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Selection of discrete multiple criteria decision making methods in the presence of risk and uncertainty

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ABSTRACT

This paper presents a new methodology to recommend the most suitable Multi-Criteria Decision Making (MCDM) method from a subset of candidate methods when risk and uncertainty are anticipated. A structured approach has been created based on an analysis of MCDM problems and methods characteristics. Outcomes of this analysis provide decision makers with a suggested group of candidate methods for their problem. Sensitivity analysis is applied to the suggested group of candidate methods to analyze the robustness of outputs when risk and uncertainty are anticipated. A MCDM method is automatically selected that delivers the most robust outcome. MCDM methods dealing with discrete sets of alternatives are considered. Numerical examples are presented where some MCDM methods are compared and recommended by calculating the minimum percentage change in criteria weights and performance measures required to alter the ranking of any two alternatives. A MCDM method will be recommended based on a best compromise in minimum percentage change required in inputs to alter the ranking of alternatives. Different cases are considered and some new propositions are presented based on potential generalized scenarios of MCDM problems.

1. Introduction

The research presented in this paper is part of a broader study to recommend the most suitable Multiple Criteria Decision Making (MCDM) method for a decisional problem by addressing factors concerning problem characteristics and MCDM methods characteristics.

A set of novel propositions have been created based on potential generalized scenarios of MCDM problems. These propositions were tested on a number of numerical example (available on request) and results showed the proposition were accurate in predicting a suitable MCDM method for certain MCDM problems and predicting the top-ranking alternative from a set of identified alternatives. Three decisional problems proposed by Expert Choice Sample Models are considered in this paper which represent a set of potential generalized scenarios of MCDM problems used to test the novel set of propositions.

Making a decision is a process where alternatives are assessed to select a choice or a course of action to fulfil desired objectives and goals. A suitable decision-making process can be essential for success in an organization. Problems and information needed for making a decision can be vague and uncertain. Many researchers stressed the need to consider uncertainty in making decisions [2,3], 2012; [6,44], however it was not often considered in practice [43].

Different decision-making methods are used for different real-life problems, and there are no superior methods. Poyhonen and Hamalainen [25] stated that although different weighting methods often consider the same theoretical algorithms, they often lead to different outcomes.

Because making judgments in a high risk, fuzzy and uncertain environment (where higher stakes and many assumptions are involved) makes decisions more vulnerable to distortion, the involvement of more complex scientific decision-making methods can help. Most human beings are only capable of dealing with a small number of criteria at the same time [21]. To manage multi-criteria problems in a more efficient manner, decision makers tend to use MCDM methods. But MCDM methods might have both advantages and disadvantages in finding a suitable final outcome.

MCDM is a field of operational research where alternatives are assessed to select the most suitable alternative that fulfils a desired goal with respect to a set of multiple and often conflicting criteria [16]. MCDM is an important part of decision-making theory and operational research. It is often considered reliable. It is a set of methods and procedures by which multiple and conflicting criteria can be incorporated into a decision process. Moreover, MCDM could be considered as a systematic process for analysing and choosing between alternatives. It aims to split a problem into smaller parts, analysing and assessing each part, then aggregating all parts to select the best feasible

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alternative from a set of alternatives using a predefined set of criteria. MCDM aims to enable decision makers to solve conflicting real world quantitative and / or qualitative multi-criteria problems, and to find best-fit alternatives from a set of alternatives in certain, uncertain, fuzzy or risky environments [27].

Durbach and Stewart [4] claimed that all multi-criteria methods improved the decision-making process by decomposing the overall assessment of alternatives to the assessment of a number of often conflicting criteria. Since it is difficult to check MCDM methods for accuracy because they utilize different means when dealing with different data sets, MCDM methods are often difficult to compare (Olson, 2007). The process of decision-making in a MCDM problem is sequential; a user can go through iterations to reach more robust and reliable comparisons. Checking the consistency of comparisons could have an important role.

Consistency of comparisons is important as it shows the reliability and robustness of outcomes [28], Saaty [34] proposed that inconsistency could be *"one order of magnitude less important than consistency or 10% of the total concern with consistent measurement."* If inconsistency was larger than 10% then it could disturb the decision-making process. Human judgments are often prone to errors and biases, but human behaviour is not the only source of inconsistency, since decision makers are required to describe criteria and alternatives on measure scales with a limited set of numbers, the measure scales used in different methods could also contribute to inconsistencies [25].

It is important for decision makers to understand the nature of uncertainty in order to enhance their ability to make decisions and to reduce the level of risk associated with their decisions. Moreover, decision makers' understanding of the nature of uncertainty could lower inconsistency rates and provide more robust and reliable representation of weights and performance measures [25]. Salo and Hamalainen [35] claimed that weighting methods that allowed decision makers to provide imprecise preference statements often produced better preference elicitation. Scholten et al. [43] claimed that uncertainty in criteria weights could occur from personal biases, inaccurate quantitative estimates, or the use of imprecise weights to reduce inconsistencies.

Scholten et al. [43] stated that detailed consideration of uncertainties might have a counterproductive effect if stakeholders become overwhelmed with uncertainties, but Scholten et al. asserted that the use of simplifying assumptions to explore (and not only to rank) alternatives may provide important insights. The process of helping stakeholders define their fundamental objectives and to use them to create and compare innovative solutions does not need a detailed consideration of uncertainties [11]. The under rating of uncertainties might have severe outcomes in long term planning, since the cost of a wrong decision due to not considering uncertainty could be severe.

