and car assembly. Some parts of this industry, such as car parts manufacturers, are small and operate as a workshop. Perhaps the concern of these small workshops is not the smart manufacturing implementation. Therefore, this study examines the two largest car manufacturers in Iran, "Iran Khodro" and "SAIPA".

This research set out to follow two objectives. The first one is to shine a light on CSFs of smart manufacturing implementation. Upon reviewing the literature, there seem to be some gaps in this area. Most studies analyzed the CSFs in Industry 4.0 or its IoT, AI, and blockchain technologies. Only [12] conducted their research to explore the CSFs of smart manufacturing. However, they do not provide a complete view of all CSFs by considering technological and managerial aspects. The next objective of this research is to determine the importance of CSFs in the automotive industry, and then evaluate their performance. Relevant studies only evaluate the importance of each CSF, although analyzing their performance of them is helpful. The performance analysis shows the weaknesses of the industry, and it would be necessary for improving the current situation.

In the first part of this study, the literature in the field of CSFs of smart manufacturing implementation is reviewed. Second, the methodology is presented. Then the result of the study is discussed, and finally, the conclusion is highlighted.

Literature Review

Smart Manufacturing

With the development of the internet infrastructure, the fourth industrial revolution has been started at the beginning of the twenty-first century. The conceptual heart of Industry 4.0 is smart manufacturing, and everything revolves around this core entity that shapes the business model. The goal of the development of smart manufacturing is to improve productivity, efficiency, reliability, and control of final products [8, 13]. Smart manufacturing increases operational capacity and reduces costs and downtime [14]. According to the National Institute of Standards and Technology (NIST), smart manufacturing is a unified system that responds immediately to variable demands, supply chains, customer needs, and any changes in factory conditions [15]. Smart manufacturing has three components: smart devices, smart human and smart products [16]. Smart device, as the first component of smart manufacturing, includes Multi-Agent Systems (MAS) that can be created through the cooperation of smart industrial robots, sensors, controllers, and Computer Numerical Control (CNCs). Smart devices increase flexibility and competitiveness. Human is another part of smart manufacturing, including the two groups of laborers and customers. The workforce using Industry 4.0 tools requires IT, manufacturing, and logistics knowledge, while customers are influential in designing and producing smart products. The third component of smart manufacturing is smart products, which include everything from pieces to the final product. These components and smart products are connected to each other and to the smart devices through embedded sensors, making it possible to be controlled in this way [16]. These components are embedded in the environment concluding new technologies such as IoT, CC, additive manufacturing, etc.

In implementing manufacturing systems, to successfully manage the outputs and performance, it is vital to take advantage of the positive effects of using CSFs [17]. CSFs are characteristics, variables, and conditions significantly impacting organizations' success and competitiveness. Organizations that use CSFs will remain stable and competently managed [18]. These factors include a few areas of an organization that, if implemented satisfactorily, an organization will perform successfully [19].

Related Work

Researchers have identified some CSFs for Industry 4.0 [20, 21] and its technologies, such as IoT [22], AI [23], and blockchain [24]. These studies mainly identified technological factors without considering managerial factors (such as dynamic business models, change management, and innovation culture). Apart from mentioned studies [21] collected smart manufacturing CSFs. However, they did not provide a complete picture of CSFs. More precisely, they did not consider some of the main factors, for instance Industry 4.0 goals and skilled users. Therefore, the first research gap in this field is to put forward a comprehensive set of CSFs that include both groups of technological and managerial factors.

In addition, despite the inevitability of manufacturers' performance in each CSF, the previous research only collected the factors and analyzed their importance. Consequently, the second research gap which we aim to fill in, in this study is to analyze the performance of each CSF in the context of a real case. Table 8.1 shows a summary of the recent related studies on CSFs.

Methodology

This research thoroughly investigated the performance of the two most prominent car manufacturers in Iran's automotive industry by considering the CSFs in implementing smart manufacturing. In the first step, existing gaps were identified by reviewing the literature on smart manufacturing. Then, research objectives and questions were defined based on the identified gaps. In the third step, by looking back over the databases such as Scopus and Web of Science (WoS), CSFs of implementing smart manufacturing were identified. To analyze the performance of two selected car manufacturers based on these CSFs, first, these factors were customized using a questionnaire to collect the opinions of 7 academics and industry experts. Second, the hybrid BWM-IPA method was used. For this step, the data was collected from 30 experts, whose demographic details are given in Table 8.2. After analyzing the results, strategies for the optimal use of CSFs in implementing smart manufacturing in Iran's automotive industry have been presented. The IPA was developed in the following sections, and the BWM steps were set out.

Table 8.1 Related work of CSFs implementing smart manufacturing

References	Goal of research	Methodology	Industry
[23]	Analyzing of CSFs of artificial intelligence in the healthcare supply chain	Fuzzy BWM	Healthcare industry
[20]	Analyzing of CSFs of implementation of industry 4.0 technologies	Cross-case analysis	Several Italian manufacturers (large trucks, water pumps, industrial machines, and food packaging)
[12]	Modeling the critical success factors of smart manufacturing adaptation	DEMATEL	Automotive industry
[24]	Identifying CSFs in using blockchain in circular supply chain	Fuzzy BWM-FCM[a]	Chemical industry
[22]	Analyzing of CSFs of internet of things	Systematic literature review	NA
[21][2]	Identifying the critical success factors of Industry 4.0 deployment	Systematic literature review	NA

[a] FCM stands for fuzzy cognitive map

Table 8.2 Demographic details

Respondent		Frequency
Work experience	1–5	4
	5–10	11
	10–15	7
	15–20	3
	20–25	5
Type of experts	Academic	11
	Industry	19

The importance-performance analysis is a multi-attribute decision-making method that was presented by [25] to measure attributes in two dimensions of importance (optimal situation) and performance (existing situation). The purpose of the IPA method is to categorize the attributes to determine which attribute should be given more attention and which requires allocating fewer resources [25]. For this classification, two dimensions of importance (vertical axis) and performance (horizontal axis) are used, and based on this, four sections are created, as shown in Fig. 8.1.

The four sections created in IPA method are defined as follows:

Keep up the good work: There are attributes in this section that are very important, and the organization's performance has been brilliant in them. Therefore, the

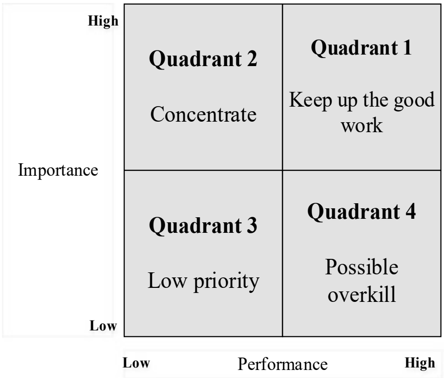

Fig. 8.1 IPA framework [25]

attributes of this section will be competitive advantages that the organization must continue to perform well to take advantage of them.

Concentrate: Despite the high importance of the attribute in this section, the organization does not perform well in them. In other words, the attribute of this part shows the weakness of the organization, and the organization should pay attention to improve them.

Low priority: There are attributes in this section that are not very important, and the organization is weak in its application. Therefore, when taking measures to improve the organization, attention will not be given to the attributes of this section.

Possible overkill: Although the attributes in this section are not very important, the organization performs well in them. This section shows that the organization is using its resources and focusing where there is no high value. In other words, resources are being wasted. Therefore, these resources should be used for more essential attributes.

IPA has been used in several areas such as opportunity recognition for entrepreneurs [26], evaluation of cloud-based technology [27], selection of green suppliers [28], analysis of sustainable food service [29], evaluation of technology service development [30], evaluation of environmental protection strategies [31] and investigation of port service quality [25]. In this study, we used BWM to evaluate the importance of CSFs. The Interval number was used to cover the uncertainty and lack of knowledge. The scale of the Interval number is shown in Table 8.3. These interval numbers were used to evaluate selected car manufacturers' performance in each CSF.

Non-linear Best-Worst Method

Best-Worst Method (BWM) was developed in 2015 by Jafar Rezaei [32]. There are several reasons for choosing BWM such as (1) it is more reliable than similar methods for pairwise comparisons, (2) it reduces the chance that respondents might be biased

Table 8.3 Converting linguistic variables to gray numbers

Linguistic variables	Interval numbers
Very low	[0, 0.15]
Low	[0.15, 0.3]
Medium low	[0.3, 0.45]
Medium	[0.45, 0.55]
Medium high	[0.55, 0.7]
High	[0.7, 0.85]
Very high	[0.85, 1]

when they weigh the data, and (3) it gives multiple optimal solutions which can be used in a complex situation [33]. This study uses a non-linear minimax model of Rezaei [32] to identify the weights to minimize the maximum absolute difference between the weight ratios and their corresponding comparisons. This model provides multiple optimal solutions.

In the following, the steps of none linear BWM will be described, and then explain how the interval analysis can be used.

Step one: Denotes decision sets by $\{c_1, c_2, \ldots, c_n\}$, where n represents the number of criteria.

Step two: According to the decision criteria system, the decision-makers should determine the best (most important) and worst (least important) criteria.

Step three: The preference of the best criterion over other criteria is determined by using numbers 1–9. The comparison vector of the best criterion compared to other criteria is as follows:

$$\mathrm{A}_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}). \tag{8.1}$$

where a_{Bj} indicates the preference for the best criterion over the criterion. It is clear that $a_{BB} = 1$.

Step four: The preference of all criteria over the worst criterion is determined using numbers 1–9. The vector of comparison of all criteria concerning the worst criterion is as follows:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW}) \tag{8.2}$$

where $\mathrm{a_{jW}}$ indicates the preference of the criterion over the worst criterion. It is clear that $\mathrm{a_{WW}} = 1$.

Step five: This step is to obtain optimal weights $\left(w_1^*, w_2^*, \cdots, w_n^*\right)$. To determine the optimal weights, for all j, an answer must be determined that minimizes the differences of $\left|\frac{\mathrm{w_B}}{\mathrm{w_j}} - \mathrm{a_{Bj}}\right|$ and $\left|\frac{\mathrm{w_j}}{\mathrm{w_W}} - \mathrm{a_{jW}}\right|$ for all j. In this way, to calculate the optimal weights $\left(w_1^*, w_2^*, \cdots, w_n^*\right)$, the following linear programming model can be used:

$$\begin{aligned} &\min \quad \varepsilon \\ &\text{st.} \\ &\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \varepsilon. \text{ for all j.} \\ &\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \varepsilon. \text{ for all j.} \\ &\sum_j w_j = 1 \\ &w_j \geq 0 \text{ for all j.} \end{aligned} \tag{8.3}$$

In the interval analysis of BWM, two models are provided to calculate the lowest and the highest weight value of criterion j. These models are solved after solving model (3) and finding the ε^*.

$$\begin{aligned} &\min \quad w_j \\ &\text{st.} \\ &\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \varepsilon^*. \text{ for all j.} \\ &\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \varepsilon^*. \text{ for all j.} \\ &\sum_j w_j = 1 \\ &w_j \geq 0 \text{ for all j.} \end{aligned} \tag{8.4}$$

$$\begin{aligned} &\max \quad w_j \\ &\text{st.} \\ &\left| \frac{w_B}{w_j} - a_{Bj} \right| \leq \varepsilon^*. \text{ for all j.} \\ &\left| \frac{w_j}{w_W} - a_{jW} \right| \leq \varepsilon^*. \text{ for all j.} \\ &\sum_j w_j = 1 \\ &w_j \geq 0 \text{ for all j.} \end{aligned} \tag{8.5}$$

When the two presented models are solved for each criterion, the optimal weight of the criteria is determined as an interval. We could use the middle of the intervals as representative weights for further analysis. An alternative approach would be to use intervals. If we use interval weights, we need to use interval analysis which is shown in the following section.

Interval Analysis

This section discusses some basic definitions and operations related to interval numbers, interval calculations, and comparison of interval numbers [34, 35].

Definition 1: A closed interval is an ordered pair in a bracket, such as:

$$A = [a_L, a_R] = \{x: a_L \leq x \leq a_R, x \in R\} \tag{8.6}$$

So, in the above formula, a_L and a_R are the left and the right limits, respectively. Also, the closed interval is displayed based on its center and width, such as:

$$A = \langle a_C, a_W \rangle = \{x: a_C - a_W \leq x \leq a_C + a_W, x \in R\} \tag{8.7}$$

where in the above formula, a_C and a_W are the center and width.

Definition 2: If we consider $* \in \{+, -, \times, /\}$ as a binary operation on the intervals A and B, then the binary operation on a set of closed intervals is defined as follows:

$$A * B = \{x * y: x \in A, y \in B\} \tag{8.8}$$

If the division operation is considered, it is assumed to be $0 \notin B$. Below are some definitions for comparing interval numbers.

$A = [a_L, a_R]$ and $B = [b_L, b_R]$ are considered as two interval numbers [36]:

Definition 3: The degree of priority of A compared to B (or $A > B$) is defined as follows:

$$P(A > B) = \frac{\max(0, b_R - a_L) - \max(0, b_L - a_R)}{(a_R - a_L) + (b_R - b_L)} \tag{8.9}$$

The degree of preference of B over A is calculated similarly:

$$P(B > A) = \frac{\max(0, b_R - a_L) - \max(0, b_L - a_R)}{(a_R - a_L) + (b_R - b_L)} \tag{8.10}$$

It is clear that if the equality of $A = B$ holds, that is, if $a_L = b_L$ and $a_R = b_R$ so we have: $P(A > B) + P(B > A) = 1$ and $P(A > B) = P(B > A) = 0.5$.

Definition 4: If $P(A > B) > P(B > A)$ (or equivalently 0 $P(A > B) > 0.5$), then A is said to be superior to B to the degree of $P(A > B)$ denoted by $A^{P(A>B)} \succ B$; if $P(A > B) = P(B > A) = 0.5$ then A is said to be indifferent to B; denoted by $A \sim B$ if (or equivalently $P(B > A) > P(A > B)$ (or equivalently $P(B > A) > 0.5$), then A is said to be inferior to B to the grade of $P(B > A)$ denoted by $A^{P(B>A)} \prec B$.

To compare interval weights, according to the following formulas, the "priority degree matrix" and "preference matrix" are calculated, respectively.

$$DP_{ij} = \begin{array}{c} \\ A \\ B \\ \vdots \\ N \end{array} \begin{array}{c} \begin{array}{cccc} A & B & \cdots & N \end{array} \\ \begin{pmatrix} P(A > A) & P(A > B) & \cdots & P(A > N) \\ P(B > A) & P(B > B) & \cdots & P(B > N) \\ \vdots & \vdots & \ddots & \vdots \\ P(N > A) & P(N > B) & \cdots & P(N > N) \end{pmatrix} \end{array} \tag{8.11}$$

As:

$$P_{ij} = \begin{cases} 1, & \text{if} \quad P(i > j) > 0.5, \\ 0, \text{ if} & P(i > j) \leq 0.5, \quad i, j = A, \ldots, N. \end{cases} \tag{8.12}$$

Then, the sum of the elements in each row of the P_{ij}-matrix is calculated, and the metrics are ranked based on their sum of the values.

Therefore, as discussed above, we can measure the weight of criterion j in the form of an interval such as $w_j = \langle w_{jC}, w_{jW} \rangle = \{x: w_{jC} - w_{jW} \leq x \leq w_{jC} + w_{jW}, x \in R\}$. After determining the weight as an interval number, the formulas (8.9) and (8.10) can be used to rank them. As mentioned earlier, this range can be used as input to discuss and agree on a set of weights within the ranges. In these cases, one way is to consider the w_{jC} (central value).

Results

By reviewing the literature, a large number of CSFs related to Industry 4.0 and smart manufacturing were collected. Due to the overlap and relationship between some factors, they were put out together under a common title. For example, "The need for cooperation and communication" (CSF_9 in Table 8.4) includes four factors: establishing communication between employees based on the principles of Industry 4.0, establishing a smart network, establishing machine-to-machine communication, and central coordination for Industry 4.0. Similarly, all other factors were categorized, and finally, 21 category of CSFs were identified, shown in Table 8.4.

To have a clearer picture of CSfs, the Technology-Organization-Environment (TOE) framework has been used to categorize them. TOE was presented in 1990 by Tornatzky and Fleischer. Based on this model, the technology innovation adaptation process is influenced by three organizational concepts [37]: technology, environment, and organization.

The following definitions were used to classify CSFs in this framework [38]:

Technology: This category includes factors related to internal and external technologies available to the organization.

Organization: In this category, some factors examine the adoption and implementation of technology, and in addition, factors related to organizational structure, size, and communication are evaluated.

Table 8.4 CSFs of smart manufacturing implementation

Category	CSFs		Description	References
Technological factors	Big data management	CSF_1	Big data analysis is very effective in creating a sustainable business. In addition, converting these data into knowledge will increase quality of decisions	[39, 40]
	Improve privacy and security	CSF_2	With the smart manufacturing, a large amount of information is shared, which requires formulating and implementing policies to protect privacy	[24]
	Digitization of processes	CSF_3	Digitization of processes in smart manufacturing will increase assignability, decentralize processes, create self-control and self-organization ability	[41]
	Customization and digitization of products	CSF_4	Products are digital in a smart manufacturing system. These products are customized according to customers' needs and have self-control and self-repair capabilities	[41]
	Scalability	CSF_5	In smart manufacturing, due to the connection of all components, a large amount of information will be stored, so scalability will be necessary	[42]
	Standardization	CSF_6	Standardization is necessary to establish communication between different parts of the organization as well as communication with other organizations	[24]

(continued)

Table 8.4 (continued)

Category	CSFs		Description	References
	Technological infrastructures of Industry 4.0	CSF_7	The establishment of smart manufacturing requires the implementation of Industry 4.0 technologies, and use of these technologies requires the creation of various infrastructures, such as a powerful internet platform	[24, 40, 41]
	The need for cooperation and communication	CSF_8	The way of communicating and working smart manufacturing systems will change due to new technologies	[39, 40, 43]
Organizational factors	Define organization's goals based on Industry 4.0	CSF_9	Accepting smart manufacturing requires the organization's goals to be associated with Industry 4.0 and smart manufacturing	[44, 45]
	Change management	CSF_{10}	With the changes in the business, the way of producing goods and providing services to organizations will require continuous improvement and change management	[41]
	Dynamic business model	CSF_{11}	With the spread of smartness, organizations must change their goals, strategies and business model to maintain their position	[44, 45]
	Innovation culture	CSF_{12}	Discovering ideas and innovation is very necessary for the survival of organizations in a dynamic environment	[44, 46]

(continued)

Table 8.4 (continued)

Category	CSFs		Description	References
	Integration	CSF_{13}	The smartization of manufacturing systems requires vertical and horizontal integration within the organization and among the components of the supply chain	[39, 40]
	Financial support	CSF_{14}	Smartening a manufacturing system requires many changes in all aspects of the organization, and in addition to that, the use of new technologies also brings high costs	[39, 41]
	Organizational culture	CSF_{15}	The alignment of organizational values and culture with smart manufacturing reduces employees' resistance	[44, 46]
	Management of organizational structure	CSF_{16}	With the implementation of smart manufacturing, the way of performing activities, communication, and the way of sharing information will change, and for this reason, it requires managing the organizational structure	[41, 43]
	Skilled workforce	CSF_{17}	In smart manufacturing, the way of doing activities will change, and new technologies will be used. Therefore, working in these new conditions requires new skills in the workforce	[39, 41]
	Teamwork	CSF_{18}	To implement smart manufacturing, the cooperation of all members and teamwork skills are required	[47]

(continued)

Table 8.4 (continued)

Category	CSFs		Description	References
Environmental factors	Legal issues	CSF_{19}	In order to control the new working conditions created by implementing smart manufacturing, it is necessary to develop new laws that are appropriate to these conditions	[24, 39]
	Skilled users	CSF_{20}	Using smart products and services require users to acquire the necessary skills to use them	[40]
	Supportive actions	CSF_{21}	To implement smart manufacturing, the support of all stakeholders, such as management, employees, government, and shareholders, is needed	[39, 40]

Environment: This category includes external factors that affect the organization, which can include factors related to the industry's structure, government, and competitors as examples.

Table 8.4 shows the CSFs Classification in TOE Based on their descriptions.

After collecting and categorizing CSFs, to confirm their relevance and importance in Iran's two largest car manufacturers, experts were asked to express their opinions based on their experience and familiarity with this industry. In this way, by summarizing experts' opinions, "integration" was removed, and other CSFs were declared related to the automobile industry in Iran.

After customization, the weight of each factor was obtained using the experts' opinions and none-linear BWM. As it is shown in Table 8.5, there are interval numbers the weight of CSFs ($\underline{I_i}$ is the left limit of the importance of CSF_i and $\overline{I_i}$ is the right limit of the importance of CSF_i).

Based on the definition which is offered in Sect. 3.3, the interval numbers can be compared, for instance, see the following equation:

$$P(CSF_1 > CSF_2) = \frac{\max(0, 0.086 - 0.010) - \max(0, 0.016 - 0.079)}{(0.086 - 0.016) + (0.079 - 0.010)} = 0.547$$

As shown above, 0.547 > 0.5, So $P(BCSF_1 > CSF_2) = 1$.

Table 8.5 Importance of Iran's two largest car manufacturers CSFs

Category		CSFs	$\underline{I}_i$	$\overline{I}_i$	Summation P_{ij}	Ranks
Technological factors	[0.161, 0.829]	CSF_1	0.016	0.086	5	9
		CSF_2	0.010	0.079	1	11
		CSF_3	0.029	0.141	16	2
		CSF_4	0.025	0.131	12	4
		CSF_5	0.017	0.073	3	10
		CSF_6	0.014	0.082	5	9
		CSF_7	0.033	0.132	15	3
		CSF_8	0.018	0.107	10	12
Organizational factors	[0.209, 1.138]	CSF_9	0.049	0.166	19	1
		CSF_{10}	0.024	0.140	16	2
		CSF_{11}	0.030	0.138	15	3
		CSF_{12}	0.017	0.123	9	7
		CSF_{14}	0.025	0.154	16	2
		CSF_{15}	0.017	0.102	8	8
		CSF_{16}	0.017	0.093	8	8
		CSF_{17}	0.016	0.130	11	5
		CSF_{18}	0.015	0.093	8	8
Environmental factors	[0.016, 0.247]	CSF_{19}	0.009	0.063	0	12
		CSF_{20}	0.012	0.078	3	10
		CSF_{21}	0.019	0.106	9	7

When weights are compared pairwise for all CSFs, a matrix will be obtained by using formula (8.11). The sum of each row in this matrix indicates the CSF score for that row. These scores are given in Table 8.5.

It is evident from the results of BWM that CSF_9 (Define organization's goals based on Industry 4.0), CSF_3 (Digitalization of processes), CSF_{10} (Change management), CSF_{14} (Financial support), CSF_{11} (Dynamic business models) and CSF_7 (Technological infrastructures of Industry 4.0) were identified as important factors, respectively.

To assess the consistency of experts' opinions and determine if they are reliable, the consistency ratios are calculated based on Rezaei [33] and checked with the related thresholds provided by Liang et al. [48]. The results showed that the pairwise comparisons are consistent.

For information about the industry's current performance in terms of different CSFs, experts were first asked via a questionnaire to rate the performance of selected car manufacturers based on 20 factors. The integrated opinions of experts can be seen in Table 8.6 ($\underline{P}_i$ is the left limit of the performance of CSF_i and $\overline{P}_i$ is the right limit of the performance of CSF_i). As well as the interval weights of CSFs can be compared for instance, see the following equation:

$$P(CSF_1 > CSF_2) = \frac{\max(0, 0.370 - 0.325) - \max(0, 0.220 - 0.475)}{(0.370 - 0.220) + (0.475 - 0.325)} = 0.167$$

As shown above, $0.167 < 0.5$, So $P(BCSF_1 > CSF_2) = 0$.

According to findings, Iran's two largest car manufacturers have performed relatively better in the following four factors: CSF_{20} (Skilled users), CSF_{12} (Innovation culture), CSF_{15} (Organizational culture), and CSF_8 (The need for cooperation and communication).

The most important part of these findings is plotting CSFs based on importance and performance. After calculating the interval weights and performance for all CSFs, the resulting image will be unclear if all of them are displayed as intervals. For instance, we plotted CSF_1 in Fig. 8.2 with two interval dimensions. To decrease the unclarity and to better show each factor's location, the center point and the intersection of the drawn lines are used (see Fig. 8.3).

Moreover, in Fig. 8.3, as Iran's automotive industry's performance in nearly all CSFs is low, we rescaled the performance scores to make a better distinction among the CSFs. This makes the performance scores relative in the following section.