Ozernoy [24] asserted that there was no perfect MCDM method because decision-makers might be unable to provide all the required information and/or different decisional problems require different algorithms to deliver their intended outcomes. Miettinen and Salminen [20] claimed that in real life problems, criteria weights were often hard to provide as "exact" numbers and provided a number of examples were criteria values could not be defined as exact numbers. They modelled uncertainty in criterion weights as probability functions and fuzzy values. They claimed that inaccuracy might be better understood by using Pseudo criteria; introducing preference and indifference thresholds where the inaccuracy can be filtered between these thresholds.

Durbach and Stewart [3,4] depicted uncertainty using five different models: Probabilities, Decision weights, Explicit risk measures, Fuzzy numbers and Scenarios, and they claimed that the most popular way to model uncertainty was using probabilities. Durbach and Stewart [3] stated that decision makers tend to favour the model of uncertainty that provided easier judgement and concise information.

All decision-making processes involve an element of risk. Risk is an uncertain event or condition that, if it occurs, has a positive or negative effect on at least one objective. Since risks originate from uncertainty, a risk with probability of one can be considered to be a fact. The outcomes of a decision-making process are significantly shaped by internal and external factors. Some of these factors are known, while others are unknown to decision makers.

Risks are inevitable in real world problems. Internal risks include time, cost and team changes, external risks include change in regulations, market shift, technical issues, and unforeseeable risk. Studies suggest that 90% of problems could be avoided with better risk management [26]. Decision makers should exploit, enhance and capture positive risk (opportunity), and avoid, mitigate, and transfer negative risk (threats).

Severity = Impact * Probability [26]. Risks with high severity require priority action and an aggressive response strategy. Risks with medium severity require proactive action and should be added to a watch list for future monitoring. Accepted risks with low severity should be added to the watch list for future monitoring.

Moreover, sensitivity analysis should be conducted to check for robustness and validate feasibility of MCDM outcomes [33]. Saltelli et al. [36] defined sensitivity analysis as the analysis of the effect of uncertainty in the output of a model, affected by uncertainty in its inputs.

Wolters and Mareschal [49] defined three types of sensitivity analysis for a decisional problem:

- Sensitivity of a ranking to changes in scores of all alternatives depending on certain criterion. In this case uncertainties are in particular criterion scores.
- The effect of changes in performance measures of one alternative with respect to a criterion.
- The minimum change in criteria weights required to make an alternative ranked first.

The decision maker would seek the judgment of individuals or groups who possessed specialized knowledge or past experience in a particular area. The judgment provided by people with expertise could be utilized at various stages in order to carry out effective decision-making. However, expert knowledge is not always enough to fill a gap. Making judgments based on historical data is not new. When dealing with uncertainty, unknown consequences are modelled as random variables. Using past experience and historical data to predict the probabilities of these variables is often impossible. Judgments provided based on past experience and historical data might be inaccurate and unacceptable [7]. Decision-making tools aim to improve the general process of decision-making.

Haddad [14] identified the following steps to reach a most suitable (best compromise) solution in any multi-criteria problem:

1 Identify the problem.
2 Define goals and targets.
3 Define a set of criteria.
4 Identify alternatives.
5 Select a MCDM method to evaluate the overall score of alternatives with respect to the criteria set.
6 Review and evaluate outcomes.

At the end of a decision process, decisions should be reviewed and validated. Unsuccessful or inappropriate decisions should be reassessed, and the process started again.

Fig. 1. A model of a general decision-making process under uncertainty [7].

Grechuk and Zabarankin [7] modelled the general decision-making process under uncertainty as four stages as shown in Fig. 1, They said that decision makers and analysts possess historical and experimental data which is insufficient. Data acquired from statistical understanding of various assumptions depending on the nature of the problem might provide better understanding of risk and uncertainty associated with the problem.

The impact of the choice of a method on actual decisions is also well known, as well as the consequences of poor decisions [17]. Eldarandaly et al. [5] asserted that applying different MCDM methods to the same decisional problem could often generate different outcomes. The use of an inappropriate MCDM method could lead to inappropriate decisions [24]. Ishizaka and Siraj [16] asserted on the importance of good decisions and claimed that several MCDM methods were improving them.

This paper explores the impact of the choice of method when risk and uncertainty may exist. A novel automated system selects a group of candidate methods and then sensitivity analysis is applied to the group of candidate methods to recommend the most suitable method for a particular decisional problem. Finally some new general proposition are developed based on a set of generalized potential MCDM scenarios and then explained.

2. New MCDM methods selection approach

Many researchers have proposed different MCDM methods selection approaches [12]; Hobbs, 1986; [1,5,13,17,18,22–24,32,33,47,48]. MacCrimmon [19] might be the first to recognize the importance of the MCDM methods selection problem and the need to compare MCDM methods. MacCrimmon also identified preference information and proposed a classification of MCDM methods based on a method specification chart in the form of a tree diagram that included illustrative application examples.

Many researchers compared different MCDM methods based on the final outcome provided by these methods but such comparison of final results could be considered as "ill founded" [32]. Researchers considered MCDM methods as a tool for better understanding decisional problems, and exploring, studying, and evaluating different possibilities, rather than just considering MCDM methods as a tool for making decisions.

Many factors could affect the selection of MCDM methods. They could be selected randomly, the decision maker might have previous knowledge or experience with them, or they may just be available [17,18,47]. Considering the diversity of MCDM methods, several researchers proposed approaches to select a suitable MCDM method for a problem. However, a well-structured way of selecting MCDM methods is missing from the literature.

A new structured approach was developed by the authors as a part of broader research. A number of factors that needed to be addressed when selecting a MCDM method were identified, including problem characteristics and MCDM methods' characteristics [15].

By addressing these factors, a framework could provide decision makers with a group of candidate MCDM methods appropriate for their problem. In this paper, MCDM methods dealing with discrete sets of alternatives were considered. Sensitivity analysis was carried out on this subset of candidate methods to select a MCDM method that delivered the most robust outcome according to decision makers' anticipation of risk factors and uncertainty.