Table 8.6 Performance of Iran's two largest car manufacturers CSFs

Category		CSFs	$\underline{P_i}$	$\overline{P_i}$	Summation P_{ij}	Ranks
Technological factors	[2.042, 3.242]	CSF_1	0.220	0.370	3	14
		CSF_2	0.325	0.475	9	9
		CSF_3	0.242	0.392	4	13
		CSF_4	0.115	0.265	0	16
		CSF_5	0.318	0.468	8	10
		CSF_6	0.267	0.417	5	12
		CSF_7	0.155	0.305	2	15
		CSF_8	0.400	0.550	16	3
Organizational factors	[3.102, 4.452]	CSF_9	0.328	0.478	10	8
		CSF_{10}	0.377	0.527	13	5
		CSF_{11}	0.283	0.433	5	12
		CSF_{12}	0.402	0.552	18	2
		CSF_{14}	0.223	0.373	3	14
		CSF_{15}	0.392	0.542	16	3
		CSF_{16}	0.340	0.490	11	7
		CSF_{17}	0.380	0.530	15	4
		CSF_{18}	0.377	0.527	13	5
Environmental factors	[1.067, 1.517]	CSF_{19}	0.350	0.500	12	6
		CSF_{20}	0.418	0.568	19	1
		CSF_{21}	0.298	0.448	7	11

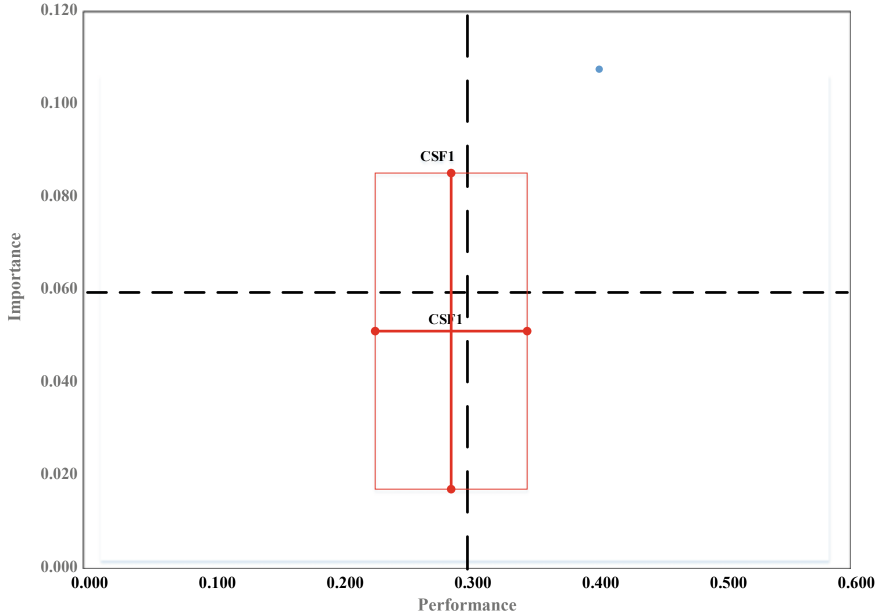

Fig. 8.2 Example for showing the center point of CSF_1

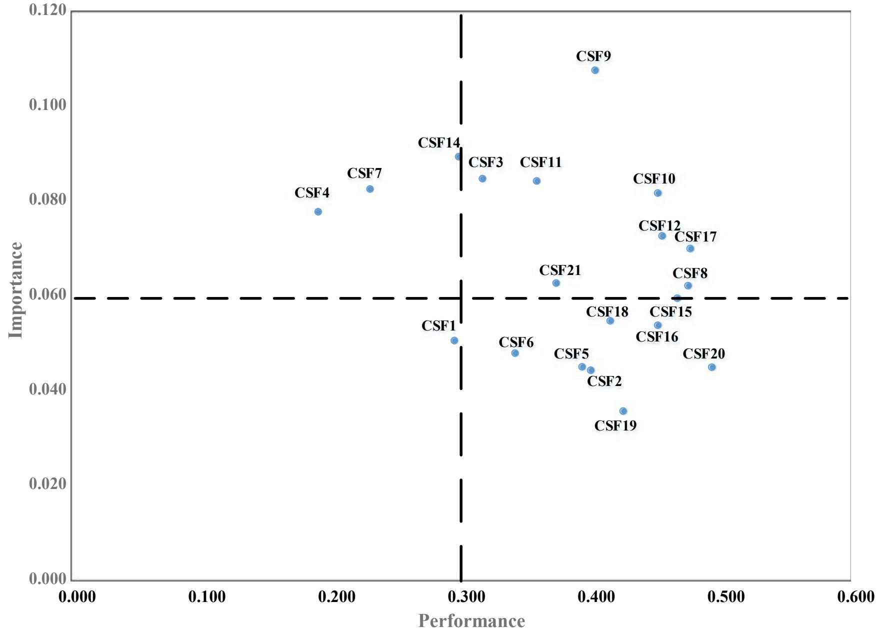

Fig. 8.3 IPA based on center points

Discussion

According to the findings, CSF_9 (Defining organization's goals based on Industry 4.0) is the most critical factor in successfully implementing smart manufacturing in Iran's largest manufacturers. By defining the goals accurately, a better picture of a business and its progress will be made. Clear goals can create more satisfaction in the organization's stakeholders [12]. Therefore, if the car manufacturers in Iran want to implement smart manufacturing, it is advised to align its goals with Industry 4.0 in the first step. The second important CSF is CSF_3 (Digitalization of processes). Digitalizing all activities and services is essential to establish a smart manufacturing system because it makes manufacturing systems more flexible and efficient [47]. A smart manufacturing system should have the ability to self-structure [49], the ability to self-organize [50], the ability to self-repair [51], and decentralize processes [52]. All these abilities will be created if the processes are digitized. Implementing smart manufacturing requires changes in all aspects of a traditional manufacturing system, and these changes will be available with spending a high investment.

Our results show that one of the most important prerequisites for implementing smart manufacturing is the provision of financial resources (CSF_{14}) [39]. Change management (CSF_{10}) is also essential to use this opportunity and perform well during these changes [41]. Based on these changes, organizations must design a business model to meet customers' different needs and determine their position compared to other companies in the value chain. Therefore, with the spread of smartness, organizations need to change their strategies and procedures and generally need to have a dynamic business model (CSF_{11}) [46, 53]. CSF_7 (Technological infrastructures of Industry 4.0) is another factor that is identified with high importance based on the opinion of our experts. In smart manufacturing, all components are connected, which requires a strong, robust internet platform. Shukla and Shankar [12] have also introduced "technology factors" and "vision of the future", which have the same meaning as CSF_7 and CSF_9. Based on their research, the most critical factors for implementing smart manufacturing in the automotive industry are "technology factors" and "vision of the future". Moreover, Kumar et al. [23] have considered "technology infrastructure" as the main factor in examining the healthcare industry in using Industry 4.0.

According to the findings, the two considered car manufacturers performed relatively better in CSF_{20} (Skilled users) and CSF_{12} (Innovation culture). This may be because these manufacturers have felt the need for change and are seeking to target based on them and find a way to implement changes. Organizations must discover new ideas and innovations to survive in a dynamic environment and create a culture based on innovation [46]. This action is more make sense in the context of smart manufacturing.

Figure 8.3 shows that the two manufacturers performed relatively better in CSF_9, considered more important than other factors. So, continuing their good current performance in this factor is advised. Another noteworthy point in this figure is that the performance of these car manufacturers in factors such as CSF_2 is relatively high, while it has low importance. Therefore, it may be better for these car manufacturers to spend their resources on having better performance in factors with higher importance to increase their chances of success.

In addition, they have a weaker performance in factors such as CSF_7, which is relatively more important. So, it shows they need to change their attention to increase their performance in factors that underperformed.

Conclusion

In this article, a framework is proposed to evaluate the performance of car manufacturers in implementing smart manufacturing. Factors that are critical in the successful implementation of smart manufacturing have been used in this framework. These factors include three categories of technological, organizational, and environmental factors. Using this framework, it is possible to establish a clear picture of a manufacturer's status. In other words, this framework can help identify the weaknesses and strengths points of a car manufacturer in implementing smart manufacturing.

In the proposed framework, the factors are divided into four groups based on the importance and performance of critical success factors. When managers and decision-makers decide to implement smart manufacturing, they can take help from the proposed framework shows which factors need to be focused on more to make smart manufacturing successful. In other words, it helps decision-makers first to address the factors that will make more progress in making production smarter. In this way, if there is a limitation in time, cost, and labor, they can work more efficiently.

The framework proposed in this research has been applied to evaluate Iran's two largest car manufacturers. The results show that selected manufacturers have a weaker performance in some factors that are more important in the success of smart manufacturing and perform better in less important factors. These results are a sign of wasting resources. Based on the findings, these companies' managers and decision-makers can reconsider the priority of these factors for the implementation of smart manufacturing and act more efficiently.

Below, suggestions have been made to improve the current situation of selected car manufacturers in Iran to move towards smart manufacturing.

- Deep research in the field of smart manufacturing has made a significant change. Smart manufacturing involves technologies that are very important to know before they are implemented. The use of these technologies makes fundamental changes in the processes of a business.
- After acquiring knowledge in the field of smart manufacturing, the organization's vision and mission must be defined based on this concept. In other words, it should be determined what the organization's philosophy is and what desirable conditions it wishes to achieve. Then the appropriate goals and strategies should be defined based on them.

- The next suggestion would be to examine the organization's current situation to identify strengths and weaknesses. Identifying strengths and weaknesses will give managers an idea of their position in the market, allowing them to make effective and efficient decisions when carrying out actions.
- Managers should develop a road map including detailed plans and steps towards being close to smart manufacturing system.

The framework presented in this research was used to assess to what extent the automotive industry in Iran is smart. We can also use this framework to assess the smartness of other industries in other countries. The main difference would be the customization of the factors (CSFs) according to the industry and country conditions. However, the findings of this research can be suitable for car manufacturers in countries similar to Iran in terms of political, economic, and social conditions.

One of the limitations of the current research is the difficulty of finding experts who, in addition to having experience working in car manufacturers, are familiar with concepts of Industry 4.0 and smart manufacturing. Familiarity of experts with these concepts creates a common language, which is very important in filling out questionnaires and increasing data accuracy.

Industry 4.0 encompasses different technologies such as IoT, big data, and AI. However, the existing literature is unclear whether having all (or some) such technologies is necessary for a manufacturer to be categorized as smart. This would be an interesting area to be studied in the future.

Some external factors could affect an industry's smartness, such as political and economic situations in Iran and the smart ecosystem. The impact of these external factors was not considered in this research, while it can be a research area for other researchers.

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Chapter 9
Determining the Criterion Weights for the Selection of Volunteers in Humanitarian Organizations by the Best-Worst Method

Umit Ozdemir, Suleyman Mete, and Muhammet Gul

Abstract Today, it is vital for humanitarian organizations operating in many different fields to select volunteers from the determining criteria according to the needs of the institution. Failure to select volunteers in accordance with the institution's needs may cause the volunteers to be unable to continue their duties and interrupt the institution's work. When choosing volunteers, it is essential for effective volunteer management to classify (expert, experienced, inexperienced, and insufficient) them according to the institution's needs and assign them starting from the volunteer in the best class volunteer when necessary. The aim of this study is to determine the criteria weights in the classification of volunteers who want to participate in search and rescue activities in humanitarian aid organizations according to the criteria determined before their assignment. In this study, a questionnaire is applied to field experts in Turkey to determine the most important and least important criteria, then criteria weights are calculated by using the Best-Worst Method (BWM). The findings obtained as a result of our study are evaluated and suggestions are made on how to improve it for future studies.

Keywords Volunteer selection · Classification · Search and rescue · Criterion weights · Best-Worst method

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Introduction

Volunteers, who aim to serve in many fields such as education, health and disaster, make economic and social contributions to many organizations established for different purposes in a country. Professionals are often supported by volunteers in humanitarian organizations. For example, 3200 volunteers participated in the rescue of flood victims in the Western Black Sea Region in 2021 [1]. These and similar organizations need human resources and they have to use them in the best way. The most important element in volunteer management is the selection of the most appropriate task according to the abilities of the individual, and the suitability of the job is as important as the request of the applicant. Giving a job that does not match the volunteer's qualifications may result in the applicant not volunteering again. To avoid these, volunteers should be assigned tasks according to their suitability. Especially in organizations such as disaster, search, and rescue; Volunteers who are experts in their fields or have previous experience are needed during and after the disaster. For this reason, creating a pool of volunteers such as experts, experienced, and inexperienced by classifying the people who apply voluntarily in any organization according to the determined criteria will facilitate the assignment of volunteers and reduce the time and complexity of selecting volunteers. Endo and Sugita [2] suggested the categorization of volunteers to prevent chaos and increase the effectiveness of work during disaster recovery. They divided the volunteers into 4 groups expert, experienced, inexperienced, and troublesome volunteers according to their practical knowledge, and suggested that the troublesome group be excluded from disaster recovery activities. However, they only chose disaster knowledge and computer-using skills as criteria in their work and did not evaluate their method in a real environment. Cvetkoska et al. [3] presented how recruitment and selection processes can be carried out to select volunteer students to participate in institution activities in a higher education institution. In order to develop the AHP model, computer skills, foreign language, motivation, clear and precise expression skills, creativity, and entrepreneurship criteria were selected, but only criteria were determined for their studies, no comparison was made between the criteria, and criteria weights were not calculated. Godelyte et al. [4] aimed to reveal the selection criteria of volunteers to work with children in the risk group. In order to achieve this aim, snowball sampling is done with the participation of 6 volunteer coordinators. As a result of his studies; In the selection of volunteers, motivation, self-confidence, empathy, preference for virtues, special skills, conflict resolution, and leadership criteria were determined, but only the criteria including social skills were examined and the criteria were not compared among themselves. Mazlan et al. [5] aimed to determine the criteria that are important in assigning volunteers to tasks. According to the literature and interviews with experts from non-governmental organizations (NGOs), seven dimensions were determined with 17 criteria. The Fuzzy Delphi method was applied in the selection of basic volunteer selection criteria. Their results showed that "Teamwork" and "Commitment" were the two most important elements. The criteria they used in their studies were generally determined and not adapted to a specific area. In addition, with the multi-criteria decision-making method, the importance of the criteria can be determined and the two methods can be compared. Ozdemir et al. [6] determined 5 criteria for voluntary classification in search and rescue activities, and the AHP method was used to evaluate the criteria weights, however, the number of criteria was kept very limited in the studies and no comparison was made with other multi-criteria decision-making methods. These studies demonstrate that the criteria and their relative weights should be chosen to assign the tasks chosen in the volunteer selection process. In addition, the AHP method was used in the published studies and a different criterion weight determination method was not preferred. Therefore, the Best-Worst method (BWM) is preferred in determining the weights of the criteria in this study. The aim is to fill the gap in the literature on the determination of the necessary criteria for the selection of volunteers and to provide the opportunity to compare with other methods by using different multi-criteria decision-making methods.

The rest of the paper is organized as follows; In the selection of volunteers, criteria are determined according to experts and published papers, and a questionnaire containing these criteria is applied to experts who have knowledge in the field of search and rescue, and the importance of the best and least important criteria is determined according to other criteria. BWM is mentioned and applied to obtain criterion weights. After a discussion of our results findings, Sect. "Discussion" concludes the study and provides suggestions for future research.

Methodology

In this study, the Best-Worst method, which is one of the multi-criteria decision-making methods, is selected instead of the AHP method in previous studies. Before making pairwise comparisons between criteria in BWM, the best and worst criteria are determined by experts or decision-makers, and then the importance of each criterion and criteria weights are obtained by examining its effects on other criteria. In this method, the use of two pairwise comparison vectors is created according to the best and worst criteria that the decision-maker may have in the pairwise comparison process. The purpose of choosing the method is to reduce personal biases when evaluating criteria according to AHP and to obtain more consistent and reliable results by making fewer comparisons between criteria [7].

Determining the Selection Criteria

As a result of our literature research, about 35 criteria including physical, mental, and social skills are selected in studies conducted in different fields related to the selection of volunteers. However, since our study includes search and rescue activities, 9 criteria are selected among the criteria determined in other studies as a result of the evaluations of field experts in selecting volunteers who want to participate in this field. In this context, the opinions of five experts with high experience in the area were taken. Detailed information about the titles and experiences of the experts is given in Table 9.1.

The determined criteria and details are given as follows.

Criteria-1: First aid knowledge

First aid is described as immediate help provided to a sick or injured person until professional help arrives. It is concerned with physical injury or illness and other forms of initial care, including psychosocial support for people suffering emotional distress from experiencing or witnessing a traumatic event (International Federation of Red Cross and Red Crescent Societies [8]). Kureckova et al. [9] studied the effect of first-aid knowledge on drivers in emergency situations. Their results showed that experienced-based first aid training can help reduce fatalities and serious health damage caused by traffic accidents.

Criteria-2: Search and Rescue knowledge

Search and rescue activities are of great importance after any natural disaster or explosion, especially after an earthquake. The chance of surviving the injured people is quite high in the first 24 h. Goltz and Thierney's study [10] show that many of the victims who were buried beneath the collapsed buildings in the earthquake in Kobe, Japan, were rescued by local volunteers.

Criteria-3: Computer Knowledge

Computer knowledge is needed for assigning personnel, ensuring information flow in the disaster area, creating a disaster plan, and dispatching the injured before and

Table 9.1 Titles and experiences of experts

Expert ID	Title	Area of expertise	Last education level	Years of experience
Expert-1	Academician	MCDM, fuzzy logic, disaster Management	Ph.D.	16
Expert-2	Academician	MCDM, operational research, volunteerism	Ph.D.	12
Expert-3	Academician	MCDM, operational research, volunteerism	Master	6
Expert-4	Disaster specialist	Search and rescue	Bachelor	15
Expert-5	Disaster education specialist	Search and rescue	Bachelor	7

after the disaster. Endo and Sugita [2] checked the computer skills of volunteers to supply information flow in the disaster area by three interfaces: the broadcast user interface, selectable user interface, and search user interface, for the classification of volunteers. They aimed to eliminate trouble-making volunteers by using different user interfaces before distributing them in the disaster area.

Criteria-4: Teamwork

Teamwork enables individuals to act together as a group, carry out their duties without interruption, and quickly get things done. O'Neil et al. [11] showed that teamwork skills are needed to participate effectively in a team. Team members are efficient when they have been trained to be so; they know how to coordinate tasks, how communicate with the other team members, and how react to the changing conditions in their environment.

Criteria-5: Learning Ability

Learning is linked to people's empowerment to be both socially and economically more active members of society, and the "individual employability potential" becomes of primary interest [12]. Khasanzyanova [13] argued that volunteering can be actively incorporated into students' learning process, making their overall experience of higher education more active, enjoyable, and relevant. Learning through action was found to be the most important factor in the acquisition of soft skills.

Criteria-6: Experience

Experience enables people to adapt to a new environment, overcome the difficulties they will encounter, and develop new ideas and strategies with their acquired knowledge. Jannat et al. [14] studied the selection of local volunteers in hospitals before disasters. Their result showed that among the 16 personnel and social criteria, practical and voluntary attendance experience were important criteria for the selection of volunteers.

Criteria-7: Physical Ability

Physical ability is required to carry out search-rescue activities that require immediate response and take long hours after a disaster occurs. Heimburg et al. [15] examined the physiological responses of firefighters during the simulated rescue of hospital patients and correlate the performance of firefighters with their endurance, strength, and working techniques. In their study, the performance of firefighters with high physical capacity was measured by comparing their oxygen-carrying capacity.

Criteria-8: Equipment and devices knowledge

Personnel who will work during search and rescue activities need many auxiliary equipment and electronic devices. It is very important that the volunteer personnel who want to take part in this field have basic knowledge about these types of equipment. Cuber et al. [16] examined the teams and vehicles that should be used separately in their work on the execution of search and rescue activities with robots and state why they should be supported by robots. They also announce the European Union

ICARUS project to ensure optimum human–robot collaboration. ICARUS aims to equip first responders with A comprehensive and integrated set of drone search and rescue tools.

Criteria-9: Language Translation Ability

During search and rescue activities, an interpreter is needed in order to quickly scan and organize information with foreign organizations. O'Brien et al. [17] showed that increasing cultural and linguistic diversity around the world has created a demand for information to be available in multiple languages. As such, they argued that language translation should be a key element in disaster management. Their work provided a framework for assessing the ways in which knowledge is disseminated through the lens of usability, accessibility, adaptability, and acceptability in language translation.

Best-Worst Method (BWM)

The BWM is applied to determine the criterion weights in the selection of volunteers for humanitarian organizations in this study. BWM, one of the multi-criteria decision-making methods developed by Rezaei [7] is used to decide the weights of the criteria based on the pairwise comparison of the best and worst criteria with other criteria. This method includes five steps to obtain the weights of the criteria.

Step 1. Determine a set of decision criteria. $\{C_{1,}, C_{2,}, \ldots, C_n\}$

Step 2. Determine the best and the worst criteria.

Step 3. Determine the preference of the best criterion over all the other criteria using a number between 1 and 9. The results of the vector Best to others are equal to $A_{BO} = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ where a_{Bj} represents the preference of the best criterion C_B over criterion C_j, $j = 1, 2, \cdots, n$.

Step 4. Determine the preference of the worst criterion over all the other criteria using a number between 1 and 9. The results of the vector Worst to others are equal to $A_{OW} = (a_{1W}, a_{2W}, \ldots, a_{nW})T$ where a_{jW} represents the preference of criterion Cj over the worst criterion Cw, $j = 1, 2, \cdots, n$.

Step 5. Find the optimal weights $(w_1^*, w_2^*, \ldots, w_n^*)$ by solving the following model

$$\min_j \max\left\{ \left|\frac{w_B}{w_j} - a_{B_j}\right|, \left|\frac{w_j}{w_W} - a_{jW}\right| \right\}, \tag{9.1}$$

Subject to

$$\sum\nolimits_{j=1}^{n} w_j = 1, w_j \geq 0, for\ all\ j \tag{9.2}$$

Application of the BWM in Determining the Citeria Weights

In this section, the criteria will be determined in the selection of volunteers according to the degree of importance by applying the steps of the BWM in order.

Step 1. As a result of the literature review and experts' opinions, 9 criteria are determined to be used in the selection of volunteers and are shown in Table 9.2.

Step 2. The best and worst important criteria selected by the experts who participated in the survey are in the Appendix.

Step 3. The best-to-others vectors of each expert according to the evaluation scale (from 1 to 9), which is formed by comparing the best criterion with the other criteria, are as in Table 9.3.

Step 4. Similarly, the vector Others-to-Worst for each expert is given in Table 9.4.

Step 5. In the last step of BWM, with the help of Excel-Solver, our criteria weights are solved separately according to the values given by each of our experts, and the values obtained are shown in Table 9.5.

Input-Based Consistency Ratio(CR^I): The method of determining a consistency level by using the decision maker's preferences instead of all optimization process steps is called the Input-Based Consistency Ratio. The formulation of CR^I is as follows:

Table 9.2 Volunteer selection criteria

Criteria	
First aid knowledge (**C_1**)	Experience (**C_6**)
Search and rescue knowledge (**C_2**)	Physical ability (**C_7**)
Computer knowledge (**C_3**)	Equipment and device knowledge (**C_8**)
Teamwork (**C_4**)	Language translation ability (**C_9**)
Learning ability (**C_5**)	

Table 9.3 Experts' preference of the Best criterion over all other criteria

Best to others	The best criterion	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Expert-1	Search and rescue knowledge	2	1	6	4	9	4	2	4	8
Expert-2	First aid knowledge	1	2	5	5	9	4	7	7	9
Expert-3	First aid knowledge	1	1	9	6	4	3	8	5	5
Expert-4	Search and rescue knowledge	2	1	9	4	5	8	3	6	8
Expert-5	Search and rescue knowledge	3	1	6	5	4	9	2	6	7

Note The best-to-others vector is the row vector corresponding to the values given by each expert to the criteria, respectively. For example, the vector best for Expert 3 is equal to $A3_B = (1, 1, 9, 6, 4, 3, 8, 5, 5)$

Table 9.4 Experts' preference of the worst criterion over all other criteria

Others to worst	Expert 1	Expert 2	Expert 3	Expert 4	Expert 5
The worst criterion	Learning ability	Learning ability	Computer knowledge	Computer knowledge	Language translation ability
C_1	3	9	8	8	6
C_2	9	6	6	9	9
C_3	4	5	1	1	4
C_4	8	5	4	8	7
C_5	1	1	3	3	2
C_6	5	7	3	7	1
C_7	9	7	8	7	7
C_8	3	6	3	4	3
C_9	2	2	7	4	3

Note The worst vector is the column vector corresponding to the values given by each expert to the criteria, respectively. For example, the vector worst for Expert 2 is equal to $A2_W = (9, 6, 5, 5, 1, 7, 7, 6, 2)T$

Table 9.5 Criteria weights for each expert opinion

Weights	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8	C_9
Expert-1	0.147	0.277	0.060	0.090	0.022	0.090	0.180	0.090	0.045
Expert-2	0.319	0.212	0.085	0.085	0.024	0.106	0.061	0.061	0.047
Expert-3	0.268	0.229	0.020	0.063	0.095	0.126	0.047	0.076	0.076
Expert-4	0.200	0.298	0.022	0.100	0.080	0.050	0.133	0.067	0.050
Expert-5	0.187	0.412	0.043	0.052	0.065	0.029	0.130	0.043	0.037
Average	0.2160	0.2777	0.0395	0.0758	0.0482	0.0705	0.0977	0.0655	0.0495

$$CR^I = \max_j CR_j^I \tag{9.3}$$

where

$$CR_j^I = \begin{cases} \frac{|a_{Bj} \times a_{jw} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}}, a_{BW} > 1 \\ 0, a_{BW} = 1 \end{cases} \tag{9.4}$$

While calculating the consistency ratio according to the formula above, the consistency of the data is measured by comparing against a threshold value. If your obtained data is greater than the threshold value, these data cannot be used. According to the study of Liang et al. [18], the threshold value was calculated as 0.3662 (9 criteria and 9 evaluation scale.). The input-based consistency ratio of each expert according to the evaluation scores is equal to (0.0972, 0.1250, 0.3611, 0.3194, 0.1667) respectively. Since the criteria values of each of the experts with different opinions give consistent results, the criteria weights are determined by taking the geometric mean of each criterion.