Traintaphyllou and Sanchez [45] claimed that weights assigned to criteria characterize the importance of the criteria, thus identifying the critical criteria and accurately re-evaluating their weight could improve the decision-making process. They proposed a framework to determine the minimum percentage change required in criteria weights to change the ranking of any two alternatives, and, the minimum percentage change required in performance measure to change the ranking of any two alternatives "in terms of a single decision criterion at a time".

Research conducted by the authors and presented in this paper has resulted in a new set of propositions that considered seven generalized potential scenarios for MCDM problems. Three scenarios depended on the human decision makers:

SCENARIO ONE: If decision makers were uncertain of criteria weights and / or anticipate a risk factor of high severity that could affect criteria weights.

SCENARIO TWO: If decision makers were uncertain of performance measures and / or anticipate a risk factor of high severity that could affect performance measures.

SCENARIO THREE: If decision makers were uncertain and / or anticipate a risk factor of high severity that could affect **both** criteria weights and performance measures.

Three scenarios depended on performance measures and criteria weights:

SCENARIO FOUR: Whenever two alternatives were indifferent from each other in the final outcome, and they had different performance measures with respect to criteria.

SCENARIO FIVE: If an alternative scores highest on the most important criterion or criteria and did not have poor performances on others.

SCENARIO SIX: For an alternative to be ranked first in an equal criteria weight decisional problem.

3. Numerical examples

As examples, this section describes three decisional problems put through the Novel MCDM Methods Selection Framework [15], and the application of sensitivity analysis to select the most appropriate method from a subset of suggested candidate methods.

3.1. Numerical example 1 (U.S. coast guard)

This example considered how members of the U.S. Coast Guard were rated by their superiors. A set of six criteria were identified, and a set of six anonymous alternatives (officers) were assessed by the identified set of criteria. Results were submitted as part of the officers' service record and results of this assessment were used for the eligibility of officers to be selected for the next superior rank.

The set of criteria were:

- C_1: Performance of Duties
- C_2: Interpersonal Relations
- C_3: Leadership Skills
- C_4: Communication Skills
- C_5: Personal Qualities
- C_6: Representing the Coast Guard

Criteria weights and performance measures for all the alternative with respect to all the criteria are shown as a decision matrix in Table 1.

The Novel MCDM Methods Selection Framework was applied to this decisional problem as shown in Fig. 2. Eight questions addressing MCDM problem characteristics and the MCDM methods characteristics were asked. The nature of the alternative set was considered to be "Discrete" because the alternative consisted of integer values. Inputs considered in this numerical example were quantitative. All input information was deterministic. The aim behind applying MCDM methods to this problem was to rank the set of alternatives using pairwise comparisons to achieve a total order of alternatives. An absolute criteria measure scale was used considering a preference structure between alternatives.

A screen shot of the user interface of the structured MCDM Methods Selection Framework is shown in Fig. 3. A group of candidate methods were suitable for this decisional problem as shown at the bottom left the screen shot shown in Fig. 3 and listed here:

- The Analytical Hierarchy Process (AHP)

Table 1
Decision matrix for U.S. coast guard example.

Alternative criteria	A_1 Officer A	A_2 Officer B	A_3 Officer C	A_4 Officer D	A_5 Officer E	A_6 Officer F
C_1: Performance of Duties = 0.296	0.152	0.181	0.172	0.170	0.172	0.153
C_2: Interpersonal Relations = 0.254	0.172	0.150	0.176	0.161	0.150	0.191
C_3: Leadership Skills = 0.159	0.193	0.156	0.186	0.166	0.162	0.137
C_4: Communication Skills = 0.125	0.183	0.173	0.150	0.174	0.150	0.170
C_5: Personal Qualities = 0.084	0.196	0.170	0.161	0.162	0.157	0.155
C_6: Representing the Coast Guard = 0.082	0.170	0.203	0.142	0.175	0.164	0.145

- The Best Worst Method (BWM)
- Preference Ranking Organization METHod for Enrichment Evaluations II, (PROMETHEE II)
- Elimination Et Choix Traduisant la Realite III, (Elimination and Choice Expressing Reality III), (ELECTREE III)

AHP and PROMETHE II methods were selected for this decisional problem because they were available and easy to use. AHP and PROMETHEE II were applied to this numerical example. AHP provided the following ranking of alternatives: $A_1 > (A_2 = A_3) > A_4 > A_6 > A_5$, with a global score of alternatives: $A_1 = 0.172$, $A_2 = 0.169$, $A_3 = 0.169$, $A_4 = 0.167$, $A_5 = 0.160$ and $A_6 = 0.162$. PROMETHEE II provided a different ranking of alternatives: $A_3 > A_2 > A_1 > A_4 > A_6 > A_5$, with a net outranking flow of alternatives: $\Phi(A_1) = 0.139$, $\Phi(A_2) = 0.155$, $\Phi(A_3) = 0.167$, $\Phi(A_4) = 0.063$, $\Phi(A_5) = -0.283$ and $\Phi(A_6) = -0.241$, where Φ is a net outranking flow Φ (a) = Φ + (a) – Φ -(a). The higher the net outranking flow the more preferred the alternative.

Because AHP and PROMETHEE II methods delivered a different ranking of alternatives, sensitivity analysis was conducted on both methods' outcomes to recommend a method that best suited this decisional problem and provided the most robust outcome. Minimum percentage change required to alter the ranking of alternatives for the most critical criterion weight and most critical performance measure were calculated. Results are shown in Tables 2, 3, 4 and 5. N/F shown in Tables 4 and 5 stands for a non-feasible value where ± 100% change in the value of that performance measure did not affect the original ranking of the alternatives.