Discussion

The data presented in Fig. 9.1 provides valuable insights into the key characteristics required of volunteers participating in search and rescue activities. According to the data obtained, the two most important characteristics expected of volunteers who will take part in search and rescue activities are search and rescue and first aid knowledge, and these two criteria have a very high weight value compared to other criteria. In addition, physical ability is a feature that should not be ignored.

On the other hand, the criteria of learning ability and language translation skills are deemed less crucial for volunteer participation in search and rescue activities. These criteria possess comparable weight values, indicating that while they are considered important, they are not as central as search and rescue knowledge, first aid proficiency, or physical ability. Computer knowledge is the least important criterion in search and rescue activities and its weight value is 0.0395.

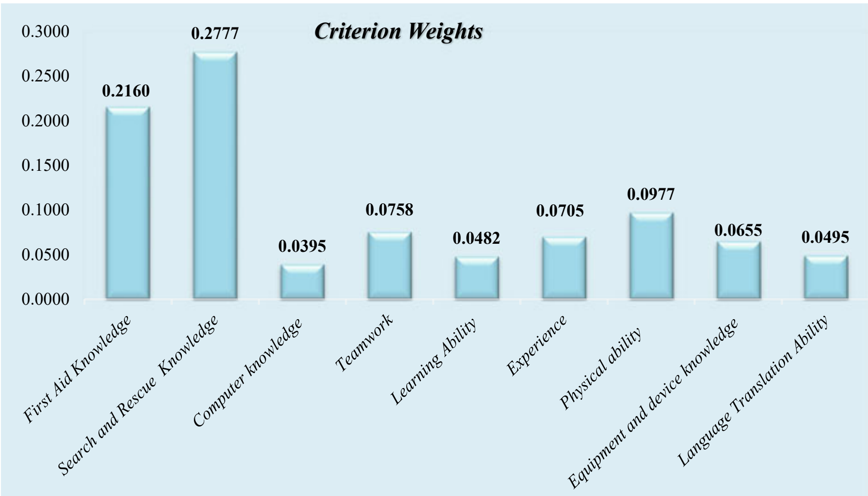

Fig. 9.1 The criterion weights for the selection of volunteers

Conclusion

In this study, criteria were determined according to the needs of the organization in the selection of volunteers who will carry out search and rescue activities, and criteria weights were calculated according to the importance of these criteria. Using the criterion weights obtained with this preliminary study, it aims to divide the volunteer group into classes and prevent confusion and waste of time in the selection of volunteers. According to the results obtained, the most important criteria are search and rescue knowledge and first aid knowledge. When compared with the study conducted between the AHP method [6] and 5 criteria, first aid knowledge was obtained as the most important criterion weight, but search and rescue and learning ability were found to be equal, unlike the study here. Similarly, computer knowledge was found to be the least important criterion in both studies. While teamwork was found as a criterion of moderate importance according to the criteria determined for search and rescue activities, the volunteer criteria determined without focusing on a specific area were found to be the most important criterion in their paper [5].

However, the scope of the study is only applied to determine the criterion weights, and the effectiveness of the method is not evaluated by comparing it with other multi-criteria decision-making methods. Moreover, criteria can be expanded and divided into subgroups according to physical, social, and mental characteristics. For future studies, the criteria weights obtained in this study can be used by applying the Topsis-Sort or Oreste-Sort methods for the selection and classification of the volunteers, and the effectiveness of these two methods can be compared.

Appendix

Questionnaire to Determine the Criteria Weights in the Selection of Volunteers

This questionnaire has been prepared for the determination of volunteer selection criteria weights in search and rescue activities. Select the criteria that you think are the MOST IMPORTANT in search and rescue activities among the determined criteria and indicate your preference of the most important criterion over all the other criteria with a number between 1 and 9 according to the other criteria.

The most important criterion	First aid knowledge	Search and rescue knowledge	Computer knowledge	Teamwork	Learning ability	Experience	Physical ability	Equipment and device knowledge	Language translation ability

Similarly, Select the criteria that you think are the LEAST Important among the criteria and indicate your preference of all the criteria over all the least important criterion with a number between 1 and 9.

The least important criterion
First aid knowledge
Search and rescue knowledge
Computer knowledge
Teamwork
Learning ability
Experience
Physical ability
Equipment and device knowledge
Language translation ability

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Chapter 10
Emergency Service Quality Assessment Using SERVQUAL and BWM

Pelin Gulum Tas and Geqie Sun

Abstract Understanding the perceptions and needs of patients regarding the quality of the emergency department (ED) is crucial for enhancing the performance of provided health care services. As an acknowledged quality measurement method in many industries, SERVQUAL has been used for hospitals and EDs. Although it is convenient to define the gaps between customer expectations and the quality of received services, SERVQUAL requires an explicit prioritization strategy to decide between further actions. In addition, this method heavily relies on self-reported data from participants who might be subject to many behavioral anomalies while assigning direct values to their expectations. To address these shortcomings, we propose a novel service quality measurement methodology by integrating the SERVQUAL method with Best-Worst Method (BWM). First, by treating the five main dimensions of the SERVQUAL method as our main criteria, we identified several ED-specific sub-criteria and structured a questionnaire following the BWM procedure. Then by analyzing the collected data, the weights of the main and sub-attributes were calculated and discussed. The results show that Reliability and Assurance are the two most important attributes for both patience and accompanying people with patients while evaluating ED service quality. The main contribution of this study is providing insights into the quality measurement of healthcare services from a multi-criteria decision-making perspective and helping practitioners and researchers design patient-oriented services.

Keywords Emergency department service quality · SERVQUAL · Best-worst method

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Introduction

Emergency departments (ED) play a crucial role in the individual well-being and countries' healthcare systems by providing people with immediate and specialized care in situations of injury, sudden illnesses, and life-threatening incidents [1–4]. Since EDs often serve as initiators of future treatment processes, the given first care can affect people's long-term well-being and overall health status. Therefore, ED services should be designed and delivered carefully considering patient needs, time constraints, facilities, and other limited resources. The number of patients expected to visit the EDs and the urgency of their healthcare needs are always stochastic processes and cannot be accurately defined beforehand [5]. In order to provide high-standard healthcare on time and to make the best possible use of the scarce labor force and equipment, there is a need for a systematic quality assessment [6]. Each sub-system of the ED should be considered within and between systems regarding the performance of provided services, the competence of healthcare experts, and the adequacy of equipment used [7]. Because the emergency department is a comprehensive, complicated, and multi-actor system, it is challenging to develop a proper quality measurement tool that covers all these components and the possible interactions between them. In addition, it is inevitable to consider the values and perceptions of the patients as service receivers while focusing on service quality. All these challenges and the dynamic nature of EDs require a systematic point of view to service quality measurement problems.

There are various tools and methods for service quality measurement, and SERVQUAL is one of the widely-used and accepted methods put forward by Parasuraman [8]. It is designed based on five dimensions to identify the gap between "expected quality" and "received quality" from the eyes of clients. Although it is not special to healthcare services, thanks to its adaptability, there is a vast literature on SERVQUAL applications in the health domain and fewer examples regarding EDs [9–12]. In a classical SERVQUAL application, participants are asked to evaluate the service quality by filling out a Likert scale questionnaire. Later, the difference between expectations and perceived quality is analyzed to identify in which areas the quality is high and which areas need further improvement. Despite its systematic background and well-accepted performance in many service areas, there are some difficulties regarding using SERVQUAL for healthcare services. Firstly, it requires self-reporting data from patients who may have conflicting views, and all the further analyses are done by assuming that individuals have a clear understanding of their expectations and perceptions. Secondly and more importantly, even if the SERVQUAL method is practical while defining the gaps between customer expectations and real perception about the delivered services, it does not provide any guidance for determining relative importance. This means someone can measure the service quality by collecting data and analyzing these gaps. However, there is still a need to decide which gap is more important and which areas are worth further improvement or investment by prioritization. In addition, the SERVQUAL method is a general tool for service quality and may not capture various nuances stemming from industrial differences as healthcare special circumstances. To cope with all these drawbacks by considering the dynamics of the emergency room setting, we propose a methodology that integrates the SERVQUAL method with Best-Worst Method (BWM). BWM is a well-known multi-criteria decision-making method that provides a systematic approach to compare many attributes to each other in a consistent manner [13]. Also, recent experimental studies have revealed that BWM shows promising performance regarding cognitive biases, which are systematic errors that may affect judgments and so assessments seriously [14]. From this point of view, integrating the SERVQUAL method with BWM can provide a more consistent prioritization method for further decisions and a less fragile approach in terms of subjectivity and possible behavioral influences. Also, by introducing many ED-special sub-criteria for each SERVQUAL dimension, we aim to propose a more specialized tool for healthcare service quality measurement. The significance of this study lies in its potential to increase the performance of the conventional SERVQUAL method by taking advantage of BWM with a particular focus on health and ED services. In addition, a real case pilot study illustrates the method's applicability and performance by using judgments of real service receivers.

The remainder of the paper is organized as follows: Sect. "Literature Review" presents a literature review for healthcare quality measurement. In Sect. "Methodology", the proposed methodology is discussed. After giving the case study in Sect. "Case Study", data analysis and results are presented in Sect. "Analysis and Results". Finally, the conclusion and future work are provided in Sect. "Conclusion and Future Work".

Literature Review

This section presents a literature review on service quality measurement with a special focus on health, emergency departments, and the SERVQUAL method. In addition, parallel to the proposed multi-criteria decision-making approach, a few studies in this scope are also briefly discussed. Table 10.1 shows these studies and explains the methods they applied and their important findings.

There is a vast literature on quality measurement in healthcare systems [21–23], and some of the studies particularly focus on emergency departments by applying the SERVQUAL method [11, 12, 17]. These applications reveal important insights regarding the factors that affect quality perceptions of people, such as the importance of the waiting time and attitudes towards patients [11], the role of information sharing [15], hygiene, and comfort of the EDs [18] and physical conditions of the emergency departments [20].

The applicability of the SERVQUAL method for ED quality measurement is studied by Ibarra and others [17], and their findings for Mexican hospitals pointed out that SERVQUAL is an appropriate method for defining improvement areas. As an alternative method, Kuisma and others [19] have used customer satisfaction surveys and studied the quality perceptions of patients. Their case study showed that while

Table 10.1 Literature review findings for service quality measurement in emergency departments

Author(s)	Purpose	Method(s)	Findings
Gholami and others [11]	Measuring the service quality in the emergency department of a hospital in Iran	SERVQUAL	There is a significant gap between expectations and received quality, especially for the responsiveness dimension The facilities, waiting time of the patients, ordering system, and the attitude of service providers towards patients are identified as improvement required areas
Taylor and Benger [15]	Identifying patient satisfaction parameters for emergency departments	Systematic literature review	There are three common areas that affect the emergency service quality perception: attitudes of healthcare providers, provision of information, and waiting time. If an ED focuses on these areas, an increase in perceived quality can be observed
Mohammadi-Sardo and others [12]	Identifying factors affecting patient satisfaction in EDs	Cross-sectional study with SERVQUAL	The Tangibles dimension is found as the most effective factor, while Empathy is defined as the least effective one
Abdel-Basset and others [16]	Evaluating the efficiency of some EDs in Egypt	Data envelopment analysis (DEA) and analytic hierarchy process (AHP)	By focusing on eleven factors, the efficiency of twenty EDs are compared. private hospital emergency rooms are found to be more efficient than public hospitals in Egypt
Ibarra and others [17]	Measuring the service quality of an ED located in Mexico	SERVQUAL	The findings show that SERVQUAL is a suitable tool for health quality measurement and can be used for defining improvement opportunities
Lima and others [18]	Evaluating the quality of emergency rooms by focusing on user satisfaction	A cross-sectional descriptive study with a quantitative approach	It has been found that the majority of the participants were dissatisfied with the received service because of delays, waiting time, confidence, cleanliness, and comfort of the EDs. The role of including service receivers in the decision-making process is highlighted

(continued)

Table 10.1 (continued)

Author(s)	Purpose	Method(s)	Findings
Kuisma and others [19]	Measuring customer satisfaction levels for EDs	Questionnaire	The major dissatisfaction cause is not being taken to the preferred ED by paramedics. Also, communication is found as a crucial factor for customer satisfaction. The applicability of customer satisfaction surveys for ED is proved via a case study
Fatima and others [20]	Presenting a literature review on the dimensions of quality in healthcare	Systematic literature review	SERVQUAL and its dimension Tangibility are found to be the most commonly used method and parameter, respectively There are some core parameters while measuring health service quality, and they are parallel to the sub-components of the SERVQUAL method

considering the service quality, the factors before reaching the emergency room, such as the attitude of paramedics, have an important effect on patient satisfaction. Another alternative methodology is proposed by Abdel-Basset and others [16] by integrating DEA and AHP methods. They compared the performance parameters using AHP and set one of the recent examples of the applicability of MCDM methods in the emergency department quality assessment.

Literature review findings show the importance of measuring the service quality in emergency departments and the role of the SERVQUAL method while doing so. However, the promising performance of MCDM methods in complex problems such as emergency department-related ones and their possible contributions to the prioritization stage of the SERVQUAL method are overlooked. Therefore, this study aims to fill this gap by introducing a methodology that integrates BWM, a widely-used MCDM method, with SERVQUAL for emergency departments. Evaluating the representative service quality criteria using BWM can provide a more systematic way than traditional methods and ensure the suitability of the tool since it is designed for this particular problem.

Methodology

This section focuses on the methodology to understand which parameters are most important to people when assessing the quality of the services they receive from EDs. First, with the help of the literature review findings and expert opinions, we listed all possible criteria for measuring emergency department service quality. Later, by using the five dimensions of SERVQUAL as the main criteria, the sub-criteria are categorized under them. A questionnaire designed in the Qualtrics program [24] has

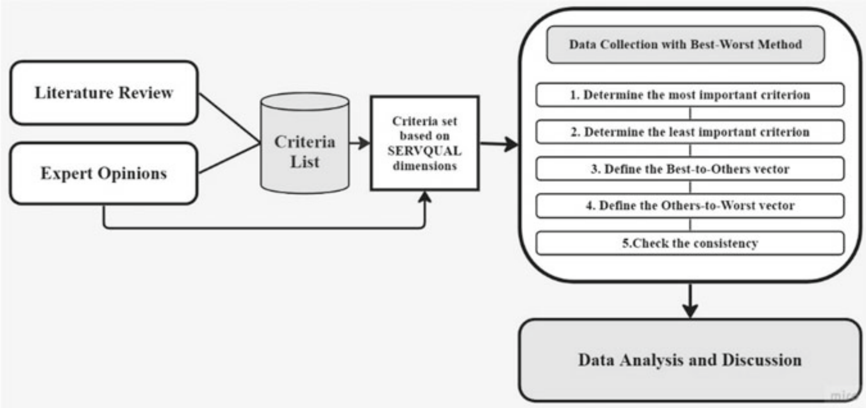

Fig. 10.1 Emergency department service quality assessment model

been used to collect data from participants. In this questionnaire, subjects followed BWM steps one by one and evaluated the main and sub-criteria. Then, these comparison matrices are used for weight calculation, and all the weights are aggregated by geometric mean. Finally, the results are analyzed and discussed. Figure 10.1 illustrates the proposed methodology with a diagram and covers all sub-components of the application. The following subsections explain two main methods, SERVQUAL and BWM.

SERVQUAL

Different from the quality of goods, measuring service quality is a more challenging task since it may have various abstract and undefined parameters. In order to provide a systematic evaluation tool for service quality, the SERVQUAL method was introduced by Parasuraman [8]. This relatively old but well-accepted method focuses on measuring the gap between the expectations of clients and the quality of the service they receive. The "perceived quality" term is used to illustrate the satisfaction level of customers from the service they are provided with. SERVQUAL method has five main dimensions named (1) tangibles, (2) reliability, (3) responsiveness, (4) assurance, and (5) empathy. In the traditional SERVQUAL method, these main dimensions have twenty-two items in total, each considering different service quality components. Even if these items may change depending on the context and type of the service considered, the five main dimensions are generally fixed. Table 10.1 presents brief explanations of these five dimensions as given in the SERVQUAL method [8] and shares some representative examples to explain the role and content of these main dimensions in an emergency room setting parallel to the aim of our study [9] (Table 10.2).

Table 10.2 Five dimensions of SERVQUAL and their explanations

Dimensions	Explanation and ED examples
Tangibles	Refers to physical facilities and the conditions of the equipment used while providing the services (e.g., the comfort of the EDs, medical equipment used, etc.)
Reliability	Ability to provide consistent and reliable services (e.g., giving the treatments on time, standardized tools for each patient)
Responsiveness	Having fast, efficient, and customer-oriented systems (e.g., having an efficient triage system for fast emergency detection, good communication, etc.)
Assurance	Employee's attitudes and skills related to the job (e.g., the accuracy of diagnosis and treatments, competency of doctors and nurses)
Empathy	Valuing the feelings and needs of customers (e.g., prioritizing patients' needs and showing emotional support)

The main idea behind the SERVQUAL applications is gathering customer perceptions via case-based structured surveys and specifying the dimensions where improvement is required. While doing so, participants assign some scores to their expectations and perceptions, and the difference between these scores gives ideas to service providers about improvement opportunities. In this study, we propose a multi-criteria evaluation approach with BWM. Instead of using classical items to evaluate dimension, we considered them the main service quality measurement criteria and defined some sub-criteria for each. In the data collection part, the participants compare these defined attributes instead of assigning scores to their expectations and perceived quality measures. By doing so, we can elicit the relative importance of each component and systematically identify which area requires improvement. Also, its robustness to some cognitive biases [14] and providing decision-makers with consistent evaluations strengthens the encouragement to use BWM in this type of study. With this motivation, we define nineteen sub-criteria representing the five main criteria, as illustrated in Table 10.3. While defining these criteria, first, we did a literature review and described a list of possible criteria for hospital service quality measurement, emergency department, and health quality in general. After that, with the help of a medical expert with experience in the emergency department, we narrowed down these criteria set. Finally, following the definition of SERVQUAL dimensions, we categorized the criteria under these five categories. The Tangibles criterion has five sub-criteria to represent the physical conditions of the emergency room, including its cleanliness and the appearance of healthcare providers. Reliability has three sub-criteria: timeliness of health care and treatments, transparency of processes, and standardization of treatments and applications. Four sub-criterion are defined under the Responsiveness criterion as effective communication and information sharing, the willingness of nurses and doctors to help, sensitivity to complaints, and an effective triage system for emergency detection. For the Assurance main

Table 10.3 Criteria set for emergency department service quality assessment

Main criteria	Sub-criteria
1. Tangibles	1.1 Hygiene of emergency room [7, 21–23, 25–27]
	1.2 The comfort of the emergency room [7, 21–23, 25–27]
	1.3 Quality of medical equipment [7, 20, 23, 25–28]
	1.4 Appearance of healthcare providers [10, 22, 23, 25, 26]
	1.5 Signages for wayfinding [26, 28]
2. Reliability	2.1 Timeliness of care and treatment [7, 21–23, 25–27]
	2.2 Transparency of processes [10, 22, 23, 25, 26]
	2.3 Standardization of care and treatment [10, 22, 23, 25, 26]
3. Responsiveness	3.1 Effective communication and information sharing [7, 21–23, 25–27]
	3.2 The willingness of nurses and doctors to help [21–23, 25–27]
	3.3 Sensitivity to complaints [21–23, 25–27]
	3.4 Effective triage system for emergency detection [5, 29, 30]
4. Assurance	4.1 Medical staff competency [7, 21–23, 25–27]
	4.2 Accuracy of provided treatment plans [7, 21–23, 25–27]
	4.3 Regular health monitoring [22]
	4.4 Accuracy of diagnosis [7, 21–23, 25–27]
5. Empathy	5.1 Prioritized patient needs and personalized care [7, 21–23, 25–27]
	5.2 Courtesy of medical staff to patient and family [7, 21–23, 25–27]
	5.3 Conveying emotional support [7, 21–23, 25–27]

criterion, we defined four sub-criteria named medical staff competency, the accuracy of provided treatment plans, regular health monitoring, and accuracy of diagnosis. Finally, three sub-criteria are specified for representing Empathy as prioritizing patient needs and personalized care, courtesy of medical staff to patient and family, and conveying emotional support.

Best-Worst Method

The Best-Worst Method (BWM) is a multi-criteria decision-making method introduced in 2015 by Rezaei [13] and has attracted significant attention since then. Compared to most pairwise comparison methods, BWM requires less pairwise comparison but provides decision-makers with more consistent results. In addition, recent research has revealed that BWM is less prone to some systematic errors, such as anchoring and equalizing biases that arise while decision-makers elicit the attribute weights [14, 31, 32]. The steps of the BWM method are given as follows:

Step 1: The decision-maker identifies criteria set $\{c_1, c_2, \ldots, c_n\}$ for evaluating the alternatives.

Step 2: The best (the most important or most desirable) and the worst (the least important or least desirable) criteria are identified by the decision-maker.

Step 3: The decision maker expresses their preferences for the best criterion compared to all the other criteria using a number between 1 and 9. Best-to-Others (BO) vector is obtained as a result of this evaluation and shown as:

$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn})$ where a_{Bj} illustrates the preference of the best criterion B over criterion j.

Step 4: The decision maker expresses their preferences for all the other criteria compared to the worst criterion using a number between 1 and 9. Others-to-Worst (OW) vector is obtained as a result of this evaluation and shown as:

$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})$ where a_{jW} shows the preference criterion j over the worst criterion W.

Step 5: The optimal criteria weights, w_j^* are calculated considering the following requirements:

For each pair of w_B/w_j and w_j/w_W, the ideal solution is where $\frac{w_B}{w_j} = a_{Bj}$ and $\frac{w_j}{w_W} = a_{jw}$. A solution should be found to minimize the maximum absolute differences $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ and $\left|\frac{w_j}{w_W} - a_{jw}\right|$ for all j to satisfy the conditions. Under the non-negativity and unit-sum conditions for weights, the following is obtained:

$$\min_j \max \left\{ \left| \frac{w_B}{w_j} - a_{Bj} \right|, \left| \frac{w_j}{w_W} - a_{jW} \right| \right\}$$

$$\text{s.t.} \sum_j w_j = 1 \tag{10.1}$$

$$w_j \geq 0, \text{ for all } j$$

Rezaei [33] also proposed a linear model with slight differences as follows:

$$\min \xi.$$

s.t.

$$\left| w_B - a_{Bj} w_j \right| \leq \xi, \text{ for all } j,$$

$$\left| w_j - a_{jW} w_W \right| \leq \xi, \text{ for all } j, \tag{10.2}$$

$$\sum_j w_j = 1$$

$$w_j \geq 0, \text{ for, all } j$$

By solving Eq. (10.2), the optimal weights w_j^* and ξ^* are obtained. The closer ξ value to zero, the higher the consistency of comparisons becomes. This means more reliable pairwise comparisons. In this study, we use the linear version of BWM [33] and the input-based consistency check, as suggested by Liang and others [34].

Case Study

In this study, we propose a methodology to identify the importance of parameters while measuring the emergency service quality from the eyes of people who experienced emergency service before as patients or accompanied people. An extended set of criteria is defined and classified following the dimensions of the SERVQUAL method. After that, a special questionnaire based on BWM is structured in Qualtrics, given its user-friendly interface and powerful tools to design, distribute and analyze the questionnaire [24]. Participants were asked to complete the questionnaire by pairwise comparisons with respect to all criteria. There were two determinative questions while choosing the subjects: " *Have you ever been into the emergency department as a patient?*" and "*Have you ever been into the emergency department as an accompanying person?*". First, every participant sees the former question, and if the answer is *No*, then the participant faces the second question. If the answer is *Yes* to the first question, then they skip the second one and directly start answering the questionnaire. If a person has not been either a patient or an accompanying person in the emergency room before, they could not participate. By doing so, we ensure that the evaluations are based on real experiences and observations. After this test, the five main attributes of SERVQUAL (Tangibles, Reliability, Responsiveness, Assurance, and Empathy) are presented and explained in the context of ED, and participants are asked to choose which is the most and least important attribute for them. Later, they determine the preference of the best criterion over all the other criteria and the preference of all the criteria over the worst criterion by using a number between 1 and 9, as stated in the importance scale in Table 10.4. Finally, participants were asked to evaluate the sub-attributes of each main attribute with the same procedure, and their evaluations were recorded.

The Participants

The questionnaire was shared with participants in the Netherlands, Turkey, and China. In total, there were 57 respondents, 47 of them were people who had been patients in the ED before, 5 of them were accompanying persons, which means they have been in the ED with a patient, and 5 of them had never been into the ED which means they could not complete the survey (see Table 10.5). After cleaning the data by removing non-complete surveys, 34 were found to be usable in this study.

Table 10.4 The importance scale for pairwise comparison

Intensity of importance	Meaning	Clarification
1	Equal importance	Two factors contribute equally to the objective
3	Moderate importance	The parameter slightly favors over another
5	Strong importance	The parameter strongly favors over another
7	Very strong importance	The parameter is strongly favored, and its dominance is demonstrated in practice
9	Absolute importance	The highest possible order of importance
2, 4, 6 and 8	Intermediate values	Used to represent a compromise between the priorities listed above

Table 10.5 Respondents to the questionnaire

Respondents	Numbers	Numbers who completed the questionnaire
Patient	47	30
Accompanying person	5	4
Neither of them	5	NA
In total	**57**	**34**

Analysis and Results

This section presents the analysis and results based on the collected data from questionnaires. By completing the calculations of BWM using the provided pairwise matrices, the importance weights of the attributes are determined and discussed.

Characteristics of the Participants

The majority of participants were patients (88%), outnumbering the accompanying persons (12%) by a significant margin. In terms of gender distribution, females accounted for a larger proportion (59%) compared to males (41%). Furthermore, the majority of participants fell within the age range of 26 to 49 years old. When considering the educational background, a significant portion of participants had achieved a master's degree (44%), followed closely by those with a bachelor's degree (32%). Table 10.6 illustrates the profile of the participating people.

Table 10.6 Profile of the participants

Characteristics of the participants	Numbers	Percentage (%)
Former experience in the ED		
Patient	30	88.24
Accompanying person	4	11.76
Gender		
Female	20	58.82
Male	14	41.18
Age		
18–25	8	23.53
26–49	25	73.53
50–65	1	2.94
Education level		
High school	3	8.82
Bachelor degree	11	32.35
Master degree	15	44.12
Ph.D. degree	5	14.71
In total	**34**	

Table 10.7 Consistency of the evaluations

Groups of weights that passed the consistency test	Groups of weights	Percentage of consistency
130	204	**63.73%**

Determination of the Weights and General Discussion

After collecting the data, the Linear BWM Solver (BWM Solvers | Best-Worst Method) was used to compute the weights of the attributes. As this solver also provides an input-based consistency ratio check procedure, the consistency of the answers was checked as well. For each participant, six groups of weights were computed (one group of main attributes and five groups of sub-attributes), there were 204 groups of weights in total, and we found that 63.73% of them were consistent (see Table 10.7). It can be said that the pairwise comparisons were mainly consistent.

The Main Attributes

For the main attributes, the most important attribute is defined as reliability, whose average weight is 0.34; the second most important attribute is assurance, with an average weight of 0.21, followed by responsiveness and tangibility, ranking third and

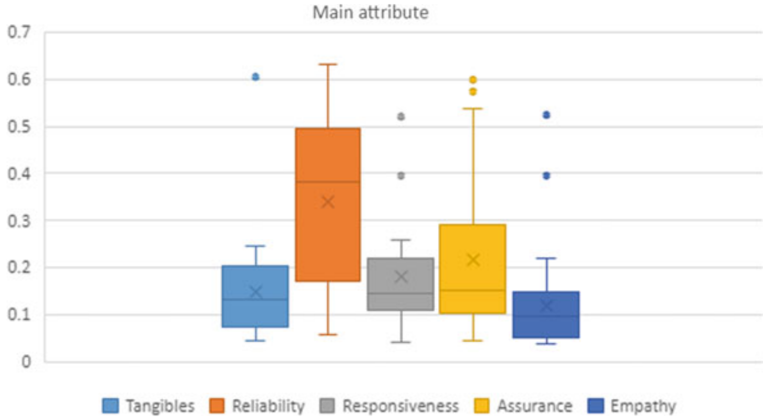

Fig. 10.2 The weights of the main attributes

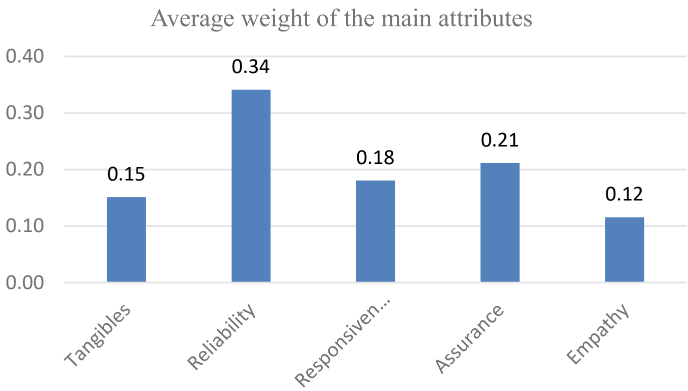

Fig. 10.3 Average weight of the main attribute

fourth, respectively, with average weights of 0.18 and 0.15; and the least important attribute is empathy, with an average weight of 0.12. Figures 10.2 and 10.3 illustrate the weights of the main attributes. These weights are a general indication of how people evaluate the quality of ED services, and hospitals should focus on reliability because people attach more importance to it.

The Sub-Attributes for the Main Attribute Tangibles

Regarding the sub-attributes of Tangibles, the most important sub-attribute is Hygiene of the emergency room, whose average weight is 0.36, followed by the second most important sub-attribute, Quality of medical equipment, with an average weight of 0.2, and the rest three sub-attributes are of similar importance (see Figs. 10.4 and

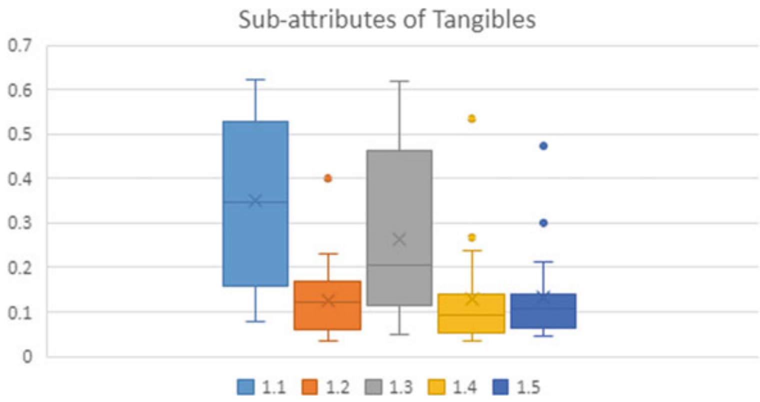

Fig. 10.4 Sub-attributes of tangibles

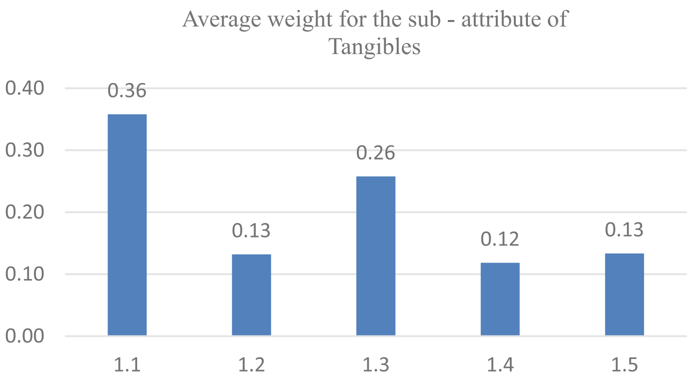

Fig. 10.5 Average weight for the sub-attribute of tangibles

10.5). These findings emphasize the importance of preserving a clean and sanitary emergency room environment and a focus on the quality of medical equipment in terms of the Tangibles of medical care.

The Sub-Attributes for the Main Attribute Reliability

For the sub-attributes of Reliability, the data reveals a clear structure in importance. The most critical sub-attribute is Timeliness of care and treatment, which holds an average weight is 0.56, highlighting its significance in determining Reliability perceptions; the second and third most important sub-attributes are Transparency of processes and Standardization of care and treatment; they are of similar importance, with an average weight of 0.24 and 0.20, respectively (see Figs. 10.6 and 10.7).

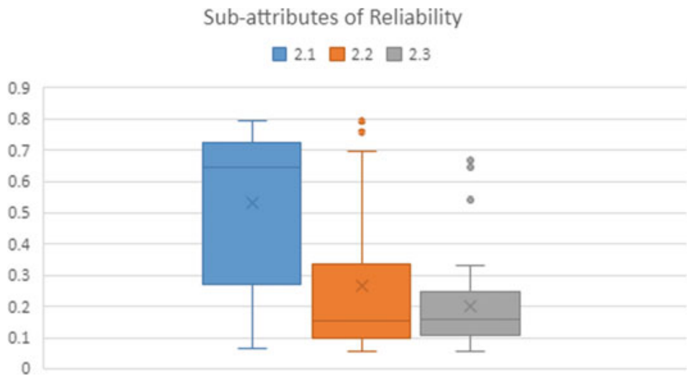

Fig. 10.6 Sub-attributes of reliability

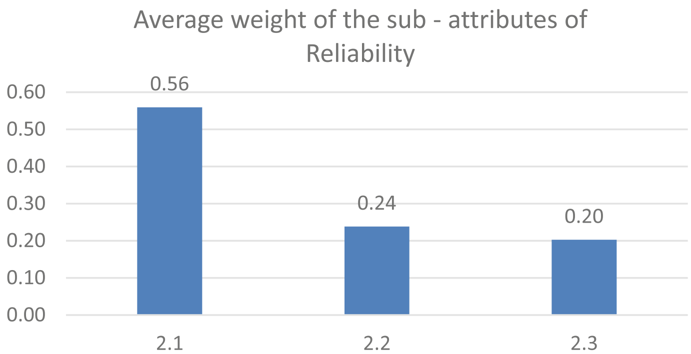

Fig. 10.7 Average weight of the sub-attributes of reliability

The Sub-Attributes for the Main Attribute Responsiveness

With regard to the Responsiveness sub-attributes, the Effective triage system for emergency detection, whose average weight is 0.34, appears to be the most important sub-attribute, followed by Effective communication and information sharing, The willingness of nurses and doctors to help and Sensitivity to complaints, ranking second, third and fourth, respectively, with average weights of 0.28, 0.22 and 0.16 (see Figs. 10.8 and 10.9).

The Sub-Attributes for the Main Attribute Assurance

When considering the Assurance sub-attributes, a clear hierarchy occurs with respect to their average importance. With an average weight of 0.42, Accuracy of diagnosis emerges as the most critical sub-attribute, followed by Accuracy of provided treatment plans (mean weight of 0.25), Medical staff competency (mean weight of

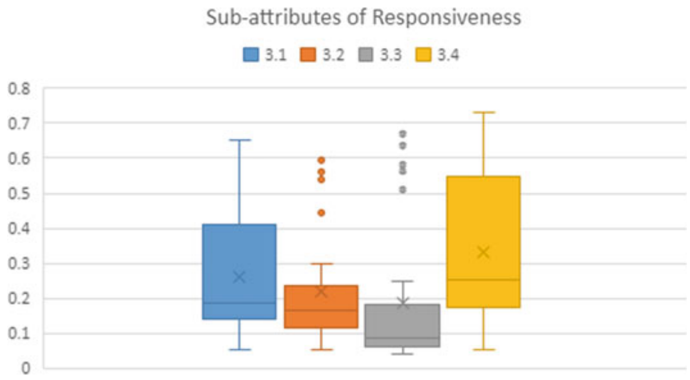

Fig. 10.8 Sub-attributes of responsiveness

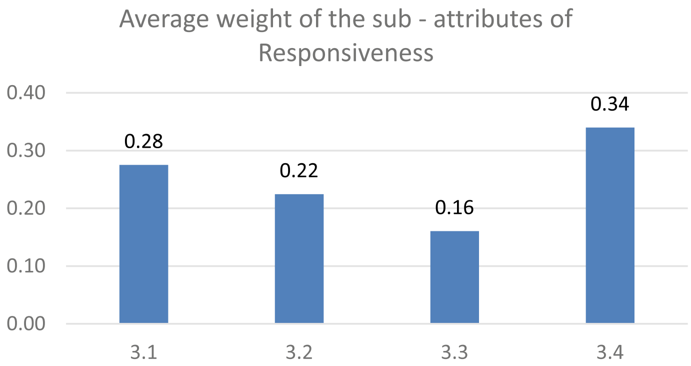

Fig. 10.9 Average weight of the sub-attributes of responsiveness

0.19), and Regular health monitoring (mean weight of 0.15) in descending order (see Figs. 10.10 and 10.11).

The Sub-Attributes for the Main Attribute Empathy

The Empathy sub-attributes show a similar pattern to the Reliability sub-attributes in terms of average weights. With the highest sub-attribute, Prioritized patient needs and personalized care (mean weight of 0.58); the second and third most important attributes are of similar importance, Courtesy of medical staff to patient and family holds an average weight of 0.25, and Conveying emotional support, at a mean weight of 0.17 (see Figs. 10.12 and 10.13).

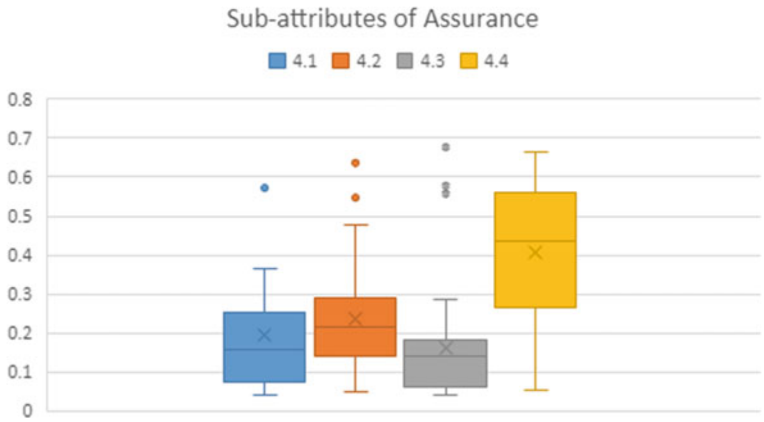

Fig. 10.10 Sub-attributes of assurance

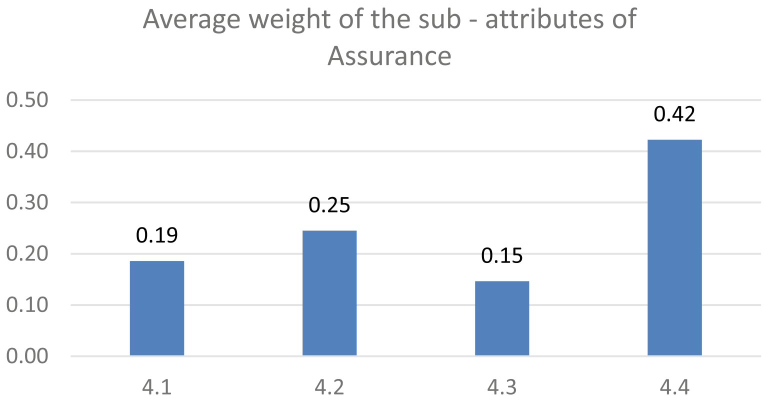

Fig. 10.11 The average weight of the sub-attributes of assurance

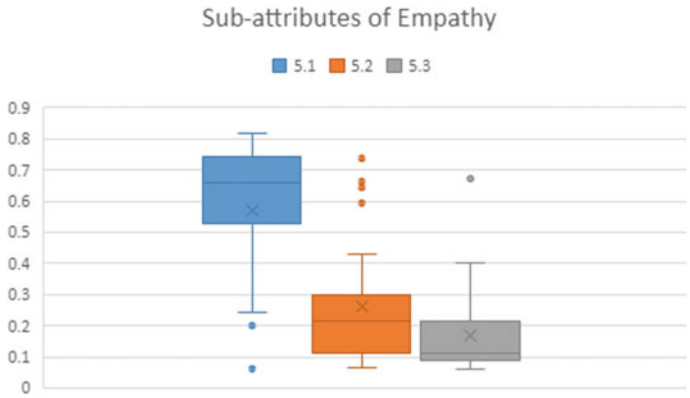

Fig. 10.12 Sub-attributes of empathy

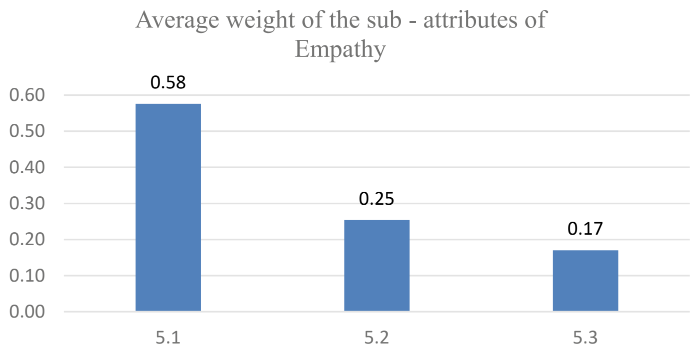

Fig. 10.13 Average weight of the sub-attributes of empathy

The Global Weights

After obtaining the local weights, the final weights of the sub-attributes can be determined by multiplying them with the weights of the main attributes, as is presented in Table 10.8. Among all the sub-attributes, Timeliness of care and treatment and Transparency of processes are the most and third most important attributes. Since the most important main attribute is Reliability, this situation is quite normal. The second most important attribute is the Accuracy of diagnosis, which is a sub-attribute of Assurance. Considering that the other three sub-attributes of Assurance ranked quite low, this seems interesting. One reason might be that, once a diagnosis is established, patients often assume that the medical staff is capable of formulating appropriate treatment plans and monitoring their health accordingly. After that, the fourth important attribute is Standardization of care and treatment, another sub-attribute of Reliability, again demonstrating the importance of Reliability. Another interesting finding is from the Empathy attribute. While empathy as a main attribute ranked last, prioritized patient needs and personalized care receives high importance. This might be because people have different expectations in terms of empathy as a general concept in EDs, and they may not explicitly prioritize it. However, they may highly value the specific aspects of empathy and recognize that this sub-attribute is directly facilitating their overall satisfaction. The least three important attributes are from Tangibles and Empathy, which is normal considering that they ranked fourth and fifth among the main attributes. It suggests that these sub-attributes are not crucial and that ED service providers may prefer to prioritize other attributes to increase the quality of their services.

Comparing the Difference Between Patients and Accompanying Persons

These data shed light on some interesting observations of the quality dimensions of ED services by patients and escorts. As seen from Table 10.9, from the patient's

Table 10.8 The weights of the sub-attributes

Sub-attributes	Local weight	Global weight	Rank
1.1 Hygiene of emergency room	0.358	0.054	7
1.2 The comfort of the emergency room	0.132	0.020	17
1.3 Quality of medical equipment	0.258	0.039	12
1.4 Appearance of healthcare providers	0.119	0.018	19
1.5 Signage for wayfinding	0.134	0.020	16
2.1 Timeliness of care and treatment	0.559	0.191	1
2.2 Transparency of processes	0.238	0.081	3
2.3 Standardization of care and treatment	0.203	0.069	4
3.1 Effective communication and information sharing	0.275	0.050	9
3.2 The willingness of nurses and doctors to help	0.224	0.040	10
3.3 Sensitivity to complaints	0.161	0.029	15
3.4 Effective triage system for emergency detection	0.340	0.061	6
4.1 Medical staff competency	0.186	0.039	11
4.2 Accuracy of provided treatment plans	0.245	0.052	8
4.3 Regular health monitoring	0.146	0.031	13
4.4 Accuracy of diagnosis	0.423	0.089	2
5.1 Prioritized patient needs and personalized care	0.576	0.067	5
5.2 Courtesy of medical staff to patient and family	0.254	0.029	14
5.3 Conveying emotional support	0.170	0.020	18

perspective, reliability comes out on top with an average weight of 0.35, indicating their strong preference for reliable ED services. Assurance and responsiveness ranked second and third with similar weights, indicating the importance of building trust and responding quickly to the needs of patients. The least two important attributes are the Tangibles and Empathy.

On the other hand, assurance (mean weight of 0.42) and reliability (mean weight of 0.25) seem to be the most important attributes for escorts. This indicates that they are very committed to trust and confidence in the medical services offered. Responsiveness (mean weight of 0.16) followed closely behind, emphasizing the importance of timely and attentive support. Similar to the results from patients,

Table 10.9 Ranking of the attributes according to the two groups

Attribute	Patient	Accompanying person
Tangibles	4	5
Reliability	1	2
Responsiveness	3	3
Assurance	2	1
Empathy	5	4

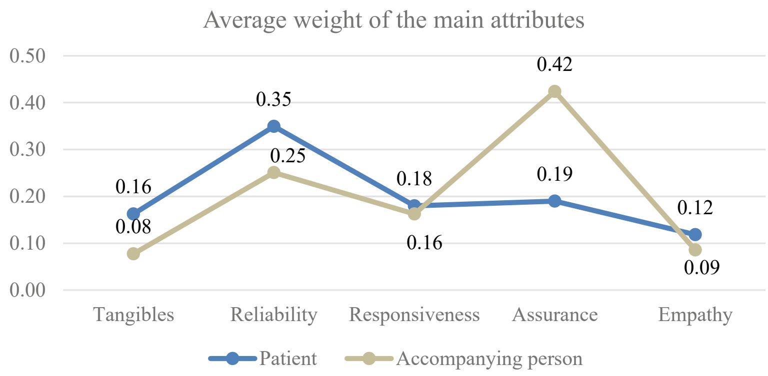

Fig. 10.14 Average weights of the main attributes for two groups

Tangibles and Empathy are the two least important attributes. The average weights for these two groups are illustrated in a graph in Fig. 10.14.

In general, we can see a difference in the prioritization of the attributes, which can be attributed to the different roles and viewpoints of patients and escorts. For patients, their health is at stake, and they want to receive timely care and treatment. Whereas escorts care more about the well-being and comfort of the patient, this can also be seen from the different importance they place on assurance, indicating their willingness to make sure that the healthcare providers are competent and knowledgeable.

Conclusion and Future Work

The main objective of this study is to provide a novel SERVQUAL method by taking advantage of BWM specifically for healthcare services in the emergency rooms. The applicability and performance of this method are demonstrated by conducting a case study by collecting data from fifty-seven individuals. We measured their perceptions of emergency service quality from the answers they gave, considering their previous experiences in the EDs. After data analysis, we found that Reliability is recognized as the essential main attribute, followed closely by Assurance and Responsiveness. Furthermore, with respect to the sub-attributes, the top three important ones come from Reliability and Assurance: Specifically, Timeliness of care and treatment, Transparency of processes, and Accuracy of diagnosis. The three least important sub-attributes all come from Tangibles. Our findings about the importance of the Tangibles dimension differ from previous studies conducted by Gholami and others [11], Mohammadi-Sardo and others [12], and Fatima and others [20] since they reported it as the most critical parameter. Different from them, in our application, Tangibles is ranked as the fourth out of five main attributes. Various reasons can be given for this difference, such as participant profiles and their preferences, the country of study and its healthcare policies, and the sub-criteria considered. For instance, if the application takes place in a developing country that has relatively old technological devices at EDs and uncomfortable facilities, Tangibles might be seen as more important. Also, we think instead of giving direct values to sub-criteria as in the traditional SERVQUAL method, comparing them might be motivated people to think harder about their preferences, and naturally, they may end up with different results. On the other hand, our findings are parallel to the findings of Lima and others [18], where Reliability received high importance. It shows that when it comes to health-related outcomes, people want to make sure they are receiving accurate and reliable care on time. Therefore, similar to studies conducted by Gholami and others [11] and Taylor and others [15], in our application, timeliness of care is ranked as one of the most important sub-attributes showing that people attribute great importance to time-efficient treatments in ED.

We also see a difference in the answers of different roles in the ED. For instance, patients view Reliability as the most crucial main attribute, while the accompanying person values Assurance highly. Also, Empathy is viewed as the least important attribute for the patients, whereas accompanying people place the least importance on Tangibles. These differences might stem from their different expectations and roles in emergency situations. For instance, while an accompanying person needs to communicate with doctors and nurses more, they might assign a higher weight to Empathy. On the other hand, as the main care receiver, the patient may place a higher weight on treatment-related attributes.

The outputs of this study can be used to improve the quality of provided services in EDs by taking into account the voice of patients. New services can be designed by following the findings, or current ones can be improved with a better understanding. For instance, EDs should mainly focus on providing timely and accurate diagnoses and treatments. This can be done by increasing the competence and expertise of the medical staff and improving the processes. On the other hand, the performance of triage systems is important and should be fast and efficient. The latest decision support systems can be used to increase the performance of the triage process. Emergency department staff need to be sensitive to prioritizing patient needs and personalized care. Companion people and patients have different priorities, and their expectations should be considered differently. Waiting rooms, signages in EDs, and administrative processes should be designed by considering the expectations of accompanying people. Continuous quality assessment is crucial for improvement, and it should be done regularly with proper methods that consider ED from different perspectives.

Apart from the managerial implications stated, this study also makes a contribution to the research field by developing a novel service quality measurement method integrated with BWM. In this new method, the consistency can be measured and therefore is able to provide a more reliable analysis compared to the traditional method. Therefore, the application of this model is not limited to healthcare or emergency services, and it can be applied to different service domains by carefully identifying and organizing the sub-attributes.

The main limitation of this study is the number of respondents which is relatively low for this type of questionnaire study. A more extensive study is recommended to present a more reliable understanding of how people evaluate the quality of ED services. In addition, the number of sub-attributes can be extended for a more comprehensive evaluation method. As key players in the ED system, doctors' and nurses' evaluations and expectations can be integrated into a different study to see how service quality perceptions differ for service receivers and providers. In conclusion, this study provides valuable insights into the quality measurement of healthcare services from an MCDM approach and helps both practitioners and researchers in their way of designing better services and tools.