The most critical criterion in this numerical example using AHP was the second criterion (C_2) that represented "Interpersonal Relations" signified by the smallest value (bold number) in Table 2. This value represented the minimum percentage change required in the weight of

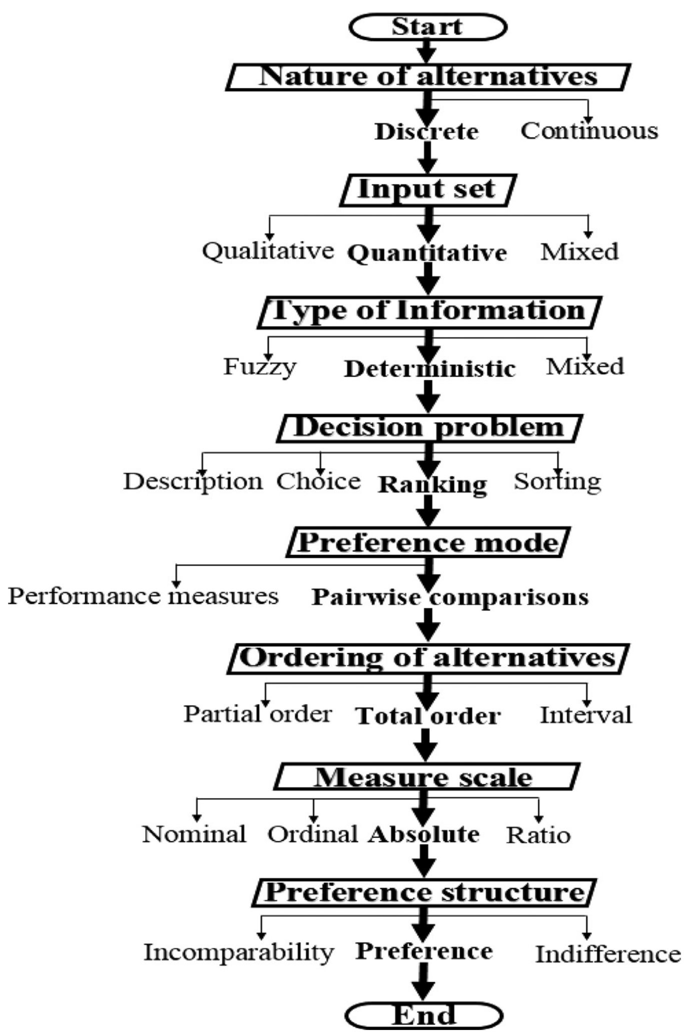

Fig. 2. New MCDM methods selection framework branch for numerical example 1, 2 and 3.

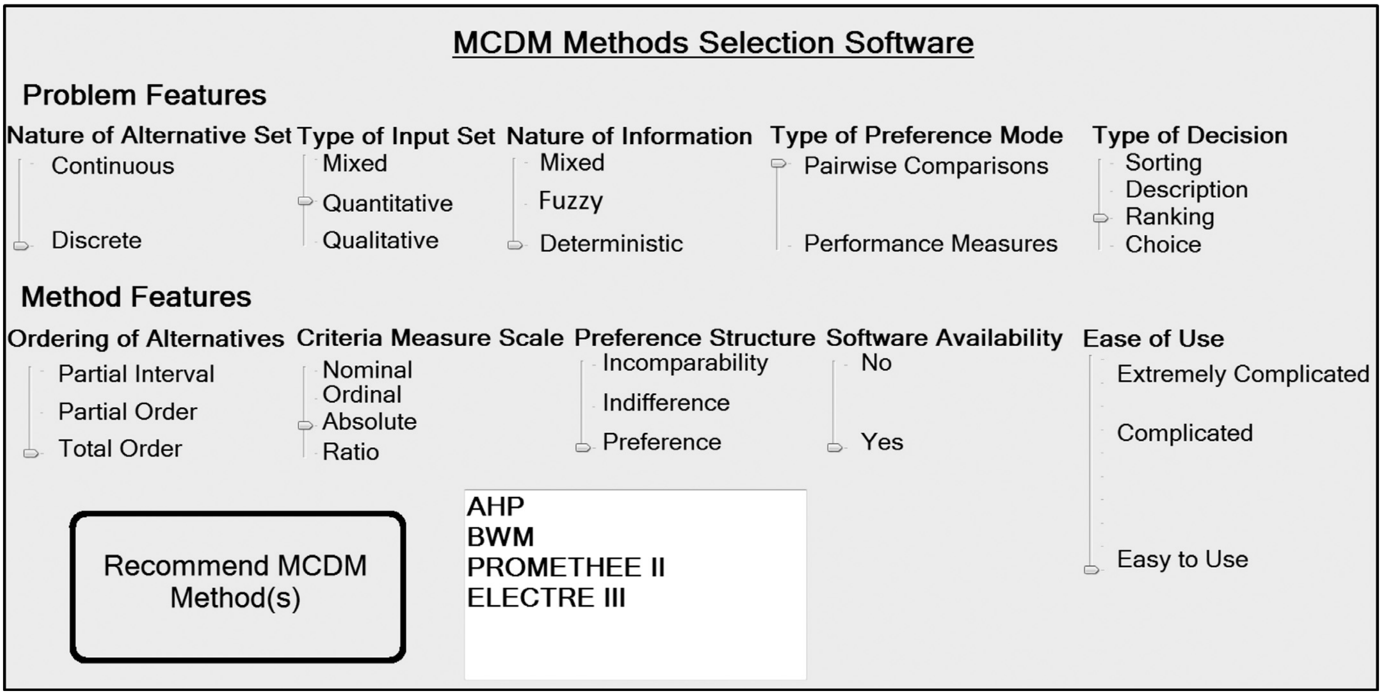

Fig. 3. Screen shot of the new MCDM methods selection framework for numerical example 1, 2 and 3.