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Chapter 11
Avalanche Risk Analysis by a Combined Geographic Information System and Bayesian Best-Worst Method

Zekeriya Konurhan, Melih Yücesan, and Muhammet Gul

Abstract The formation of avalanches is related to the land structure, climatic conditions, and snow cover. It is usually seen in mountainous and sloping terrains without vegetation. In Turkey, especially in Eastern Anatolia and the Black Sea Region, which have high elevations, avalanche events are observed. This study aims to perform a risk analysis by integrating the Bayesian Best-Worst method (BWM) and Geographic Information System (GIS) for Tunceli province, which is the scene of significant avalanche events. Bayesian BWM is a method that improves the original BWM by effectively integrating the preferences of multiple experts. In the study, 16 sub-criteria, such as elevation, slope, and the number of snowy days, were determined, and experts evaluated these criteria through questionnaires created. The weight of each criterion were calculated using the Bayesian-BWM. By integrating the criteria weights from the Bayesian-BWM model into GIS, the risky places for natural avalanche disasters in Tunceli province were determined, according to which the risk in the northern part of the study area is identified as high.

Keywords Avalanche risk analysis · GIS · Bayesian-BWM

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Introduction

Avalanches are snow masses starting from slopes and flowing downhill rapidly. They are destructive and unpreventable [1, 2]. They have natural triggers such as snowfall, snow carried by the wind, temperature rise, and artificial triggers such as explosives and skiers [3]. They can create speeds higher than 200 km/h and pressure up to 50 T/m^3 [4]. They can also ingest vegetation, ice, and rocks [5]. They can damage people, residential areas, and infrastructures in the avalanche zone [6]. Due to the high flow rate, avalanches can destroy everything in their way [7].

For this reason, it is vitally essential to predict hazard-prone areas and take preventive measures in line with these predictions [8]. Although the parameters affecting avalanche formation are known, it is impossible to determine the exact time and place of the avalanche under current conditions [3, 5]. Usually, avalanches occur in mountainous regions. Altitude, slope, vegetation, climate, and weather conditions are among the parameters that affect avalanches [9]. Avalanche predictions are made using various models due to the spread of avalanche regions to large areas and the difficulty of accessing these regions, keeping reports of past events regularly, and the scarcity of historical data for effective forecasting, high costs, and technical difficulties of field studies [2, 10]. Avalanche risk mapping is a complex process requiring a combination of parameters affecting avalanche formation [1]. To avoid this limitation, GIS-based tools are used to graphically integrate different types of data. GIS-based tools are very effective in performing this integration, managing large volumes of data, and performing sensitivity analysis [2, 11]. Quantitative methods (probabilistic and deterministic techniques) and qualitative methods (expert opinions) were used together with GIS [12]. AHP, which is one of the MCDM methods, has been used to determine avalanche risks [13]. At the same time, many studies exist in the literature with GIS and AHP integration [1, 7, 14–16]. The AHP method has been criticized for needing too much evaluation to create comparison matrices [17] and too much time to collect conflicting expert opinions [18]. On the contrary, Best-Worst Method (BWM) proposed by Rezaei [19], requires less time and data than AHP. It also allows for more consistent evaluations. One of the most significant limitations of BWM, the inability to aggregate the preferences of multiple decision makers, has been overcome with the Bayesian BWM proposed by Mohammadi and Rezaei [20]. On the other hand, although there are studies on various topics [21–24] and risk analyses involving BWM or different BWM models in the literature, there is no article on avalanche risk analysis. The fact that there was only GIS in the study would cause the importance of the criteria to not be determined. For this reason, since the effect levels of the criteria affecting the avalanche are different, it was used together with the Bayesian BWM method, which is one of the MCDM methods, in order to determine the importance of the effects of these criteria.

The study aims to identify avalanche-sensitive areas in an integrated manner with GIS. In this context, the process of the study first started with a literature review, and according to the evaluations, the Bayesian BWM method, which is more limited within the scope of avalanche risk analysis, was selected. Subsequently, the study area was determined, and the criteria to be used were chosen according to the literature and the characteristics of the study area. For each selected criterion, maps containing the features according to the study area were made. Again, the criteria were evaluated in the presence of experts, and weighting calculation was created using the Bayesian BWM method. Each criterion whose global weights were determined was transferred to the GIS environment, and overlay analysis was performed using the "Weight Sum" tool, one of the ArcGIS tools, and avalanche-sensitive areas were identified. As a result, fieldwork was carried out for some avalanche-sensitive areas, photographs were taken, and necessary interpretations were made.

Literature Review

Most avalanche studies [5, 25–28] focus on avalanche measurements, avalanche prevention, avalanche accidents, and avalanche regulation, while others perform various analyses, measurements, and modeling [29, 30]. In Turkey, avalanche-related studies have been carried out on the general situation of avalanche events [31, 32] as well as the calculation of the high-risk potential created by the current conditions in the Black Sea and Eastern Anatolia regions [33–37]. Several studies integrate MCDM and GIS to determine avalanche susceptibility. For example, Nasery and Kalkan [38] analyzed the avalanche susceptible areas of Van province by integrating AHP and GIS. Varol [15] used Frequency Ratio (FR), AHP, and Fuzzy-AHP (FAHP) methods by integrating GIS and considered "elevation, slope, aspect, curvature, and vegetation" criteria. In another study, Wen et al. [39] used various methods, especially machine learning methods, and followed a predictive method for the avalanche-sensitive areas of the Qinghai-Tibet Plateau. Gret-Regamey and Straub [40] integrated Bayesian Network and GIS on a real avalanche data. Apart from these examples, there are some studies on integrating MCDM and GIS to detect avalanche-prone areas [29, 30, 33, 36, 37].

From Bayesian BWM perspective, as it is on the focus of this study, the literature is not so broad [23, 41–45]. However, an avalanche analysis study integrating Bayesian BWM and GIS was not found to the best of authors' knowledge. Therefore, the Bayesian BWM method is preferred for weighting the criteria in this study.

Material and Method

Study Area

Tunceli province is placed in the Eastern Anatolia Region. Mountains constitute 70% of the surface area, plateaus 25%, and lowland areas 5% (Fig. 11.1).

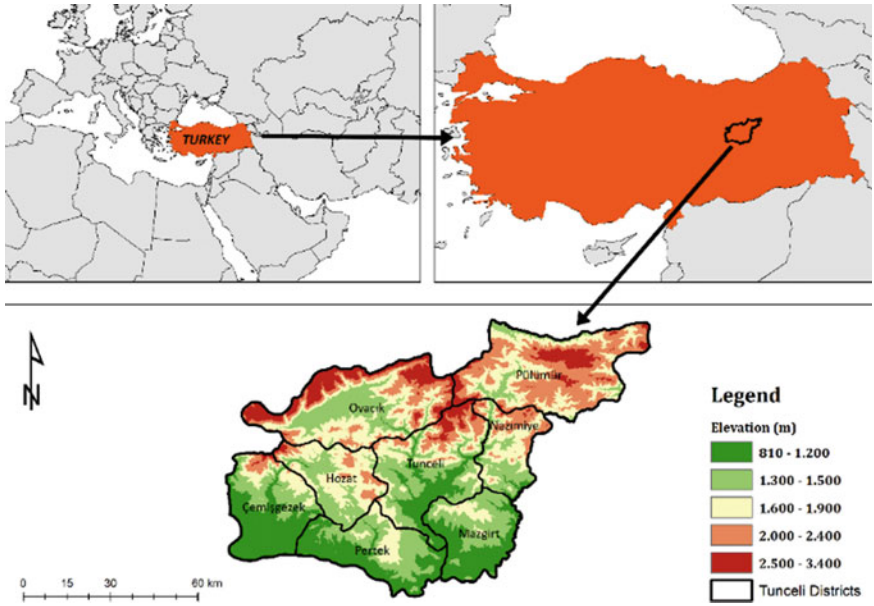

Fig. 11.1 Tunceli province

The elevation steps in Tunceli generally increase from south to north and west to east. The elevation difference between the north and south of the region is approximately 2500 m. The altitude rises to over 3500 m in places. The average elevation of the province is 1264 m [46]. The high and steep Munzur Mountains rising in the north and south are covered with snow for most of the year. Transportation between Erzincan and Tunceli is carried out along the Pülümür valley between these mountains. Especially in the winter, these transport routes are closed due to snow. Avalanche tunnels have also been constructed on this road due to high risk (Fig. 11.2).

Turkey, especially the Eastern Anatolia Region, where the elevation is high, has the highest avalanche risk. The study area is also located in this region. Avalanche risk regions have been determined by Disaster and Emergency Management in the country (Fig. 11.3). Tunceli, which is the study area, is among these provinces. For this reason, Tunceli province was selected as the study area.

Criteria Used in the Location Selection

In this study, 16 criteria were determined under four main criteria (topography, climatic conditions, location, and environmental-land conditions). As mentioned, the requirements were based on the existing literature, characteristics of the study area, and expert opinions (Table 11.1).

Fig. 11.2 Avalanche tunnels and "avalanche zone" warning sign on Erzincan-Tunceli motorway

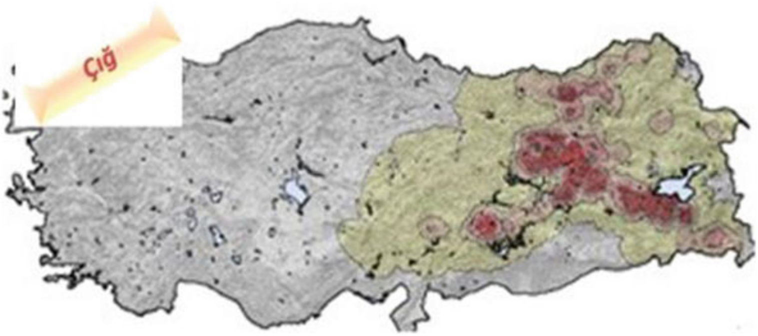

Fig. 11.3 The avalanche risk map of Turkey prepared by AFAD [47]

Topography: Within the scope of the study, "elevation, slope, aspect, curvature and lithology" criteria are included under the main criterion of topography. The elevation is one of the most critical factors in avalanche formation. As the elevation increases, the temperature decreases, and precipitation falls as snow and wind speed increase. Therefore, avalanche risk increases. Avalanches generally do not occur below 1000 m [15, 36]. Almost 75% of the study area is above 1000 m. Another vital criterion is the slope. The slope is the essential criterion in avalanche risk maps [5]. Although there are minor differences in the studies in the literature, avalanche movements can occur in the range of 28–50° on average. Since snow cannot accumulate above 50°, avalanches cannot occur [11, 48, 49]. Tunceli province has a very sloping terrain, especially in the northern regions, slope values reach 30–35%.

Table 11.1 Criteria for avalanche risk analysis

Topography (A)	Climatic conditions (B)	Location (C)	Environment-land conditions (D)
Elevation (A1)	Average temperature in December, January, and February (B1)	Distance to road (C1)	Vegetation cover (NDVI) (D1)
Slope (A2)	Average precipitation in December, January, and February (B2)	Distance to fault lines (C2)	Land use (D2)
Aspect (A3)	Number of snowy days (B3)	Distance to stream (C3)	Topographic wetness index (TWI) (D3)
Curvature (A4)	Normalized difference snow index (B4)	Distance to settlement areas (C4)	
Lithology (A5)			

Another important criterion in avalanche risk mapping is aspect. Aspect is the angle obtained regarding the azimuth of any slope to the north. The stability of the snow layer changes according to the aspect factor; temperature, evaporation, sunlight exposure, and water retention [50]. Statistics for the Austrian and Swiss regions show that 50% of all avalanches occur in the northern part (NW–SE) [51]. North-facing slopes of the northern hemisphere are characterized by high temperature differences and are, therefore, more prone to avalanches [52]. Since the study area is in the northern hemisphere, the relevant directions are considered risky according to the above information. Another criterion is curvature. Curvature consists of concave, convex, and flat slopes. According to AFAD, most avalanches in Turkey are encountered on concave slopes [33]. Within the scope of the study, a curvature map was created, and classification was made, as mentioned above. Lithology is the last criterion of the main topography criterion. In avalanche risk analyses, the lithology of the terrain is evaluated according to factors such as the strength of the rocks (such as andesite, granite, or mica), roughness, or bareness. Avalanches can move in the direction of gullies/pools with channels. These channels can follow the unstable rock types [48, 49]. The lithological structure of Tunceli was also determined in the study (Fig. 11.4).

Climatic Conditions: Climatic condition's main criterion includes "Average Temperature in December, January, and February, Average Precipitation in December, January, and February, Number of Days with Snowfall, and Normalized Difference Snow Index (NDSI)". The primary source of avalanche formation is snow cover. Avalanche formation cannot be expected where there is little or no snowfall. For snowfall, especially the temperatures and snowfall in December, January, and February were considered. Because the study area is in the northern hemisphere, December, January, and February coincide with this period. In addition, the fundamental causes of avalanches in Turkey are a cooling down to just below the freezing point following the passage of frontal cyclones and a warming up to near the freezing point following the passage of frontal cyclones and rainfall [53]. Therefore, temperature and precipitation in the region were determined as a criterion. The number of

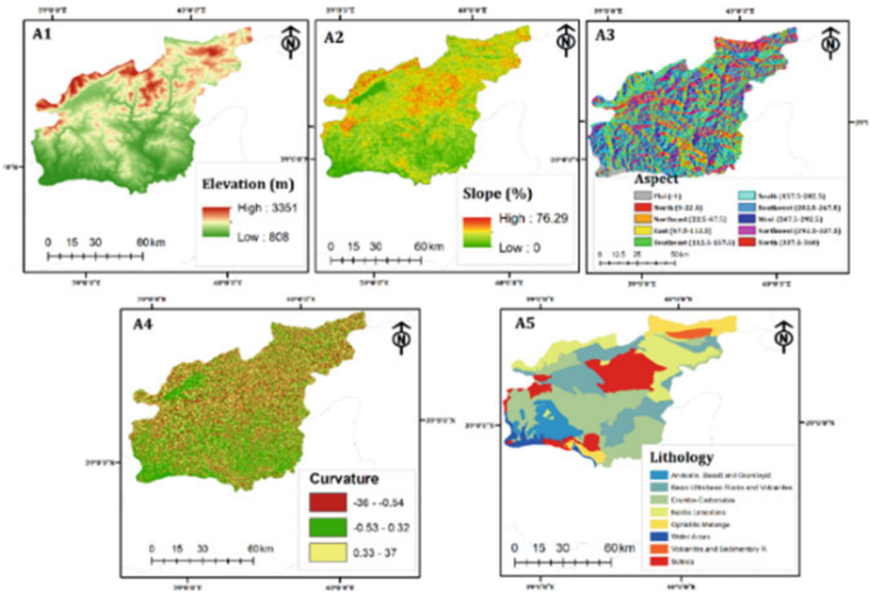

Fig. 11.4 Elevation (A1), Slope (A2), Aspect (A3), Curvature (A4) and Lithology (A5)

snowy days and snow density is effective in avalanche formation. A region's high snowy days can cause avalanches due to increased snow depth and snow density (Fig. 11.5).

Location: Within the main criterion of location, there are sub-criteria "distance to road, distance to fault lines, distance to rivers, and distance to settlement areas". In some cases, avalanches can affect roads even though they are far from settlements. Especially in rural areas, avalanche hazards occur on transport roads. Here, the road can disrupt the balance of the structure for the place where it is built, and in some cases, the lack of retaining walls on the roadsides causes avalanches. In the study area, tunnels were built on the Erzincan-Tunceli access road against landslide and avalanche risk (Fig. 11.2). Another important criterion is the distance to fault lines. The tremors caused by earthquakes in the vicinity of faults may cause avalanches, although the probability is low [36, 49]. The fact that essential fault lines are located in and around the study area required this criterion to be considered. Another criterion is the distance to river networks. The river criterion has not been included much in the literature. However, the two main rivers in the study area have been added as a criterion to the study considering their indirect avalanche effect due to their erosion activities for many years and their erosion activities, especially in the impactor areas. The last sub-criterion of the main location criterion is the distance to settlements. Many human activities in settlements indirectly affect avalanche movements for reasons such as noise, house construction, excavation, and road construction. Especially human activities in settlements on mountain slopes

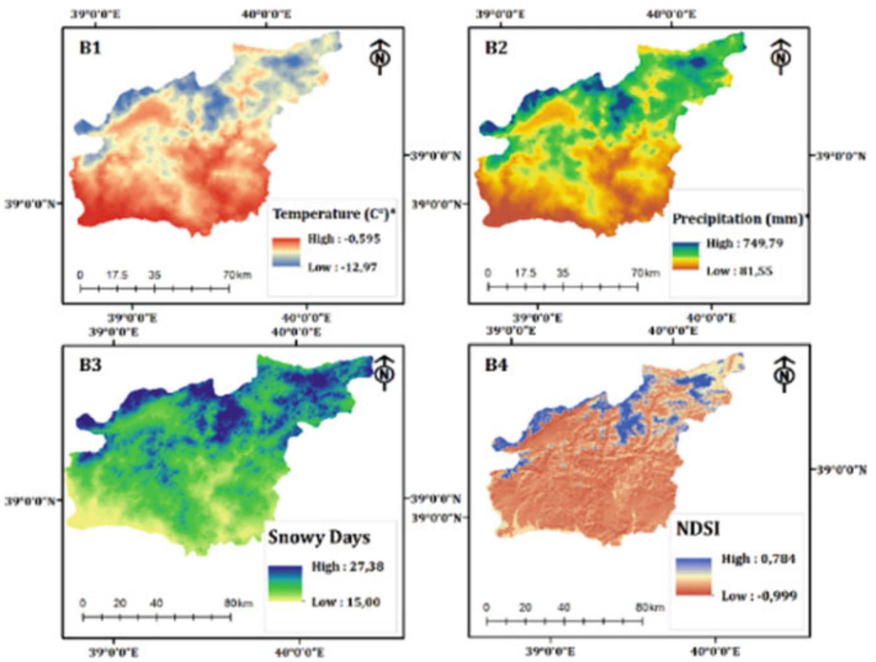

Fig. 11.5 Average temperature in December, January, and February (B1), average precipitation in December, January, and February (B2), number of snowy days (B3) and NDSI (B4)

trigger avalanches. Therefore, the distance criterion to settlement centers was added to the study (Fig. 11.6).

Environment-Land Conditions: The main environmental-terrain criteria include "vegetation cover, land use, and topographic wetness index (TWI)". Vegetation cover is essential in avalanche movements. Flat and grassy slopes facilitate avalanche formation. Moist grass vegetation creates a slip plane that accelerates the movement of avalanches. On the other hand, forests covered with tall trees undertake critical tasks in the prevention of avalanche formation; because the trees prevent the snow mass from starting to move, they stop the avalanche formation before it starts [49]. Another vital criterion is land use. In land use, the avalanche risk increases significantly in urban areas, bare areas, mining areas, and bare areas. Therefore, the study added the land use criterion as a sub-criterion. The last sub-criterion of the environment-land main criterion is the topographic wetness index. TWI shows the wetness ratio of the soil. In some regions, increasing the temperature and wetness ratio may weaken the snow mass [54]. Therefore, an avalanche may trigger this avalanche. TWI was determined and evaluated for the study area (Fig. 11.7).

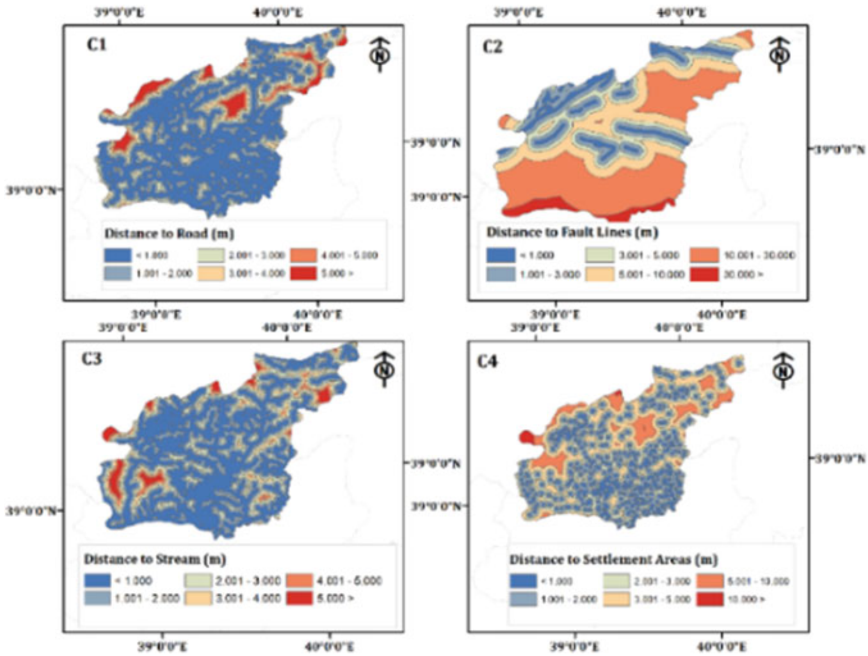

Fig. 11.6 Distance to road (C1), distance to fault lines (C2), distance to stream (C3) and distance to settlement areas (C4)

Research Methodology

This section gives detailed information regarding Bayesian BWM and GIS. Firstly, the main and sub-criteria were created by the aid of relevant literature, study area characteristics, and experts' opinions. Then Bayesian BWM is used to calculate the weights of these criteria.

The BWM is developed based on the pairwise comparison in the field of MCDM by Rezaei [19]. It is superior to existing pairwise comparison-based approaches in providing a reasonable reduction in the amount of comparison and its ability to reduce inconsistency in the comparison data. Bayesian BWM, the continuation of BWM developed specifically for multi-expert decision-making situations, gives perfect results in group decision-making environments with its probabilistic decision-making algorithm [20]. It is a sensitive measure for preventing loss of information and interpreting the "credal ranking" features and criterion weights. The use of classical BWM in group decision-making causes a lot of errors and inaccurate information due to the use of the averaging operator [42]. Assigning equal importance to each expert is another vital handicap. However, its probabilistic structure and aggregating of multiple experts enabled many researchers to find this method useful. Bayesian BWM is applied to many fields today [24, 29, 41, 43, 45, 55–62].

Bayesian BWM is implemented in four basic steps [20, 42, 44]:

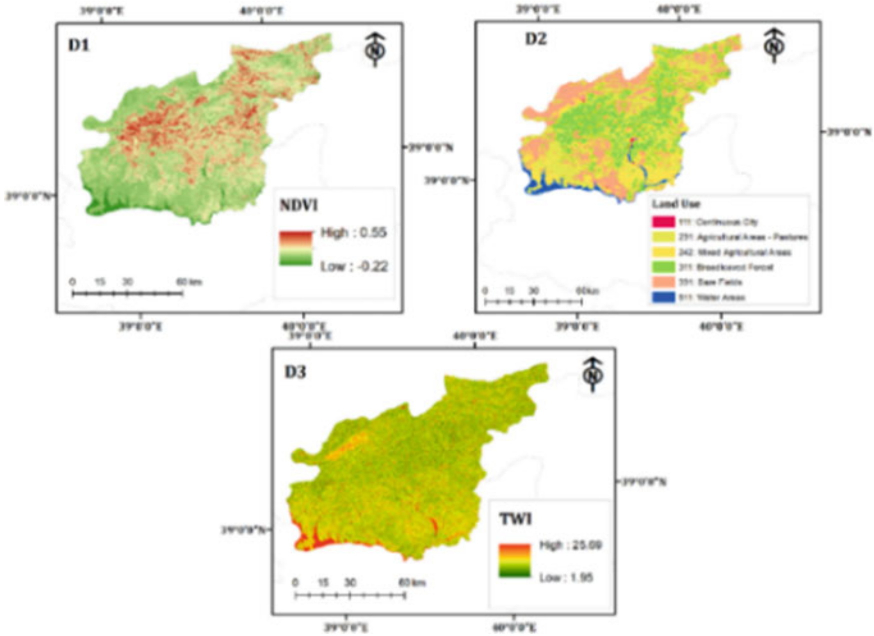

Fig. 11.7 Vegetation cover (NDVI) (D1), land use (D2) and topographic wetness index (TWI) (D3)

(1) Determination of the best and worst criteria. If a criteria hierarchy is mentioned, this step is applied separately for all sub-branches of the hierarchy.
(2) Performing a pairwise comparison of the best criterion to other criteria. The linguistic assessment scale used in Rezaei [19] and other studies are used here.
(3) Performing a pairwise comparison of other criteria to the worst criterion.
(4) Calculate the aggregated weight of criteria and graph the credal rankings. This step is what separates Bayesian BWM from classical BWM. This step uses probabilistic Markov-chain Monte Carlo sampling, and mathematical models are solved with a MATLAB decision support system.

Weighted criteria are then integrated into GIS, and avalanche risk analysis for Tunceli is presented. The expert staff applied within the scope of the study are from the fields of geography, emergency-disaster management, MCDM and GIS, industrial engineering, and geology. The relevant experts have sufficient knowledge about the study area, the country's general geography, and the avalanche issue.

Application Results

Weighting Criteria with the Bayesian Best-Worst Method

Questionnaires were created according to the hierarchy determined in Table 11.1. In these questionnaires, seven decision-makers, experts in their fields, first identified the Best (most important) and Worst (least important) criteria. Then they made the necessary pairwise comparisons to create the best-to-others and others-to-worst vectors. The evaluations obtained were determined whether they were consistent according to the input-based consistency procedure proposed by Liang et al. [63]. Evaluations above the threshold value were sent back to the decision-makers. It was ensured that all assessments were consistent. Input-based consistency ratios are presented in Table 11.2.

MATLAB codes presented in [64] were used to obtain weights and credal ranking. The local weights obtained were converted to global weights in accordance with the hierarchy. The global weights of the criteria are presented in Table 11.3.

Thanks to credal ranking, it was determined at which confidence level the criteria were superior to each other. As an example, the credal ranking graph for the main criteria is presented in Fig. 11.8. According to the graph, while criterion B is superior to criterion A at a 93% confidence level, it is superior to C and D at a 100% confidence level.

Table 11.2 Input-based consistency ratios

	Main criteria	A1–A5	B1–B4	C1–C4	D1–D3
Expert-1	0.0000	0.0714	0.0500	0.0238	0.0238
Expert-2	0.0667	0.0238	0.0667	0.0238	0.0000
Expert-3	0.0500	0.1000	0.0000	0.0238	0.0500
Expert-4	0.0500	0.0000	0.0500	0.0000	0.0500
Expert-5	0.0500	0.2000	0.1500	0.0000	0.0500
Expert-6	0.0500	0.1500	0.0238	0.0238	0.0000

Table 11.3 Global weights of criteria

Criteria	Global weight	Criteria	Global weight
A1	0.0653	B4	0.1270
A2	0.1125	C1	0.0255
A3	0.0429	C2	0.0633
A4	0.0568	C3	0.0238
A5	0.0253	C4	0.0254
B1	0.0869	D1	0.0827
B2	0.1516	D2	0.0204
B3	0.0617	D3	0.0290

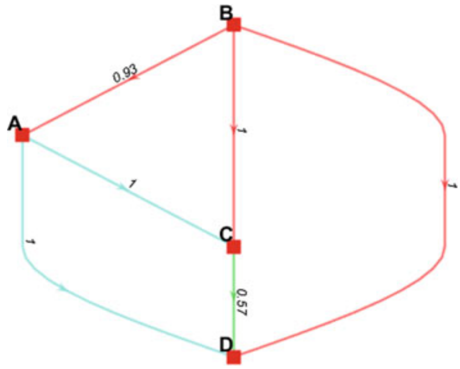

Fig. 11.8 Credal ranking visualization for main criteria

Integration of Criterion Weights to GIS Environment

After determining the criteria weights by Bayesian BWM, maps were produced for each criterion according to the relevant criterion feature to be used as a basis for each criterion. The produced maps are shown in Figs. 11.4, 11.5, 11.6 and 11.7. These maps were categorized in accordance with the criterion feature. These maps and calculated weight values were then combined in a GIS environment. In this context, by a ArcGIS tool of "Weight Sum" tool, the final weight values were entered into the produced maps, the output map was produced. Weighted Sum works by multiplying the designated values for each input raster by the specified weight. It then sums (adds) all input rasters together to create an output raster [65]. The areas shown in orange and red color on the output map are the areas with high avalanche risk. Green-colored areas indicate areas with low avalanche risk (Fig. 11.9).

In the output map produced within the scope of the study, the northern regions of Tunceli province, where the elevation is high, are identified as the riskiest places. These areas correspond to the region's high areas, high slope values, and rugged terrain. The climatic conditions of the region are much harsher than in the south. The north of the region is the region where the first snowfall falls. Therefore, the northern regions of the study area provide suitable conditions for possible avalanche formation conditions.

In the study area, certain areas of the Pülümür district and the northern regions of the Ovacık district constitute the risky areas. In these areas, the risk is relatively high, especially around the rural settlements and the transport routes to these areas. In addition, according to the study output, the highway, which is the main transport route between Erzincan and Tunceli, and its surroundings are also among the risky areas. Certain areas on this highway have been designated as avalanche and landslide zones, and avalanche tunnels have been constructed in some sections (Fig. 11.10). The avalanche incidents in Tunceli generally take place in the regions mentioned above.

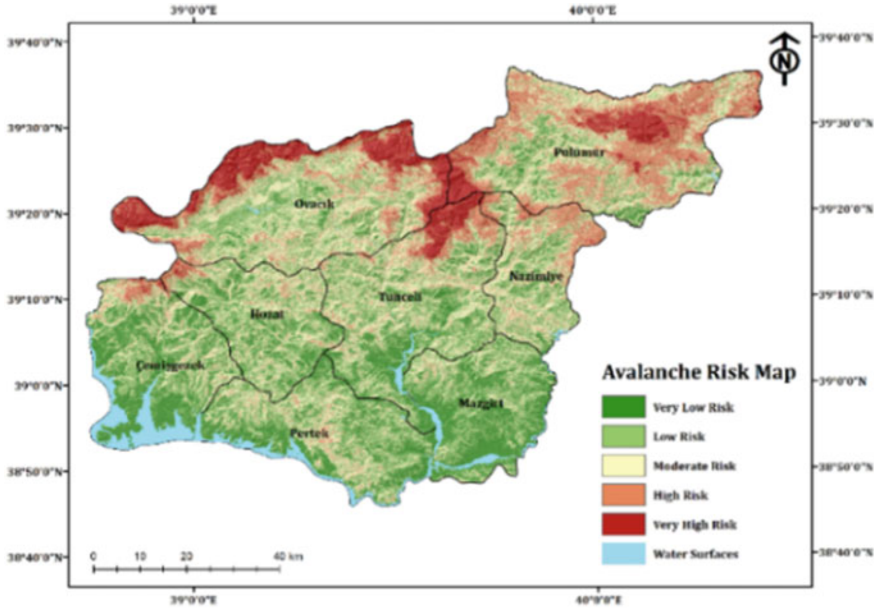

Fig. 11.9 Avalanche risk map for Tunceli

Fig. 11.10 A view of an avalanche on the Erzincan-Tunceli highway [66]

Discussion

Avalanches occurring due to various situations (topography, meteorology, social activities, etc.) are common natural phenomena. In this study, criteria including topographic and meteorological conditions and social conditions were evaluated. The most important criterion among the criteria evaluated within the scope of the study is the average precipitation in December, January, and February, with a global weight value of 0.1516. It is followed by the slope (0.1125), NDSI (0.1270), and means temperature in December, January, and February (0.0869) in December, January, and February, respectively. The least essential criterion is land use, with a global weight value of 0.204. Then, the distance to the stream (0.238), lithology (0.253), distance to the residential areas (0.254) come (Table 11.3). Accordingly, considering the global weights of the criteria evaluated by experts in the study, it is seen that topographic and meteorological factors are seen as the most important in avalanche formation. In many avalanche risk studies, topographic and meteorological factors such as slope, snowfall, aspect, and curvature come to the fore [11, 15, 33, 39, 50]. Therefore, topographic and metrological factors have come to the fore in avalanche risk assessments in the studies examined in the literature in this study.

Conclusion

It is almost impossible to predict the location and time of the snow avalanche. Avalanche is one of the natural disasters that cause loss of life and property. It is necessary to determine the areas with avalanche threat potential in advance and to take the required precautions to intervene in the relevant regions quickly and effectively to minimize the damages of this disaster. A geographical tool is needed to assess the effect of parameters that may cause an avalanche and combine the relevant regions' characteristics to determine the areas with avalanche risk.

For this reason, in this study, Bayesian BWM, which is one of the MCDM methods and can combine the opinions of many experts to minimize the loss of information, was used to weigh the parameters. The region's geographical features were mapped by GIS, and the criteria were combined with the weights obtained from Bayesian BWM.

This proposed approach provides many benefits for the managerial and society. The proposed method can be a reference in infrastructure investments, disaster planning, and risk reduction studies. It provides the opportunity to increase awareness of avalanche disasters in society and to address the avalanche risk in the daily plans of the community.

In this study, risky areas of the Tunceli province in terms of the avalanche were determined by using MCDM-GIS in an integrated manner. According to the analysis outputs, the high northern regions of the province are very high-risk areas. Especially the high parts of Pülümür and Ovacık districts are very risky. Rural settlements in these regions and the surroundings of the access roads provided to these regions are the areas where avalanche risk is present.

This study has the potential to be improved in many ways. A more effective avalanche susceptibility map can be created by making these improvements in future studies. Study limitations include using a certain number of criteria (16), conducting fieldwork in a certain area, and using a certain method. Also, this proposed model presents a static structure that does not consider the relationship between avalanche parameters and triggering each other. The study does not address human-induced states that would trigger an avalanche. Elimination of these limitations in future studies will improve this study, and deficiencies can be eliminated.

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Chapter 12
Snow Avalanche Hazard Prediction Using the Best-Worst Method—Case Study: The Šar Mountains, Serbia

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Abstract Snow avalanches are one of the most frequent natural hazards in high mountain regions. In this study, a map of the susceptibility of the Šar Mountains to snow avalanches was determined. The study area is located in the southern part of Serbia, which has the Status of a National park. Geographic information systems (GIS) and remote sensing are used to analysis and cartographical presentation of nine the most important elements of natural conditions which have an influence on avalanche development. Then, by applying the best-worst method (BWM) for each of the criteria was given a weighting coefficient depending on its importance for the avalanche occurrence. A synthetic map of snow avalanche susceptibility was created by processing geospatial data in the GIS software. The obtained results show that high susceptibility covers 16.9% of the territory, while 10.7% of the total area is very highly susceptible. The final results may be useful to decision-makers, local self-governments, emergency management services, and mountaineering services to mitigate human and material losses from snow avalanches. This study is the first to use the BWM methodology for snow avalanche hazard analysis.

Keywords Natural conditions · Snow avalanche · Best-Worst method · GIS · Environment

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Introduction

Snow avalanches can be defined as natural disaster caused by the release, movement, and accumulation of large masses of snow on mountain slopes under the influence of gravity. Avalanches are a natural hazard that often causes great human and material losses in high mountain regions worldwide [1–3].

According to the European Avalanche Warning Service [4], 2148 people have lost their lives because of snow avalanches in Europe in the last 20 years. The first research on the subject of snow avalanches was conducted at the beginning of the eighteenth century in the territory of Switzerland. The head of the Swiss Forestry Inspectorate, Johann Coaz (1822–1918), made a major contribution to establishing awareness of the danger of snow avalanches in Switzerland and other countries [5].

Globally, avalanches are not among the deadliest natural disasters, but they have significant destructive potential in several mountainous countries in temperate climate zones [6, 7]. Furthermore, avalanches can induce major consequences for economic activity in developed and developing countries, as they can seriously disrupt rail and road traffic.

Skiers, adventurers, and extreme athletes are often responsible for the occurrence of avalanches. Anthropogenic activities in mountain regions, such as illegal deforestation, residential development, and the construction of winter sports facilities, are leading to an increasing need to identify avalanche-prone areas and to adopt protection measures [8, 9].

In developed countries, systems and methods have been developed over the past 25 years to provide an overview of the geospatial distribution of snow avalanches [10–12]. However, accurate prediction of the location and timing of avalanches is still not completely possible due to the complex physical processes that occur in avalanches. In the Republic of Serbia, very few studies deal with the geospatial distribution of avalanches.

In recent years, multi-criteria decision–making methods have played an important role in the spatial modeling of natural hazards [13–15]. The reason for their application is the large number of used criteria, which are significant for the analysis of natural and anthropogenic conditions.

From the multi–criteria decision–making models, researchers have so far used the AHP method for geospatial modeling of snow avalanches in Turkey, India, and Serbia [16–20]. Numerous studies on snow avalanches using GIS, fuzzy logic, multi-criteria analysis and machine learning models have been published in recent years.

Precise modeling of snow avalanches is possible today only using different GIS software. GIS tools enable a detailed spatial representation of natural phenomena and processes on the topographic surface [21–24]. Arumugam et al. studied snow meteorological data in the Western Himalayas for avalanche risk forecasting using GIS, fuzzy logic and a Bayesian network [25]. Yariyan et al. in Iran assess terrain vulnerability to snow avalanches using GIS, multi-criteria analysis and hybrid machine learning models [26]. Iban and Bilgilioglu investigate the sensitivity of the terrain in northern Italy to the occurrence of snow avalanches using different machine learning classifiers (Random Forest, Gradient Boosting Machines, AdaBoost, etc.) [27].

The combination of BWM and GIS represents an innovative approach to snow avalanche prediction. This is the first study that use the BWM method, and the aim of the research is to identify the most susceptible areas and propose environmental protection measures. The obtained results will be of great use to decision-makers at the local and regional level regarding adopting and implementing various measures to protect the population and infrastructure from snow avalanches.

Material and Methods

Study Area

The Šar Mountains are located in the extreme south of Serbia and partially cover the territories of North Macedonia and Albania. Although 228 km^2 of the area is officially protected, the plan is to protect the entire study area (about 969 km^2) (Fig. 12.1). Administratively, it fully or partially covers the territories of the municipalities of Kačanik, Štrpce, Suva Reka, Prizren, and Gora. In 1993, Šar Mountains was declared a national park.

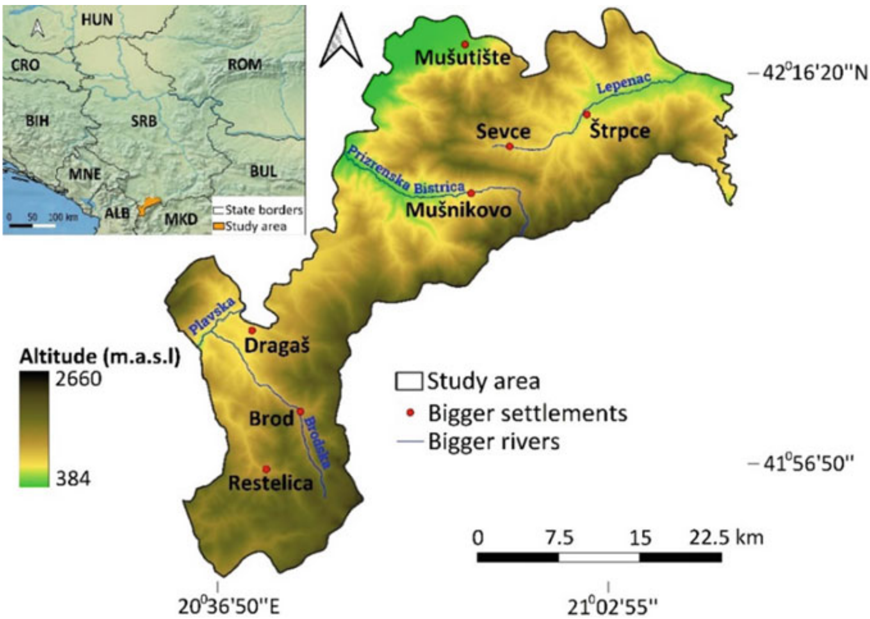

Fig. 12.1 Geographical position of the Šar mountains

This area represent one of the most significant ecological points on the Balkan peninsula, with 1800 plant species (of which 339 are endemic to the Balkan and 18 are endemic to the Šar Mountains), 147 species of butterflies, 200 species of birds and about 45 species of reptiles and amphibians [20].

The Šar Mountains are the highest mountain area in Serbia, with an average altitude of study area 1421 m and an average slope of 18°. Due to the existence of glaciers during the Pleistocene, specific glacial landforms are represented today—cirques, glacial valleys, and moraines [28].

Climatic properties differ significantly due to the vertical relief. The highest mean annual air temperature (>12 °C) and the lowest precipitation (<800 mm) were measured in the northwestern part of the investigated area (near the city of Prizren), which can be explained with the Mediterranean influence that reaches the valley of Beli Drim River from the Adriatic Sea. Terrains with the lowest air temperature (<1 °C) and the highest precipitation (>1800 mm) are characterized by alpine climate, and these zones are above 2000 m, where the snow cover often lasts over 200 days a year. During the winter months, the average maximum depth of the snow cover at altitudes above 1700 m ranges from 150 to 200 cm [20].

A large amount of snow cover and temperature inversions during the winter months cause the formation of different types of snow layers. During the formation of the weak layer, a small amount of pressure caused by the winter sports participants is enough to trigger a snow avalanche. In this case, the local population living on high-risk terrain and tourists who ski off-piste at the Brezovica ski center are at risk.

Methodology

The best-worst method (BWM) usually presents decision criteria weight coefficient. The BWM is suitable for determining kriging and semi-kriging distributions in space and can minimize data errors [29].

The linear BWM was used in this study [30]. The first step is to define decision criteria and determine the number of data entered [31]. In the second step, decision makers need to select the best and worst criteria according to their preferences from the selected set of relevant criteria (C_1, C_2, …, C_n). In the third step, decision makers assign numerical values between 1 and 9 to the best criterion in relation to all other criteria. This can be represented by a vector Best-to-Others:

$$A_B = (a_{B1}, a_{B2}, \ldots, a_{Bn}) \text{ where } a_{Bj} \text{ is} \tag{12.1}$$

the preference of the best criterion (B) over over criterion j.

In the fourth step, in order to express the preference according to the worst criterion, the decision makers assign values between 1 and 9 [30–34]. This results in the following Others-to-Worst vector:

$$A_W = (a_{1W}, a_{2W}, \ldots, a_{nW})^T, \tag{12.2}$$

where: a_{jW} is the preference of the criterion j over the worst criterion (W).

In the fifth step, the optimal weights (w_1^*, w_2^*,…,w_n^*) are calculated, where we have to find a solution by which the maximum differences of $|w_B - a_{Bj}w_j|$ and $|w_j - a_{jW}\,w_W|$ should be minimized. This can be explained by the following mathematical model:

$$\min \max_j \left\{ \left| w_B - a_{Bj} w_j \right|, \ \left| w_j - a_{jW} w_W \right| \right\} \tag{12.3}$$

such that

$$\sum\nolimits_j wj = 1, \tag{12.4}$$

$$w_j \geq 0, \ \text{for all } j. \tag{12.5}$$

This model is equivalent to the following model:

$$\min \xi .\text{such} \quad \text{that}$$

$$\left| w_B - a_{Bj} w_j \right| \leq \xi, \ \text{for all } j, \tag{12.6}$$

$$\left| w_j - a_{jW} w_W \right| \leq \xi, \ \text{for all } j, \tag{12.7}$$

$$\sum\nolimits_j w_j = 1, \tag{12.8}$$

$$w_{\text{j}} \geq \ 0, \ \text{for all j}. \tag{12.9}$$

Solving this model results in the optimal weights. In the sixth step, the consistency ratio (CR) is calculated based on the formula [32]:

$$CR = \max CR_j, \text{where} \tag{12.10}$$

$$CR_j^I = \begin{cases} \frac{|a_{Bj} \times a_{jW} - a_{BW}|}{a_{BW} \times a_{BW} - a_{BW}} & a_{BW} > 1 \\ 0 & a_{BW} = 1 \end{cases} \tag{12.11}$$

The value of the obtained weighting coefficients is finally multiplied by the values of the thematic maps in GIS software to obtain a synthetic map and final values.

Selection of Criteria by Importance

Normalized difference snow index (NDSI)—the main factor for the formation of avalanches is the presence of snow cover in the largest possible volume. NDSI was obtained by processing satellite images from the Sentinel-2 satellite, with a spatial resolution of 10 m [35]. For this purpose, the contents of satellite images from the period January and February 2019–2022 were analyzed. NDSI is obtained by the formula [36]:

$$\text{NDSI} = \frac{(\text{Green} - \text{SWIR})}{(\text{Green} + \text{SWIR})}, \tag{12.12}$$

where: Green is the green spectral band, while SWIR is the shortwave infrared spectral band. The highest values (> 0.4) of the index indicate areas covered with snow, while negative values show territories without snow cover [37]. Within the research area, values from −0.44 to 0.92 were found.

Slope (S)—a relief characteristic necessary for the formation of all types of snow avalanches. The degree of action of gravity and friction, as well as the shear strength that occurs when an avalanche is triggered, depends on the slope of the terrain. The avalanche flows mostly downstream from the area of origin through a track characterized by terrain with creek beds and gullies [38]. The data for the terrain slope are derived from the digital elevation model (DEM), and the research area is characterized by a slope of 0–80.8°. DEM with a spatial resolution of 12.5 m was obtained from the Alaska Satellite Facility (ASF) [39].

Normalized difference vegetation index (NDVI)—a parameter that shows the type of vegetation. NDVI was obtained by processing Sentinel-2 satellite images from July and August 2021 [35]. It is calculated according to the formula [40, 41]:

$$NDVI = \frac{(NIR - RED)}{(NIR + RED)}, \tag{12.13}$$

where: NIR is the near-infrared spectral band; RED is the red spectral band. Negative values indicate the presence of water surface. Values in the range 0–0.8 indicate grassy, agricultural areas and settlements. Forests cover the area indicated with values above 0.8. Grasslands (meadows and pastures) are most suitable for the formation and movement of avalanches, while forests are an obstacle and mitigate the effects of avalanches.

Wind exposition index (WEI)—an important climatological parameter that indirectly indicates where snow is eroded (windward areas) and where it mainly accumulates (leeward areas). Windblown snow is one of the main causes of snow avalanches. WEI was calculated in QGIS based on DEM. Values below 1 indicate wind shadowed areas whereas values above 1 indicate areas exposed to wind. On the Šar Mountains, WEI is 0.76–1.31.

Aspect (A)—the terrain aspect has a strong influence on insolation, temperature gradient, snow accumulation, and the dynamics of snow melting. Although snow avalanches occur in all aspects, on the territory of the Šar Mountains, it was established that the snow layers on the northern sides are very unstable [14]. Therefore, data for exposure analysis were obtained by processing DEM.

Elevation (E)—is a significant factor that can affect the amount of precipitation, temperature, wind speed, and solar radiation [42]. On the Šar Mountains, the altitude varies from 384 to 2660 m.

Temperature (T)—in this case, the average annual air temperature for the Metohija region is given based on the following formula [43]:

$$T = -0.0050 \cdot H + 13.84, \tag{12.14}$$

where: T is the average annual air temperature, and H is the digital elevation model. The snow cover retention is longer in areas with low air temperature. As the temperature rises, snow melting is more intense. The mean annual temperature of 0.51–11.7 °C was recorded on Šar Mountains.

Plan curvature (PC)—is measured perpendicular to the direction of maximum slope. In this case, a positive value indicates a convex surface. Conversely, a negative plane curvature indicates that the surface is concave, while a value around zero indicates a flat surface. Surfaces with concave plan curvature are more susceptible to the formation of snow avalanches [7, 44]. The data were generated from the DEM.

Distance from stream (DFS)—hydrological factor that can be used in the analysis of soil moisture and subterranean runoff dynamics. If the area is close to the watercourse, chances of forming wet snow avalanches increase. To obtain this parameter, river flows from 1:25,000 topographic maps were digitized [45], and then the DFS was obtained in GIS by processing DEM and watercourses in QGIS-SAGA plugins [46] (Fig. 12.2).

After processing the suitability maps, the reclassification of the values of natural conditions was approached. Susceptibility classes are ranked based on the value of natural conditions: 1-very low; 2-low; 3-medium; 4-high, and 5-very high susceptibility (Table 12.1).

In order to apply the BWM method, it is necessary to create a hierarchy of priorities in the matrix. In this case, the best criterion is the NDSI, while the worst is the DFS. The experts' opinions were obtained based on the geometric mean and the final preferences are shown. Based on previous studies in the world, opinions and experiences of experts in the fields of geography, environment and mathematics, the values in the matrix were assigned (Table 12.2).

The use of two pairwise comparisons vectors formed based on two opposite references (best and worst) in a single optimization model could mitigate possible anchoring bias that the decision-makers might have during the process of conducting pairwise comparisons [47]. By processing the numerical values in the matrix, the weight coefficients for each criteria were obtained (Table 12.3).

The pairwise comparison consistency level is acceptable. The associated threshold is 0.3662, while the consistency ratio value is 0. The consistency ratio shows that the values in the matrix are perfectly consistent.

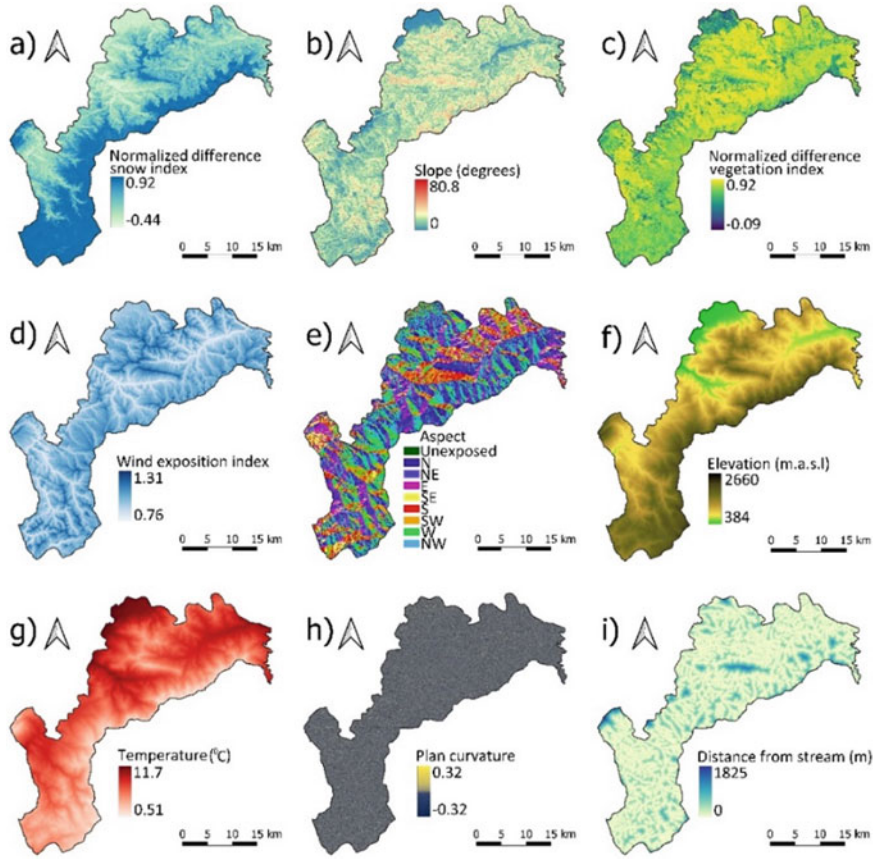

Fig. 12.2 Suitability maps of the Šar mountains. **a** Normalized difference snow index; **b** Slope; **c** Normalized difference vegetation index; **d** Wind exposition index; **e** Aspect; **f** Elevation; **g** Temperature; **h** Plan curvature; **i** Distance from stream

Results and Discussion

By processing nine criteria in GIS software and applying BWM, a synthetic threat map with a spatial pixel resolution of 12.5 m was created (Fig. 12.3). The geospatial distribution of snow avalanches on the territory of the Šar Mountains shows that 197.23 km^2 (20.4% of the total area) are at very low susceptibility. These are relatively flat areas at lower altitudes, with small amounts of snowfall during the year.