Table 2
Minimum percentage change in criteria for U.S. coast guard example using AHP.

Criteria	Percentage change	New ranking
C_1: Performance of duties	8.446	$A_1 > A_2 > A_3 > A_4 > (A_5 = A_6)$
C_2: Interpersonal relations	**−6.299**	$A_1 > A_2 > A_3 > A_4 > (A_5 = A_6)$
C_3: Leadership skills	10.063	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
C_4: Communication skills	−12	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
C_5: Personal qualities	−42.857	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
C_6: Representing the coast guard	−13.415	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$

Table 3
Minimum percentage change in criteria weights for U.S. coast guard example using PROMETHEE II.

Criteria	Percentage change	New ranking
C_1: Performance of duties	**−2.027**	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
C_2: Interpersonal relations	−5.0512	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
C_3: Leadership skills	−5.660	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
C_4: Communication skills	12	$A_2 > A_1 > A_3 > A_4 > A_6 > A_5$
C_5: Personal qualities	19.048	$A_2 > A_1 > A_3 > A_4 > A_6 > A_5$
C_6: Representing the coast guard	9.756	$A_2 > A_1 > A_3 > A_4 > A_6 > A_5$

the "Interpersonal Relations" criterion to change the ranking of alternatives two and three, a 6.299% decrease in its weight change the preference from alternative three to alternative two ($A_2 > A_3$).

The most critical criterion in this numerical example using PROMETHEE II was the first criterion (C_1) that represented "Performance Of Duties", signified by the smallest value (bold number) in Table 3. This value represented the minimum percentage change required in the weight of the "Performance of Duties" criterion to change the ranking of alternatives one and two. Where a 2.027% decrease in its weight changed the preference from alternatives two to alternative one ($A_1 > A_2$).

Table 4
Minimum percentage change in performance measures for U.S. coast guard example using AHP.

Performance measure	Percentage change	New ranking
A_1C_1	−4	$(A_1 = A_3) > A_2 > A_4 > A_6 > A_5$
A_2C_1	1	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_3C_1	2	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_3C_1	−2	$A_1 > A_2 > (A_3 = A_4) > A_6 > A_5$
A_4C_1	3	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_1	3	$A_1 > (A_2 = A_3) > A_4 > A_5 > A_6$
A_6C_1	−3	$A_1 > (A_2 = A_3) > A_4 > A_5 > A_6$
A_1C_2	−4	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_2C_2	2	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_2C_2	−2	$A_1 > A_3 > (A_2 = A_4) > A_6 > A_5$
A_3C_2	1	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_4C_2	3	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_2	4	$A_1 > (A_2 = A_3) > A_4 > A_5 > A_6$
A_6C_2	−3	$A_1 > (A_2 = A_3) > A_4 > A_5 > A_6$
A_1C_3	−5	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_2C_3	2	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_3C_3	2	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_4C_3	5	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_3	5	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_6C_3	−6	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_1C_4	−8	$(A_1 = A_2) > A_3 > A_4 > A_6 > A_5$
A_2C_4	2	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_3C_4	2	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_4C_4	6	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_4	7	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_6C_4	−6	$A_1 > (A_2 = A_3) > A_4 > A_5 > A_6$
A_1C_5	−11	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_2C_5	3	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_3C_5	3	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_4C_5	9	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_5	10	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_6C_5	−10	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_1C_6	−13	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_2C_6	4	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_3C_6	4	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_4C_6	9	$A_1 > (A_2 = A_3 = A_4) > A_6 > A_5$
A_5C_6	10	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$
A_6C_6	−11	$A_1 > (A_2 = A_3) > A_4 > (A_5 = A_6)$

Table 5
Minimum percentage change in performance measures for U.S. coast guard example using PROMETHEE II.

Performance measure	Percentage change	New ranking
A_1C_1	1	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_2C_1	−5	$A_3 > A_1 > A_4 > A_2 > A_5 > A_6$
A_3C_1	−1	$A_4 > A_2 > A_1 > A_3 > A_5 > A_6$
A_4C_1	1	$A_4 > A_2 > A_1 > A_3 > A_6 > A_5$
A_5C_1	−1	$A_3 > A_4 > A_2 > A_1 > A_6 > A_5$
A_5C_1	1	$A_2 > A_1 > A_3 > A_4 > A_5 > A_6$
A_6C_1	−1	$A_1 > A_3 > A_2 > A_4 > A_5 > A_6$
A_1C_2	2	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_2C_2	1	$A_2 > A_3 > A_3 > A_4 > A_6 > A_5$
A_2C_2	−1	$A_3 > A_1 > A_2 > A_4 > A_5 > A_6$
A_3C_2	−2	$A_1 > A_2 > A_3 > A_4 > A_6 > A_5$
A_4C_2	6	$A_5 > A_2 > A_3 > A_4 > A_1 > A_6$
A_4C_2	−6	$A_2 > A_3 > A_1 > A_4 > A_5 > A_6$
A_5C_2	1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_5C_2	−1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_6C_2	−9	$A_3 > A_1 > A_2 > A_4 > A_5 > A_6$
A_1C_3	−11	$A_3 > A_2 > A_4 > A_1 > A_6 > A_5$
A_2C_3	4	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_3C_3	−9	$A_2 > A_1 > A_4 > A_3 > A_6 > A_5$
A_4C_3	−3	$A_3 > A_2 > A_1 > A_4 > A_5 > A_6$
A_5C_3	3	$A_3 > A_2 > A_1 > A_4 > A_6 > A_5$
A_6C_3	12	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
A_1C_4	−5	$A_2 > A_3 > A_4 > A_1 > A_6 > A_5$
A_2C_4	1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_3C_4	−1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_4C_4	−1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_5C_4	1	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_6C_4	2	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
A_1C_5	−11	$A_2 > A_3 > A_1 > A_4 > A_6 > A_5$
A_2C_5	−4	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
A_3C_5	−3	$A_2 > A_1 > A_3 > A_4 > A_6 > A_5$
A_4C_5	5	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
A_5C_5	3	$A_2 > A_1 > A_3 > A_4 > A_5 > A_6$
A_6C_5	4	$A_2 > A_1 > A_3 > A_4 > A_6 > A_5$
A_1C_6	3	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_2C_6	−12	$A_3 > A_1 > A_2 > A_4 > A_6 > A_5$
A_3C_6	N/F	–
A_4C_6	−3	$A_1 > A_3 > A_2 > A_4 > A_6 > A_5$
A_5C_6	6	$A_3 > A_2 > A_1 > A_4 > A_5 > A_6$
A_6C_6	N/F	–

The most critical performance measures in this numerical example using AHP were (A_2C_1 & A_3C_2), signified by the smallest values (bold numbers) in Table 4. These values represented the minimum percentage change required in the value of performance measure (A_2C_1) or (A_3C_2) to change the ranking of alternatives two and three (A_2 & A_3). A 1% increase in the value of performance measure (A_2C_1) changed the order to prefer alternative two over alternative three ($A_2 > A_3$). A 1% increase in the value of performance measure (A_3C_2) changed the order to prefer alternative three to alternative two ($A_3 > A_2$).

The most critical performance measures in this numerical example using PROMETHEE II were (A_1C_1, A_3C_1, A_4C_1, A_5C_1, A_6C_1, A_2C_2, A_5C_2, A_2C_4, A_3C_4, A_4C_4 & A_5C_4), signified by the smallest values (bold numbers) in Table 5. These values represented the minimum percentage change required in the value of performance measures (A_1C_1, A_3C_1, A_4C_1, A_5C_1, A_5C_1, A_6C_1, A_2C_2, A_5C_2, A_2C_4, A_3C_4, A_4C_4 & A_5C_4) to change the ranking of the alternatives. A 1% increase in the value of (A_1C_1) changed the ranking of alternatives one and three ($A_1 > A_3$). A 1% decrease in the value of (A_3C_1) changed the ranking of alternatives three and four ($A_4 > A_3$). A 1% decrease in the value of (A_5C_1) changed the ranking of alternatives two and four ($A_4 > A_2$). A 1% decrease in the value of (A_6C_1) changed the ranking of alternatives one and three ($A_1 > A_3$) and alternatives five and six ($A_5 > A_6$). A 1% increase in the value of (A_2C_2) changed the ranking of alternatives two and three ($A_2 > A_3$). A 1% decrease in the value of (A_2C_2) changed the ranking of alternatives one and two ($A_1 > A_2$) and alternatives five and six ($A_5 > A_6$). A 1% increase in the value of (A_4C_1) changed the ranking of alternatives four and three ($A_4 > A_3$). A 1% increase in the value of (A_5C_1) changed the ranking of alternatives three and one ($A_1 > A_3$) and alternatives five and six ($A_5 > A_6$). A 1% decrease in the value of (A_5C_1) changed the ranking of alternatives two and four ($A_4 > A_2$). A 1% change in the value of (A_5C_2) changed the ranking of alternatives two and three ($A_2 > A_3$). A 1% increase in the values of (A_2C_4 or A_5C_4) changed the ranking of alternatives two and three ($A_2 > A_3$). A 1% decrease in the values of (A_3C_4, A_4C_4) changed the ranking of alternatives two and three ($A_2 > A_3$).

This decisional problem provided specific examples of four of the scenarios listed in Section 2 and actions were considered to address them:

SCENARIO ONE: AHP and PROMETHEE II delivered different outcomes. AHP required a 6.299% decrease in the value of most critical criterion weight (i.e. "Interpersonal Relations") to alter the ranking of alternatives, while PROMETHEE II required a 2.027% decrease to the value of the most critical criterion weight (i.e. "Performance of Duties") to alter the ranking of alternatives. AHP was 3.108 times less sensitive to changes in the value of the most critical criterion weight than PROMETHEE II. Decision makers often prefer a method that is resilient to changes in criteria weights, they often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. AHP would be recommended for this decisional problem when decision makers were uncertain of criteria weights or anticipated a risk factor of high severity that could affect criteria weights.

SCENARIO TWO: AHP required a 1% increase to the values of most critical performance measures to alter the ranking of the alternatives. PROMETHEE II also required a 1% change to the values of the most critical performance measures to alter the ranking of the alternatives. Both methods had the same sensitivity towards uncertainty in performance measures; AHP had two critical performance measures while PROMETHEE II had fourteen critical performance measures. Decision makers often prefer a method that is less sensitive to changes in the values of the performance measures, they often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. AHP would also be recommended for this decisional problem if decision makers were uncertain of performance measures or anticipated a risk factor of high severity that could affect performance measures. Analysis of these results showed that the number of critical performance measures and the number of critical criteria should be taken into consideration when recommending a MCDM method from a subset of candidate methods. From Tables 2 and 4, AHP had one critical criterion and two critical performance measures, from Tables 3 and 5 PROMETHEE II had one critical criterion and fourteen critical performance measures, AHP would be recommended for this decisional problem when the number of critical performance measures and the number of critical criteria were taken into consideration.