These are mostly settlements and agricultural plots that are unexposed or have a southern aspect. Low susceptibility has the highest percentage (32.86%) and covers an area of 317.64 km^2. The medium susceptibility covers an area of 185 km^2 (19.14%). Although it covers almost 1/5 of the total area, according to previous studies, snow avalanches have not occur in these areas. About 16.9% of the territory

Table 12.1 Reclassification of the value of natural conditions

Criteria	Values	Rank	Area (km^2)	Percentage (%)
NDSI	−0.44–0.4	1	516.33	53.40
	0.4–0.45	2	27.66	2.86
	0.45–0.5	3	24.23	2.51
	0.5–0.7	4	84.01	8.69
	0.7–0.92	5	314.76	32.55
Slope (°)	0–10	1	150.12	15.50
	10–20	2	378.66	39.08
	20–30 & 55–80.8	3	322.16	33.25
	30–35 & 45–55	4	75.91	7.84
	35–45	5	41.96	4.33
NDVI	−0.09–0	1	0.04	0.004
	0–0.3 & 0.8–0.92	3	449.73	46.42
	0.3–0.8	5	519.06	53.58
WEI	1–1.31	3	580.01	59.87
	0.76–1	5	388.80	40.13
Aspect	Unexposed	1	6.93	0.72
	S	2	88.84	9.17
	SE, SW	3	185.32	19.13
	E, W	4	228.72	23.61
	NE, NW, N	5	459.01	47.38
Elevation (m)	384–500	1	11.10	1.15
	500–1000	2	143.04	14.76
	1000–1500	3	378.07	39.02
	1500–2000	4	291.88	30.13
	2000–2660	5	144.73	14.94
Temperature (°C)	9–11.7	1	135.00	13.93
	7–9	2	295.36	30.49
	5–7	3	261.68	27.01
	3–5	4	206.76	21.34
	0.51–3	5	70.02	7.23
Plan curvature	0.005–0.32	3	286.75	29.60
	−0.005–0.005	4	406.57	41.97
	−0.32–-0.005	5	275.50	28.44
Distance from stream (m)	1600–1825	1	17.87	1.84
	1200–1600	2	4.40	0.45
	800–1200	3	22.37	2.31
	400–800	4	148.80	15.36
	0–400	5	775.38	80.03

Table 12.2 Determination the preference of all the criteria

Best to others	NDSI	S	NDVI	WEI	A	E	T	PC	DFS
NDSI	1	2	3	4	5	6	7	8	9
Others to the worst	NDSI	S	NDVI	WEI	A	E	T	PC	DFS
DFS	9	8	7	6	5	4	3	2	1

Table 12.3 Weight coefficients for each criteria

Criteria	NDSI	S	NDVI	WEI	A	E	T	PC	DFS
Weights	0.315	0.192	0.128	0.096	0.077	0.064	0.055	0.048	0.027

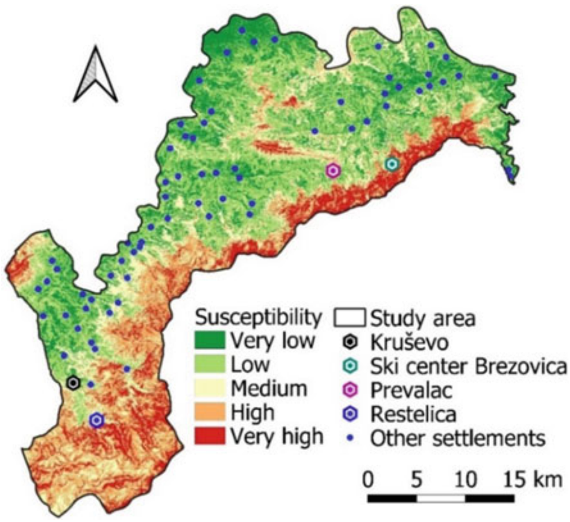

Fig. 12.3 Snow avalanche hazard map

has high susceptibility, covering an area of 163.41 km^2. The results show that the western part of the settlement Kruševo is highly vulnerable. Very high susceptibility covers 10.7% of the study area, or 103.4 km^2.

Highly susceptible areas are characterized by a set of specific natural conditions that trigger the occurrence of avalanches. These are areas exposed to the north, where snow is present in large amounts during the winter, partly because of the high altitude and partly because of the lee sides where the snow accumulates. Near watercourses, with a higher degree of terrain inclination and at low temperatures, weak layers form in the snow, and it's stability decreases. Combined with the concave plan curvature, preconditions are created for the formation of snow avalanches, which can occur naturally and anthropogenically. In the area of the settlements Restelica, Prevalac, and the ski center Brezovica, a very high level of vulnerability, partial or total, was found.

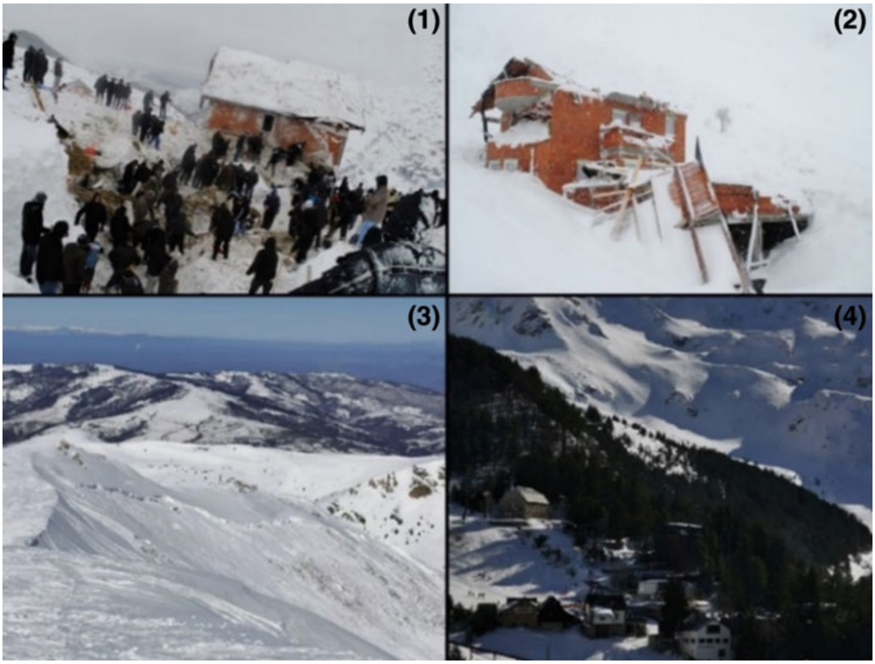

Fig. 12.4 Snow avalanche accident in Restelica in 2012 (1, 2). Slab avalanche (3) and endangered environment (4) in the Brezovica ski center [20, 48]

In February 2012, a snow avalanche killed ten people and buried 11 houses in Restelica (Fig. 12.4) [49]. Snow avalanches occur at the Brezovica ski center every year, threatening the lives of skiers who ski off-piste, as well as residential buildings.

In order to protect the local population and the existing infrastructure, it is necessary to implement adequate measures to prevent snow avalanches (administrative, organizational and biological). The most common protective measures applied in developed countries include artificial avalanche triggering, avalanche zoning, afforestation, and structural measures [50]. Artificially triggering an avalanche with explosives is an economically justified procedure that prevents the occurrence of large avalanches. Avalanche hazard mapping and land-use planning are applied throughout many countries. As a biological measure, the afforestation of risky slopes is recommended [51]. Forest ecosystems increase the stability of the snow cover by regulating the microclimate and mitigating large temperature gradients in the snow and ground-level air layer that are responsible for the formation of weak layers. For protecting buildings, one of the measures is constructing supporting steel structures and stone walls that slow down and prevent avalanches [52].

Two methods have been used in the studies dealing with the geography of avalanches on the Šar Mountains. First, for the territory of the municipality of Štrpce, the AVAPI index was used to determine the susceptible areas, according to which 9.1 km^2 of the area is suitable for the occurrence of avalanches [14]. In this case, a small number of criteria (5) were used, and a rough classification of the final values was made. The second study covers the Šar Mountains area and links avalanche prediction with the AHP method. The application of 14 criteria has shown that 20% of the area is highly susceptible by avalanches [20]. Although a large number of criteria were used, the resolution of the synthetic map of vulnerability is 25 m.

Previous studies on snow avalanche modeling show that of the multi-criteria analysis methods, AHP was mainly used. In Turkey, the AHP method was applied for Bitlis Province, where five criteria were processed. With a spatial resolution of 25 m, it was determined that 36.5% of the investigated study area is highly susceptible to avalanches [16]. In the territory of Van province, the final results show, with an accuracy of 30 m, that 5% of the area is high susceptible of avalanches, and 2% is very high susceptible [18]. In the Western Indian Himalaya (Siachen region) using the AHP method, it was determined that 12.32% of the territory is very highly susceptible to snow avalanches [17]. In addition to the MCDM approach, machine learning models play an significant role in snow avalanche prediction. For example, applying a support vector machine for the Parlung Tsangpo catchment (China) determined that 10.1% of the area is highly threatened by snow avalanches [2]. Very high susceptibility is represented in 12.1% of Darwan Watershed territory (Iran), obtained by the random forest model [6].

The application of the Best-Worst Method in the prediction of snow avalanches has certain advantages over the AHP method [53]:

- For BWM needs less pairwise assessment. AHP needs n(n–1)/2 comparisons while BWM deals with 2n–3 comparisons;
- The results obtained using BWM are more reliable due to higher consistency percentage;
- Unlike other models of multi-criteria analysis that require fractural numbers, BWM methods only use integers.

BWM is one of the most effective methods that simultaneously provides the possibility of checking the consistency of given pairwise comparisons.

The study's limitation is reflected in need for more inventory of snow avalanches and spatial resolution of geospatial data. In the future studies, the dynamical analysis supported by LIDAR data may provide more respectable results. Future avalanche research should combine GIS with multi-criteria analysis methods and machine learning models for comparative data analysis. After that, it is necessary to validate the results through field research so that the results are complete.

Conclusion

Snow avalanches are a natural phenomenon that occurs every year in the winter months in the high mountain regions of the Šar Mountains. According to previous records, since the beginning of the nineteenth century, over 100 people have died in this area as a consequence of avalanches. In addition to human losses, the avalanches also had a destructive impact on residential buildings and roads. This study analyzed nine natural conditions using GIS and remote sensing. By applying the BWM and assigning weighting coefficients, a hierarchy of criteria was created based on priorities. The results of the complex vulnerability analysis show that 16.9% and 10.7% of the studied area are high susceptible and very high susceptible, respectively.

Through satellite observation and interpretation of the synthetic map, it was determined that the settlements Kruševo, Restelica, Prevalac, and the ski center Brezovica are threatened by snow avalanches. The results can be used by local authorities, mountain rescue services, and emergency management services for adopting environmental protection measures from the consequences of snow avalanches. Furthermore, the research concept and applied method can be a starting point for studying snow avalanches in other parts of Serbia and the world, where similar natural conditions prevail.

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Chapter 13
Assessment of Renewable Energy Development Strategies with BWM-Grey TOPSIS

Hamidreza Fallah Lajimi, Forough Mohammadi, and Zahra Jafari Sorouni

Abstract The development and use of renewable energy is the undeniable necessity of societies to achieve sustainable development and economic-environmental goals. Considering Iran's strategic position and the possibility of exploiting all kinds of sustainable energy sources, the above research seeks to investigate and provide strategies to reduce the obstacles to the development of renewable energy in conditions of uncertainty. In the qualitative part, after identifying the obstacles and strategies to reduce those obstacles in the direction of the development of renewable energy, customization of options has been done through interviews with experts. The quantitative part in the first step includes the use of the Best-Worst Method for weighting the obstacles, and the second step of the quantitative method includes the ranking of strategies with the grey TOPSIS technique. Based on the results of adjusting the structures, trade and foreign direct investment and the allocation of subsidies and tax support are of higher priority to reduce the political-legal, industrial, etc. obstacles.

Keywords Renewable energy · Best-Worst method · Grey TOPSIS

Introduction

The importance of renewable energies compared to fossil fuels is being overtaken due to increasing energy demand and environmental requirements. Multi-generation systems use one or more energy sources and produce several useful outputs [1]. In these circumstances, global economies are seeking to achieve the Sustainable Development Goals (SDG) program, and regardless of whether the country is developing or developed, they focus on renewable energy sources for clean and sustainable economic growth, and their goal is to reduce carbon emissions for improvement of climatic conditions [2]. This approach has caused the necessity of energy transfer and

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increasing the efficiency of energy consumption, and at the same time, the unequal distribution of the efficiency of various types of renewable energies [3]. On the other hand, nowadays the World Bank has identified and introduced energy efficiency as a critical factor for achieving sustainable development goals, whose role is vital in limiting CO_2 emissions. Therefore, in recent years, the importance of identifying the factors that determine energy efficiency has been intensified by environmentalists [4]. This is despite the fact that countries are different in terms of socioeconomic development, population growth, and energy consumption. Many countries are still dependent on fossil fuels for adequate energy supply, while some have made significant progress in transitioning to renewable/sustainable energy sources [5]. Iran, which has abundant renewable and non-renewable energy resources, especially non-renewable resources, nonetheless faces challenges such as air pollution, climate change, and energy security. As a leading exporter and consumer of fossil fuels, it is striving to use renewable energy as part of its energy combination in order to achieve energy security and sustainability. Due to its favorable geographical features, Iran has diverse and accessible renewable resources, which are suitable alternatives to reducing dependence on fossil fuels [6]. But in Iran, the extractable gas resources are so extensive that it is very difficult to justify the use of more expensive energy sources for the near future. Also, the country's dependence on fossil fuels to meet local energy needs is known as an obvious environmental concern. Currently, reducing the use of fossil resources is not a challenge. However, in the near future, this reduction may be significant at the national policy level, especially as alternative sources of oil. Perhaps for Iran, the decision to use renewable energy is more than an absolute necessity to diversify electricity production. From June 2009 to the beginning of May 2016, three billion and 132 million kilowatt hours of energy have been produced from renewable sources, and this amount of electricity production from renewable energies can reduce the emission of about two million and 161 thousand tons of greenhouse gases. In addition, this amount of new energy production has reduced 889 million cubic meters of fossil fuel consumption in Iran, which is one of the main factors of air pollution in the country, and more than 689 million liters of water have been saved. Also, 416 megawatts of renewable power plants are under construction in the country, and the installed capacity of new energy in the country has reached 724 megawatts. The analysis of the figures of this sector shows that 44% of the country's renewable power plants are solar, 40% are wind, 13% are small hydropower plants, 2% are heat recovery and 1% are biomass, and is expected that soon Iran will be able to generate a significant percentage of its electricity from renewable energy. Iran has a high climate diversity, which has increased the potential of using renewable energy [7].

Since the development of the renewable energy industry is an important step for countries to respond to the growing demand for energy, the gradual replacement and elimination of limited fossil resources, and the improvement of environmental conditions, in Iran, the Organization of Renewable Energy and Energy Efficiency by merging the Organization of New Energy and The Energy Efficiency Organization was formed. As a result of the structural changes that took place, green technology was added to the energy portfolio of the Ministry of Energy to reflect the increasing emphasis on sustainable and renewable energy options [6]. Despite all the research and actions, the efficiency of executive projects, and the utilization of resources and achievements in this field are still low due to obstacles such as emphasis on the development of conventional energy, and the lack of sufficient government policies in the field of renewable energy development, and it was accompanied by the lack of sustainable energy security and adequate environmental policies. Moreover, the studies carried out in the field of investigating the obstacles to the use of renewable energy in Iran, have lacked the necessary integrity and included case studies. Accordingly, this research seeks to identify the obstacles to the use of renewable energy in Iran and provide solutions to solve them and ultimately increase the efficiency of implementing renewable energy projects in Iran.

In this research, after the definition of the concepts, the previous studies to identify obstacles to the development of renewable energy and strategies to overcome them were reviewed. In the next steps, based on the research methodology, the obstacles and strategies were ranked using BWM and Grey TOPSIS techniques.

Literature Review

Renewable Energy

Renewable energy describes specific types of energy production. In politics, business, and academia, renewable energy is often recognized as a key solution to eliminate the global climate challenge. Meanwhile, the concept of renewable energy dates back to the early 1900s, years before the start of the global environmental crisis. Today, by planning and focusing on the development and exploitation of renewable energy sources as an alternative to environmentally destructive energy sources such as coal and nuclear energy, the goal of societies is decentralized and small-scale energy production, including renewable energy sources [8].

Renewable energy (RE) is the key element of sustainable, environmentally friendly, and cost-effective electricity production. The official report of the International Energy Agency indicates that since 2019, the demand for the use of fossil fuels to produce electricity has decreased along with the increase in the use of renewable energy to meet global energy needs. Research on RE technologies is continuously increasing to improve the production performance of RE, especially in terms of energy conversion efficiency [9].

Renewable energy technologies such as solar, wind, biomass, geothermal, and hydrogen energies have been proposed to generate energy to overcome the current environmental crisis [9–12].

Solar Energy

Solar energy (SE) is the radiation-ionizing energy that is emitted from the sun and has been widely used among countries [13]. To improve and increase SE conversion efficiency, most researchers investigate various technologies to optimize SE system design [14]. Also in this field, researchers are optimizing energy conversion costs, to optimally reduce environmental impacts [15]. There are two main types of SE systems: solar thermal energy and photovoltaic energy, which are commonly implemented in developing and developed countries [9].

Wind Energy

While the wind power system is highly popular among all types of renewable energy for use due to the high fluctuations and intermittent ness of wind power, it faces a great challenge to increase the efficiency of the system. The conditions of wind reduction, it is considered to ensure the optimal performance of the system and maintain the economic goals from the perspective of the total cost [16]. In this system, conventional generators are equipped with Power System Stabilizers (PSS) to reduce fluctuations caused by humidity disturbances [17]. Currently, it is estimated that only 5% of the world's wind energy can be used to meet the current energy needs around the world. Wind energy is mostly available in the oceans. Oceans cover 71% of the Earth and the wind is faster in open water due to fewer obstacles. According to the report of the World Wind Energy Council, the installed capacity of wind power plants increased by 27% from the end of 2006 to the end of 2007. Techniques such as net present value, profitability index, internal rate of return, etc. have also been used to evaluate the exploited projects [18].

Biomass Energy

Biomass energy, which refers to the exploitation of any available plant material such as crops, is an alternative to oil that is used to meet almost all energy needs such as electricity generation, adequate heat supply, and advanced energy sources for an industrial plant. Biomass is used in various aspects including food, building materials, and fuel energy. According to studies, this renewable energy source is almost a main factor in reducing inflation and increasing job opportunities in rural areas. In addition, bioenergy can be converted into electrical energy, fuel, and active thermal radiation [19].

Geothermal Energy

Renewable energy sources such as wind energy and solar energy have increased their capacity in recent years and this trend is expected to continue. Wind and sun have fluctuating energy production, which can be overcome only by energy storage and can be brought to reliable operation. However, geothermal energy is an intermittent and potentially inexhaustible resource that can be used for both heating and cooling. In this system, subsurface layers at different depths can be targeted, while there is no classification and default for these layers and depths. With the help of tools such as deep drilling, various drilling equipment, fluid temperature, and the use of heat pumps, this challenge can be tackled [20].

Hydrogen Energy

The use of hydrogen energy sources has requirements such as safe, compact, light, and affordable hydrogen storage. The hydrogen gas storage system under pressure as well as the liquid state storage system of this gas creates safety problems and high costs for applications. Therefore, despite these challenges, the future goals for the hydrogen economy will not be met. Solid-state storage systems based on metal hydrides have great potential for storing hydrogen in large quantities in a completely safe, compact, and repeatedly reversible manner. However, the techno-economic feasibility of hydrogen storage systems has not yet been realized, as none of the current metal hydrides meet all the necessary criteria for a hydrogen economy and have problems such as low hydrogen storage capacity, slow kinetics, and unacceptable hydrogen absorption temperatures [21].

Obstacles and Strategies for the Use and Development of Renewable Energy

For many years, the correlation between economic growth and energy consumption has been a concern of researchers. The literature review reports a positive correlation between these variables. Of course, there are conflicting views from researchers regarding causality [22–28]. However, there are still challenges in developing and exploiting renewable energy sources in developed and developing countries.

In research that investigated the obstacles to the development of renewable energy in the agricultural industry, Streimikiene et al. [29] pointed out that one of the most important challenges of using and developing renewable energy in the European Union is meeting the growing demand for energy and complying with environmental restrictions. Based on this, the common structure and infrastructure related to energy systems are undergoing changes such as the conversion of centralized energy systems to more decentralized ones and the use of interactive energy systems that are associated with less carbon energy transfer. Smart grid technology and other innovations in the field of renewable energy micro-generation technologies have created changes in the role of energy users: They can be both producers and consumers. The development of forms of ownership of energy systems depends on the existing political processes in the country and is supported by laws and economic incentives. On the other hand, the production of renewable energy, which allows the participation of citizens, brings higher social acceptance. This model of production and consumption has been one of the managers' initiatives to expand the culture of using renewable energy in villages—characterized by low population density and extensive use of energy for agricultural purposes. Although the use of renewable energy provides many benefits and opportunities for rural communities, the rapid growth of renewable energy and energy supply faces several important obstacles in rural areas: The agricultural sector is still heavily dependent on fossil fuels. Therefore, agricultural processes are directed towards technologies that convert fossil energy into agro-food products, so it is necessary to ensure the transition of agriculture from fossil fuels to renewable energy sources. Therefore, it is necessary to rebuild the agricultural sector to use electricity produced from renewable energy sources such as wind, sun, biogas, etc. But the economic, social, institutional, regulatory, behavioral, and psychological factors in preparing the infrastructure and persuading the villagers are still not widespread. Zahedi et al. [30], studied the strategic policy of renewable energy, optimization, and sustainability in Iran. According to the results of this research, in Iran, despite the diverse potentials in the field of renewable energy, wind energy has a higher priority than other cases in terms of economic justification and competition in the market and domestic production rate. Other renewable energy sources for power generation and grid connection have lower priority for short or medium-term investment. But for non-network use in the country, they can be very useful in the short term. In general, Iran can be a pole of renewable energies. Undoubtedly, the biggest limitation in the adoption of renewable energies in Iran is the long-term access to fossil fuels and the current energy pricing system, especially the low electricity tariff due to high natural gas subsidies. Under conventional energy prices, there is no incentive for the private sector in Iran to invest in the renewable energy sector because its production cost is higher than other energy derivatives. Mungai et al. [31], have investigated the barriers to the growth of renewable energy in sub-Saharan African countries. While the countries of this region are in a unique position to benefit from the socio-economic and environmental benefits of renewable resources and are facing an increase in energy demand, economic, and political factors and lack of sufficient knowledge are the most important factors that prevent these countries from exploiting renewable energy sources. James et al. [32], investigated the obstacles to the adoption of renewable energy in Ghana. In this survey, the identified factors were classified into six categories: political, organizational, economic-financial, structural or technical, legal-regulatory, and social. The results showed that the political and economic-financial obstacles have the highest rank and the lack of market-based support plans for renewable energy and high commercial interest rates are respectively the most important sub-obstacles for each of these two categories. Kim [33], investigated the obstacles to the use of renewable energy in Korea: According to the evidence, the use of renewable energy in the electricity generation sector has grown significantly in recent years. There are still many challenges to deploying renewable energy in power plants and buildings. In this research, the most important leading challenges are the perspective of renewable energy projects, physical space limitations for renewable installations in buildings, and renewable policies based on quantitative supply. Solangi et al. [34], Obstacles: The development of energy technologies, economic-financial factors, and political factors were identified as the most important factors hindering the development of renewable energy in Pakistan. Elavarasan et al. [35], analyzed the different perspectives of India in the field of renewable energy. India, the second most populous country with a population of 1,353 billion people, is one of the largest consumers of fossil fuels in the world, which is responsible for global warming. The increasing population of the country and, as a result, the increase in energy demand in the coming decades, together with the rapid industrial growth, have sounded the alarm for the emerging crisis. Ghimire et al. [36], In research, investigated the obstacles to the development of renewable energy in Nepal using the AHP technique. Therefore, it has been argued that renewable energy technologies such as small and small hydropower plants, solar, wind, and biomass are not only suitable economic solutions, but also suitable options for providing energy resources in rural and remote areas, in developing countries such as They are from Nepal. Obstacles to the development of renewable energy in Nepal were classified into six general categories of social, political, technical, economic, administrative, and geographical factors. Table 13.1 shows the most frequent obstacles to the development of renewable energy in general.