SCENARIO THREE: AHP was less sensitive than PROMETHEE II to changes in the values of the most critical criteria weights and had fewer critical performance measures. The number of most critical criteria and most critical performance measures a method has for a certain decisional problem provides guidance towards the number of risk factors a method is vulnerable to. The higher the number of most critical criteria and most critical performance measures, the higher the number of risk factors a method is sensitive towards that might change the final outcome of the method. Moreover, the lower the minimum percentage change required in the most critical criteria and the most critical performance measure, the higher the sensitivity of the final outcome of a method to changes in the inputs (i.e. risk and uncertainty). Recommending AHP for this decisional problem when risk and uncertainty would affect both criteria weights and / or performance measures may provide a more robust outcome.

Table 6
Decision matrix for Boing strategic market decisions example.

Alternative criteria	A_1 USA	A_2 Asia	A_3 Europe	A_4 Middle East
C_1: Market size for 115–150 passengers = 0.073	0.471	0.209	0.215	0.106
C_2: Market size for 175–210 passengers = 0.021	0.471	0.209	0.215	0.106
C_3: Market size for + 260 passengers = 0.032	0.317	0.426	0.174	0.083
C_4: Market growth rate for 115–150 passengers = 0.161	0.130	0.546	0.119	0.205
C_5: Market growth rate for 175–210 passengers = 0.047	0.130	0.546	0.119	0.205
C_6: Market growth rate for + 260 passengers = 0.070	0.083	0.608	0.124	0.185
C_7: Market competitive for 115–150 passengers = 0.016	0.499	0.284	0.083	0.134
C_8: Market competitive for 175–210 passengers = 0.007	0.499	0.284	0.083	0.134
C_9: Market competitive for + 260 passengers = 0.010	0.499	0.284	0.083	0.134
C_{10}: Political factors enhancing market size for 115–150 passengers = 0.021	0.656	0.217	0.049	0.078
C_{11}: Political factors enhancing market size for 175–210 passengers = 0.021	0.656	0.217	0.049	0.078
C_{12}: Political factors enhancing market size for + 260 passengers = 0.021	0.656	0.217	0.049	0.078
C_{13}: Market share for 115–150 passengers = 0.013	0.527	0.280	0.086	0.107
C_{14}: Market share for 175–210 passengers = 0.006	0.527	0.280	0.086	0.107
C_{15}: Market share for + 260 passengers = 0.008	0.517	0.333	0.075	0.075
C_{16}: Price competition for 115–150 passengers = 0.052	0.498	0.284	0.097	0.121
C_{17}: Price competition for 175–210 passengers = 0.030	0.498	0.284	0.097	0.121
C_{18}: Price competition for + 260 passengers = 0.048	0.498	0.284	0.097	0.121
C_{19}: Product quality for 115–150 passengers = 0.094	0.250	0.250	0.250	0.250
C_{20}: Product quality for 175–210 passengers = 0.094	0.250	0.250	0.250	0.250
C_{21}: Product quality for + 260 passengers = 0.094	0.250	0.250	0.250	0.250
C_{22}: Customer knowledge for 115–150 passengers = 0.022	0.457	0.329	0.095	0.119
C_{23}: Customer knowledge for 175–210 passengers = 0.016	0.457	0.329	0.095	0.119
C_{24}: Customer knowledge for + 260 passengers plane = 0.021	0.457	0.329	0.095	0.119

SCENARIO FOUR: AHP provided the ranking of alternatives: $A_1 > (A_2 = A_3) > A_4 > A_6 > A_5$, and required a 6.299% change in the value of the most critical criterion weight or a 1% change in the most critical performance measures to change the ranking of the alternatives. Whenever two alternatives are indifferent from each other in the final outcome, the state of these alternatives might be considered as a state of equilibrium, where any change in any performance measure of one alternative with respect to any criteria might prefer one alternative to the other, and / or any change in any criteria weights might prefer one alternative to the other.

In all four scenarios, AHP would be preferred for this problem.

Moreover the analysis of the results of this numerical example and the results from other case studies conducted by the authors (available upon request) showed that the higher the weight of the criterion the higher the probability that it was the most critical criterion and the higher the probability that it was the most critical performance measure to be with respect to that criterion.

3.2. Numerical example 2 (BOING strategic market decisions)

This example considered the threat proposed by Airbus to the commercial jet aircraft market dominated by Boeing. This decisional problem evaluated the market attractiveness and competitive strength for Boeing in four global markets. A set of twenty-four criteria were identified.

Factors addressed in this numerical example considered the changing nature of airline needs and the international business environment. Market attractiveness included political climate, competitive intensity, growth and size. The competitive strength in each of the four regions was assessed based on relative market share, price competition, aircraft quality, and customer knowledge of each type of plane.

The set of criteria were:

C_1: Market size for 115–150 passengers plane
C_2: Market size for 175–210 passengers plane
C_3: Market size for 260 and more passengers plane
C_4: Market growth rate for 115–150 passengers plane
C_5: Market growth rate for 175–210 passengers plane
C_6: Market growth rate for 260 and more passengers plane
C_7: Market competitive intensity for 115–150 passengers plane
C_8: Market competitive intensity for 175–210 passengers plane
C_9: Market competitive intensity for 260 and more passengers plane
C_{10}: Political factors enhancing the market size for 115–150 passengers plane
C_{11}: Political factors enhancing the market size for 175–210 passengers plane
C_{12}: Political factors enhancing the market size for 260 and more passengers plane
C_{13}: Market share for 115–150 passengers plane
C_{14}: Market share for 175–210 passengers plane
C_{15}: Market share for 260 and more passengers plane
C_{16}: Price competition for 115–150 passengers plane
C_{17}: Price competition for 175–210 passengers plane
C_{18}: Price competition for 260 and more passengers plane
C_{19}: Product quality for 115–150 passengers plane
C_{20}: Product quality for 175–210 passengers plane
C_{21}: Product quality for 260 and more passengers plane
C_{22}: Customer knowledge for 115–150 passengers plane
C_{23}: Customer knowledge for 175–210 passengers plane
C_{24}: Customer knowledge for 260 and more passengers plane

The set of alternatives that represented the global market regions were:

A_1: United States
A_2: Asia
A_3: Europe
A_4: Middle East

Criteria weights and performance measures for alternatives with respect to criteria are shown as a decision matrix in Table 6.