Table 13.1 Obstacles to the use and development of renewable energy

Obstacles	References
Political-legal obstacles	Zahedi et al. [30], Ghiasi et al. [37], Mungai et al. [31], James et al. [32], Filho et al. [38], Xue et al. [39], Solangi et al. [34], Streimikiene et al. [29], Kim [33], Elavarasan et al. [35], Ghimire and Kim [36]
Cultural-Social obstacles	Mungai et al. [31], James et al. [32], Streimikiene et al. [29], Elavarasan et al. [35], Ghimire and Kim [36]
Industrial obstacles	Filho et al. [38], Avci et al. [40], Elavarasan et al. [35, 41], Ghimire and Kim [36]
Lack of knowledge and skills	Ghiasi et al. [37], James et al. [32], Filho et al. [38], Olabi and Abdelkareem [43], Solangi et al. [34], Kim [33], Elavarasan et al. [35, 41]
Environmental obstacles	Zahedi et al. [30], Mungai et al. [31], Olabi and Abdelkareem [43], Mehmood et al. [42], Streimikiene et al. [29], Elavarasan et al. [35, 41]
Economic obstacles	Zahedi et al. [30], Ghiasi et al. [37], Mungai et al. [31], James et al. [32], Xue et al. [39], Filho et al. [38], Xue et al. [39], Solangi et al. [34], Mehmood et al. [42], Kim [33], Elavarasan et al. [35, 41], Ghimire and Kim [36]
Dependence on fossil fuels	Zahedi et al. [30], Streimikiene et al. [29], Elavarasan et al. [41]
Management obstacles	Zahedi et al. [30], Ghiasi et al. [37], Xue et al. [39], Filho et al. [38], Streimikiene et al. [29], Elavarasan et al. [41]
Infrastructure and capacity	Zahedi et al. [30], Xue et al. [39], Olabi and Abdelkareem [43], Filho et al. [38], Streimikiene et al. [29], Elavarasan et al. [35, 41]

After determining the mission and goals, the next step is to determine the current situation and various obstacles ahead. Then by determining and applying appropriate strategies, the goals can be achieved. Strategies are management tools that help decision-makers to determine the priorities and main actions necessary to achieve the mission and goals [45].

Table 13.2 shows the strategies identified from the subject literature to reduce the effect of obstacles mentioned in Table 13.1. These strategies do not completely, but to a large extent, dispel the existing obstacles and challenges, because as can be seen in the list of obstacles, most of them are political and can be reduced by creating infrastructure and policies.

Table 13.2 Strategies for the development of renewable energy

Strategy	References
Definition of innovative goals and controls	Elavarasan et al. [35, 41], Hoang et al. [52], Zhou et al. [53], Qadir et al. [55]
Process reengineering	Mahmud and Joyashree [46], Khuong et al. [56]
Trade and direct foreign investment	Blechinger and Richter [47], Wang and Zhou [57]
Reduce operational costs	Elavarasan et al. [35, 41], Qadir et al. [55]
Establish regulatory rules to secure and attract investment	Blechinger and Richter [47], Qadir et al. [55], Khuong et al. [56]
Involving industry experts and stakeholders in strategic decisions	Mahmud and Joyashree [46], Blechinger and Richter [47]
Use of hybrid renewable energy systems	Zahedi et al. [30], Mahmud and Joyashree [46], Lian et al. [48], Jurasz et al. [49], Noorolahi et al. [50]
Energy storage	Lian et al. [48]
Adjusting the structure	Mahmud and Joyashree [46], Liu et al. [54], Wang and Zhou [57]
Allocation of subsidies and tax support	Mahmud and Joyashree [46], Blechinger and Richter [47]
Revision of the current structure and infrastructure development	Mahmud and Joyashree [46], Nguyen et al. [51], Hoang et al. [52], Wang and Zhou [57]
Empowering human resources	Zahedi et al. [30], Mahmud and Joyashree [46]
Improving coordination between the involved institutions	Mahmud and Joyashree [46], Khuong et al. [56]
Periodic modernization and upgrading of power plants	Zahedi et al. [30], Elavarasan et al. [35, 41], Noorolahi et al. [50]
Using advanced technologies	Elavarasan et al. [35, 41], Wang and Zhou [57], Zahedi et al. [30], Noorolahi et al. [50]
Supporting research and development	Elavarasan et al. [35, 41]

Research Methodology

The current study was implemented in two stages with a combined approach. During the first stage, the obstacles to the development and use of renewable energy were identified, and then the strategies for reducing the effect of these obstacles were identified by studying the literature. Then, a group of RE industry experts who graduated in master and Ph.D., and have more than 10-year work experience in this industry were selected. These experts were used in all stages of the research (choosing obstacles and strategies, determining the importance of obstacles and scoring strategies). Next, these experts were asked to comment on the importance of the identified attributes based on their experience. Finally, In the second stage, the importance of each of the obstacles and the ranking of the strategies are done with multi-criteria decision-making techniques, which can be seen in Fig. 13.1.

Best-Worst Method (BWM)

Multi-criteria decision-making methods (MCDM) are a set of techniques developed to identify the best alternative from a set of available alternatives based on multiple criteria. Due to ambiguity and uncertainty, it is common to use interval numbers to ensure decision making. In other words, interval MCDM methods attempt to provide more accurate outputs by facilitating a better understanding of decision makers'

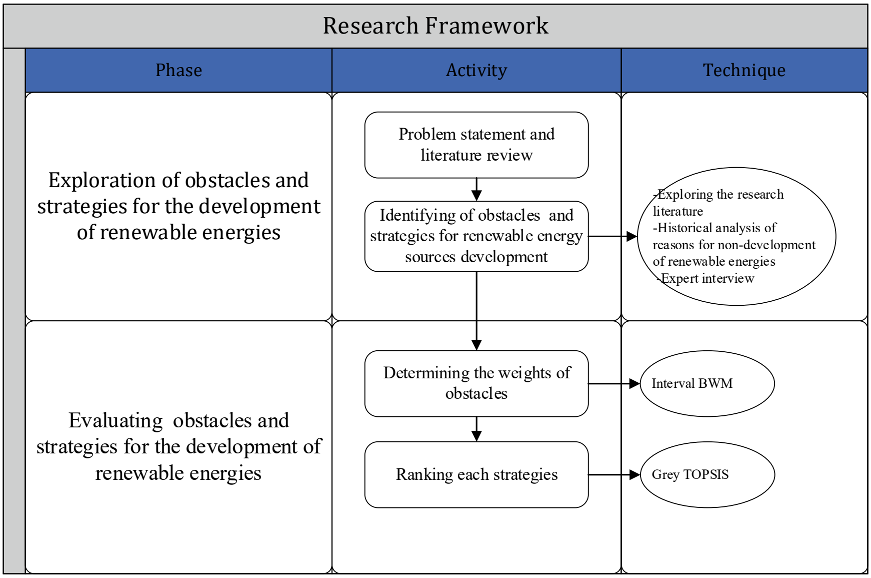

Fig. 13.1 Research framework

evaluations. In this research, the Best-Worst method and grey TOPSIS are used for decision making. The Best-Worst Method is a multi-criteria decision-making method developed by Rezaei [58]. One of the prominent features of this method is the need for less comparative data. The validity of this method is clear from its application in various fields of renewable energy, including in the development of solar energy [59], opportunities and challenges in RE [60], evaluation of renewable energy resources [61], Bioethanol facility location selection [62]. The steps to perform the best-worst method are as follows [58]:

First step: Determining the decision criteria. Represents decision sets by $\{c_1, c_2, \ldots, c_n\}$, where **n** represents the number of criteria.

Second step: According to the decision criteria system, the best (most important) and worst (least important) criteria should be determined by the decision-makers.

Third step: The preference of the best criterion over other criteria is determined by using numbers from 1 to 9. The comparison vector of the best criterion compared to other criteria is as follows: $\mathrm{A}_B = (a_{B1}, a_{B2}, \ldots, a_{bn})$ where a_{Bj} indicates the preference of the best criterion B over criterion j. It is clear that: $a_{BB} = 1$

Fourth step: The preference of all criteria over the worst criterion is determined using numbers from 1 to 9. The vector of comparison of all criteria for the worst criterion is as follows: $A_w = (a_{1W}, a_{2W}, \ldots., a_{nW})^T$ where a_{jw} indicates the preference of criterion j over the worst criterion w. It is clear that $a_{WW} = 1$.

Fifth step: This step is to obtain optimal weights $(w^*{}_1, w^*{}_2, \cdots, w^*{}_n)$. To determine the optimal weights, for all j's, a solution should be determined such that minimizes the maximum of the differences $\left|\frac{w_j}{w_W} - a_{jW}\right|$ and $\left|\frac{w_B}{w_j} - a_{Bj}\right|$ for all j. Accordingly, in order to calculate the optimal weights $(w^*{}_1, w^*{}_2, \cdots, w^*{}_n)$ the following non-linear programming model can be used.

$$
\begin{gathered}
\min \xi \\
s.t. \\
\left|\frac{w_B}{w_j} - a_{Bj}\right| \leq \xi, \text{ for all } j \\
\left|\frac{w_j}{w_W} - a_{jW}\right| \leq \xi, \text{ for all } j \\
\sum_j w_j = 1 \\
w_j \geq 0, \text{ for all } j
\end{gathered}
\tag{13.1}
$$

To obtain interval weights, two models are provided to calculate the lowest and the highest weight value of criterion j. These models are solved after solving Eq. (13.3) and finding ξ^*.

Table 13.3 Consistency index

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

$$\begin{aligned} &\min \ w_j \\ &s.t. \\ &\left|\frac{w_B}{w_j} - a_{Bj}\right| \le \xi^*, \text{for all } j \\ &\left|\frac{w_j}{w_W} - a_{jW}\right| \le \xi^*, \text{for all } j \\ &\sum_j w_j = 1 \\ &w_j \ge 0, \text{for all } j \end{aligned} \tag{13.2}$$

$$\begin{aligned} &\max \ w_j \\ &s.t. \\ &\left|\frac{w_B}{w_j} - a_{Bj}\right| \le \xi^*, \text{for all } j \\ &\left|\frac{w_j}{w_W} - a_{jW}\right| \le \xi^*, \text{for all } j \\ &\textstyle\sum_j w_j = 1 \\ &w_j \ge 0, \text{for all } j \end{aligned} \tag{13.3}$$

If the two presented models are solved with all the criteria, the optimal weight of the criteria in an interval is determined. By using the middle of the optimal weight range of the criteria, the criteria or options can be evaluated. Also, another method for evaluating criteria or options is ranking based on distance weights. In this method, the priority matrix and preference matrix are used. In the next section, distance analysis is presented, which is used to compare and rank the weights.

Then, we calculate the consistency ratio, using ξ^* and the corresponding consistency index, as Eq. (13.3) and is the objective function value of Eq. (13.1) Table 13.3 [58]:

$$Consistency\ Ratio = \frac{\xi}{Consistency\ Index} \tag{13.4}$$

In Eq. (13.4) ξ^* is the objective function value of Eq. (13.1).

Grey TOPSIS Method

TOPSIS is a multi-criteria decision-making method based on the idea that the optimal solution should have the smallest distance from the positive ideal solution and the largest distance from the negative ideal solution. A solution is determined as a positive ideal solution if it maximizes the profit criteria or minimizes the cost criteria. On the other hand, a solution that maximizes the cost criteria or minimizes the profit criteria is called a negative ideal solution [63]. This research is also looking for the best solution or strategy to reduce the effect of obstacles to the use of renewable energy, which is used in light of the ambiguity and uncertainty of the grey TOPSIS method. The steps of the grey TOPSIS method are as follows (Oztaysi) [64]:

Step 1: Determining the decision matrix (⊗G): in the decision matrix, $\otimes G_{ij}$ denote the grey score of each *i*th strategy from the perspective of *j*th obstacle.

$$\otimes G = \begin{bmatrix} \otimes G_{11} & \cdots & \otimes G_{1n} \\ \vdots & \ddots & \vdots \\ \otimes G_{m1} & \cdots & \otimes G_{mn} \end{bmatrix}, i = 1, \ldots, m; j = 1, \ldots, n$$

Step 2: Normalizing the decision matrix (⊗R): In this step, the grey decision matrix should be normalized so that all its numbers are between zero and one. Normalization is done using the Eq. (13.5) and Eq. (13.6), for the benefit criteria and cost criteria, respectively.

$$\otimes r_{ij} = \left[\frac{\underline{G}_{ij}}{G_j^{Max}}, \frac{\bar{G}_{ij}}{G_j^{Max}}\right]; G_j^{Max} = Max\{\bar{G}_{ij}\} \text{for benefit criteria} \tag{13.5}$$

$$\otimes r_{ij} = \left[\frac{G_j^{Min}}{\bar{G}_{ij}}, \frac{G_j^{Min}}{\underline{G}_{ij}}\right]; G_j^{Min} = Min\left\{\underline{G}_{ij}\right\} \text{for cost criteria} \tag{13.6}$$

where $\underline{G}_{ij}$ denote the lower value and $\overline{G}_{ij}$ represents the higher value.

Step 3: Calculation of the ideal reference: In this step, the maximum of the lower and upper limits of each criterion should be specified.

$$A^+ = \left\{\left(\max_i \bar{r}_{ij} | j \in J\right), \left(\min_i \underline{r}_{ij} | j \in J\right) | i \in n\right\} = \left[r_1^+, r_2^+, \ldots, r_m^+\right] \tag{13.7}$$

$$A^- = \left\{\left(\min_i \underline{r}_{ij} | j \in J\right), \left(\max_i \bar{r}_{ij} | j \in J\right) | i \in n\right\} = \left[r_1^-, r_2^-, \ldots, r_m^-\right] \tag{13.8}$$

where $j = \{1, 2, ..., J\}$ that j associated with benefit criteria and $j\prime = \{1, 2, ..., J\prime\}$ that $j\prime$ associated with cost criteria.

Step 4: calculating the difference of the options from the reference ideal: In this step, the probability that a grey number is smaller than or equal to the optimal value should be stated.

$$d_i^+ = \sum_{j=1}^{n} d_v\left(\overline{v}_{ij}, \overline{v}_j^*\right) \tag{13.9}$$

$$d_i^- = \sum_{j=1}^{n} d_v\left(\overline{v}_{ij}, \overline{v}_j^-\right) \tag{13.10}$$

Fifth Step: The closeness coefficient (CC_i) is a reliable value that defines an index for ranking strategies. This coefficient is calculated by using the following formula.

$$CC_i = w^+\left(d_i^- \Big/ \sum_{i=1}^{m} d_i^-\right) - w^-\left(d_i^* \Big/ \sum_{i=1}^{m} d_i^*\right), \begin{cases} -1 \le CC_i \le 1 \\ 0 \le w^+ \le 1,\ i = 1, 2, \ldots, m \\ 0 \le w^- \le 1 \end{cases} \tag{13.11}$$

In the above equation, w^+ and w^- balance the importance of the lower and upper limits. This balance can be established with the equation $w^+ + w^- = 1$.

Sixth step: In the final step, by calculating the value of RC_i, any option that is at a smaller distance from the top option (the probability of it being smaller than the top option is less) is ranked higher.

$$RC_i = \frac{1 + CC_i}{2}, 0 \le RC_i \le 1, i = 1, 2, \ldots, m \tag{13.12}$$

Findings

To identify the final obstacles and strategies after the review of documents and library sources, structured interviews with 10 experts were used and the results are shown in Tables 13.4 and 13.5.

Table 13.4 Selected obstacles according to experts

Selected obstacles	Abbreviation code
Political-legal obstacles	O_1
Industrial obstacles	O_2
Lack of knowledge and skills	O_3
Economic obstacles	O_4
Dependence on fossil fuels	O_5
Management obstacles	O_6
Infrastructure and capacity	O_7

Table 13.5 Selected strategies according to experts

Selected strategies	Abbreviation code
Definition of innovative goals and controls	S_1
Process reengineering	S_2
Trade and direct foreign investment	S_3
Involving industry experts and stakeholders in strategic decisions	S_4
Use of hybrid renewable energy systems	S_5
Adjusting the structure	S_6
Allocation of subsidies and tax support	S_7
Revision of the current structure and infrastructure development	S_8
Empowering human resources	S_9
Improving coordination between the involved institutions	S_{10}
Periodic modernization and upgrading of power plants	S_{11}
Supporting research and development	S_{12}

BWM Findings

After literature review and identification of obstacles and strategies (Tables 13.4 and 13.5), the weights of the factors are calculated based on the steps BWM. Experts after determining the best and worst obstacles, they determined the importance of other obstacles compared to the best obstacle. Table 13.6 shows the result of this.

Then, the vector of importance of other obstacles compared to the worst obstacle is determined. Table 13.7 shows the results of this step. Also, in the last row of Table 13.7, the consistency ration (CR) was calculated according to Eq. (13.4), that indicates the validity of the data.

Table 13.6 The preference of the most important obstacle compared to other indices

	O_1	O_2	O_3	O_4	O_5	O_6	O_7
Exp 1	6	5	3	9	1	8	2
Exp 2	3	5	4	8	1	2	7
Exp 3	5	4	1	9	7	3	5
Exp 4	8	7	1	7	7	5	9
Exp 5	6	8	2	9	1	5	4
Exp 6	3	4	4	3	1	7	8
Exp 7	4	7	1	9	5	3	4
Exp 8	5	7	6	3	1	5	8
Exp 9	3	2	2	8	3	1	7
Exp 10	6	6	2	7	1	7	2

Table 13.7 The preference of other indicators over the worst indicator

	Exp 1	Exp 2	Exp 3	Exp 4	Exp 5	Exp 6	Exp 7	Exp 8	Exp 9	Exp 10
O_1	7	3	3	2	2	5	6	6	2	7
O_2	7	6	5	3	7	7	6	6	5	4
O_3	4	1	9	9	7	5	9	4	3	3
O_4	1	7	1	4	1	4	1	4	1	1
O_5	9	8	3	2	9	8	3	8	7	1
O_6	6	4	5	8	3	7	4	7	8	2
O_7	2	5	5	1	5	1	2	1	2	3
CR	**0.05**	**0.17**	**0.01**	**0.1**	**0.08**	**0.12**	**0.08**	**0.06**	**0.1**	**0.07**

Table 13.8 The lower limits and the upper limit weight of the criteria

Code	Obstacle	Low weight	High weight
O_1	Political-legal obstacles	0.0586	0.1962
O_2	Industrial obstacles	0.0625	0.1819
O_3	Lack of knowledge and skills	0.0822	0.2282
O_4	Economic obstacles	0.0325	0.0724
O_5	Dependence on fossil fuels	0.1560	0.3511
O_6	Management obstacles	0.0672	0.2037
O_7	Infrastructure and capacity	0.0367	0.1204

Therefore, the optimal weight of the obstacles was determined for each of the 10 experts in an interval range. Table 13.8 shows the geometric mean of the lower and upper weights of the obstacles.

Grey TOPSIS Findings

In the next step of the research, the ranking of the strategies to reducing the effect of obstacles to the development of renewable energy was done by using formulas 13.4–13.11 of the Grey TOPSIS method. Based on Eq. (13.5), the normal decision matrix is formed. Because all criteria were positive nature, Eq. (13.5) was used. Also, the values of A^+ and A^- are obtained according to Eq. (13.7), which can be seen in Table 13.9.

Next, based on Eqs. (13.9) and (13.10), the distance of each strategy from the reference ideals is obtained. Also, in the last column of Table 13.10, the closeness coefficient was obtained according to Eq. (13.11). As stated earlier, w^+ and w^- values were considered equal to 0.5.

And finally, Table 13.11 shows the rank of each strategy based on the coefficient RC_i according to Eq. (13.12).

Table 13.9 Normal decision matrix

	O1		O2		O3		O4		O5		O6		O7	
S1	0.021	0.042	0.041	0.061	0.080	0.100	0.098	0.118	0.041	0.061	0.083	0.104	0.047	0.070
S2	0.042	0.063	0.082	0.102	0.040	0.060	0.039	0.059	0.102	0.122	0.042	0.063	0.023	0.047
S3	0.104	0.125	0.020	0.041	0.100	0.120	0.039	0.059	0.102	0.122	0.042	0.063	0.116	0.140
S4	0.104	0.125	0.102	0.122	0.080	0.100	0.098	0.118	0.020	0.041	0.083	0.104	0.023	0.047
S5	0.021	0.042	0.082	0.102	0.020	0.040	0.039	0.059	0.020	0.041	0.021	0.042	0.047	0.070
S6	0.083	0.104	0.082	0.102	0.080	0.100	0.039	0.059	0.102	0.122	0.104	0.125	0.093	0.116
S7	0.083	0.104	0.102	0.122	0.040	0.060	0.078	0.098	0.082	0.102	0.083	0.104	0.093	0.116
S8	0.042	0.063	0.041	0.061	0.100	0.120	0.020	0.039	0.041	0.061	0.021	0.042	0.047	0.070
S9	0.083	0.104	0.102	0.122	0.080	0.100	0.078	0.098	0.041	0.061	0.104	0.125	0.047	0.070
S10	0.042	0.063	0.020	0.041	0.080	0.100	0.098	0.118	0.082	0.102	0.021	0.042	0.047	0.070
S11	0.083	0.104	0.041	0.061	0.040	0.060	0.039	0.059	0.041	0.061	0.104	0.125	0.047	0.070
S12	0.042	0.063	0.041	0.061	0.020	0.040	0.098	0.118	0.082	0.102	0.042	0.063	0.093	0.116
$\mathbf{A}^{+}$	0.1250		0.1224		0.1200		0.1176		0.1224		0.1250		0.1395	
$\mathbf{A}^{-}$	0.0208		0.0204		0.0200		0.0196		0.0204		0.0208		0.0233	

Table 13.10 The distance of the strategies from the ideal and coefficient Cc_i

Strategies	d_i^+	d_i^-	Cc_i
S_1	0.0583	0.0533	−0.0103
S_2	0.0548	0.0611	−0.0022
S_3	0.0431	0.0793	0.0195
S_4	0.0547	0.0685	0.0029
S_5	0.0772	0.0336	−0.0387
S_6	0.0253	0.0822	0.0357
S_7	0.0346	0.0731	0.0221
S_8	0.0651	0.0477	−0.0194
S_9	0.0436	0.0701	0.0129
S_{10}	0.0580	0.0565	−0.0078
S_{11}	0.0564	0.0550	−0.0076
S_{12}	0.0565	0.0557	−0.0071

Table 13.11 Coefficient RC_i and rank of strategies

Strategies	RC_i	Rank
S_1	0.4949	10
S_2	0.4989	6
S_3	0.5097	3
S_4	0.5015	5
S_5	0.4807	12
S_6	0.5178	1
S_7	0.5110	2
S_8	0.4903	11
S_9	0.5064	4
S_{10}	0.4961	9
S_{11}	0.4962	8
S_{12}	0.4964	7

Based on the results, the adjusting the structure was ranked first. Also, the allocation of subsidies and tax support, trade and direct foreign investment and empowering human resources strategies were ranked next.

Conclusion

Societies constantly need energy for development and sustainable functioning. Use of renewable energy technology in every corner of the world is useful for environmental protection and economic development, more over by considering the limitation of using other sources of energy supply, the necessity of reducing obstacles and finding strategies for the development of renewable energy sources is undeniable.

On the other hand, classification, and prioritization of criteria and options is one of the necessities that decision-makers have to do because of the limitations in resources, and increasing productivity and optimal management of resources. So far, different methods for classifying the options have been presented and used, and most of these methods are based on multi-criteria decision-making methods. In this case, to avoid a high number of pairwise comparisons and increase the consistency of comparisons, the BWM method was used.

In this study, the grey TOPSIS technique was used to rank strategies for reduce ing obstacles to the development of renewable energy use. Based on this, adjusting the structure, allocation of subsidies and tax support and trade and direct foreign investment are the most important strategies which are resembling Mahmud and Joyashree [46], Liu et al. [54], Wang and Zhou [57], and Blechinger and Richter [47] study. Accordingly, use of hybrid renewable energy systems, revision of the current structure and infrastructure development are less important strategies, so this can be inconsistent with Zahedi et al. [30], Elavarasan et al. [35, 41], Noorolahi et al. [50], Mahmud and Joyashree [46], Nguyen et al. [51], Hoang et al. [52], Wang and Zhou [57], Lian et al. [48], and Jurasz et al. [49] research results.

The present research was conducted to rank the strategies of using renewable energy to reduce the effects of its obstacles. One of the limitations of the current research was finding experienced experts in the industry, which made the process of data collection and completing the questionnaire difficult, so it is suggested that the research be conducted in industries of the same family as renewable energies and in other countries and then the results of the research are compared and analyzed. Also, other external variables, such as sanctions, can affect this issue, which has not been addressed in this research, which can be investigated in future research on this topic from a technical perspective.

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