The Novel MCDM Methods Selection Framework was applied to this decisional problem as shown in Fig. 2. A screen shot of the structured MCDM methods selection framework is shown in Fig. 3. The group of candidate methods that were suitable for this decisional problem were the same as for example 1.

AHP and PROMETHE II methods were again selected for this decisional problem because they were available and easy to use. AHP provided the following ranking of alternatives: $A_2 > A_1 > A_4 > A_3$, with a global score of alternatives: $A_1 = 0.308$, $A_2 = 0.322$, $A_3 = 0.180$

Table 7
Minimum percentage change in criteria weights for Boing strategic market decisions example using AHP.

Criteria	Percentage change	New ranking
C_1: Market size for 115–150 passengers	67.123	$A_1 > A_2 > A_4 > A_3$
C_2: Market size for 175–210	242.857	$A_1 > A_2 > A_4 > A_3$
C_3: Market size for + 260 passengers	340.625	$A_2 > A_1 > A_3 > A_4$
C_4: Market growth rate for 115–150 passengers	**−19.255**	$A_1 > A_2 > A_4 > A_3$
C_5: Market growth rate for 175–210 passengers	−76.596	$A_1 > A_2 > A_4 > A_3$
C_6: Market growth rate for + 260 passengers	−38.571	$A_1 > A_2 > A_4 > A_3$
C_7: Market competitive for 115–150 passengers	375	$A_1 > A_2 > A_4 > A_3$
C_8: Market competitive for 175–210 passengers	871.429	$A_1 > A_2 > A_4 > A_3$
C_9: Market competitive for + 260 passengers	610	$A_1 > A_2 > A_4 > A_3$
C_{10}: Political factors enhancing market size for 115–150 passengers	142.857	$A_1 > A_2 > A_4 > A_3$
C_{11}: Political factors enhancing market size for 175–210 passengers	142.857	$A_1 > A_2 > A_4 > A_3$
C_{12}: Political factors enhancing market size for + 260 passengers	142.857	$A_1 > A_2 > A_4 > A_3$
C_{13}: Market share for 115–150 passengers	407.692	$A_1 > A_2 > A_4 > A_3$
C_{14}: Market share for 175–210 passengers	883.333	$A_1 > A_2 > A_4 > A_3$
C_{15}: Market share for + 260 passengers	875	$A_1 > A_2 > A_4 > A_3$
C_{16}: Price competition for 115–150 passengers	113.462	$A_1 > A_2 > A_4 > A_3$
C_{17}: Price competition for 175–210 passengers	200	$A_1 > A_2 > A_4 > A_3$
C_{18}: Price competition for + 260 passengers	118.75	$A_1 > A_2 > A_4 > A_3$
C_{19}: Product quality for 115–150 passengers	963.830	$A_1 = A_2 = A_3 = A_4$
C_{20}: Product quality for 175–210 passengers	963.830	$A_1 = A_2 = A_3 = A_4$
C_{21}: Product quality for + 260 passengers	963.830	$A_1 = A_2 = A_3 = A_4$
C_{22}: Customer knowledge for 115–150 passengers	431.818	$A_1 > A_2 > A_4 > A_3$
C_{23}: Customer knowledge for 175–210 passengers	606.250	$A_1 > A_2 > A_4 > A_3$
C_{24}: Customer knowledge for + 260 passengers	452.381	$A_1 > A_2 > A_4 > A_3$

and $A_4 = 0.191$. PROMETHEE II provided the same ranking of alternatives: $A_2 > A_1 > A_4 > A_3$, with a net flow of alternatives: $\Phi(A_1) = 0.278$, $\Phi(A_2) = 0.384$, $\Phi(A_3) = -0.521$ and $\Phi(A_4) = -0.140$.

Although AHP and PROMETHEE II methods delivered the same ranking of alternatives, sensitivity analysis was conducted on both methods' outcomes to recommend the method that best suited this decisional problem and provided the most robust outcome. Minimum percentage change required to alter the ranking of alternatives for the most critical criterion weight and most critical performance measure were calculated. Results are shown in Tables 7, 8, 9 and 10. N/F shown in Tables 9 and 10 stands for a non-feasible value where ± 100% change in the value of that performance measure did not affect the original ranking of the alternatives.

Table 8
Minimum percentage change in criteria weights for Boing strategic market decisions example using PROMETHEE II.

Criteria	Percentage change	New ranking
C_1	105.479	$A_1 > A_2 > A_4 > A_3$
C_2	376.190	$A_1 > A_2 > A_4 > A_3$
C_3	1118.75	$A_2 > A_4 > A_1 > A_4$
C_4	**−50.311**	$A_1 > A_2 > A_4 > A_3$
C_5	793.617	$A_2 > A_4 > A_1 > A_3$
C_6	328.571	$A_2 > A_4 > A_1 > A_3$
C_7	900	$A_1 > A_2 > A_4 > A_3$
C_8	2042.857	$A_1 > A_2 > A_4 > A_3$
C_9	1400	$A_1 > A_2 > A_4 > A_3$
C_{10}	661.905	$A_1 > A_2 > A_4 > A_3$
C_{11}	661.905	$A_1 > A_2 > A_4 > A_3$
C_{12}	661.905	$A_1 > A_2 > A_4 > A_3$
C_{13}	1053.846	$A_1 > A_2 > A_4 > A_3$
C_{14}	2400	$A_1 > A_2 > A_4 > A_3$
C_{15}	1775	$A_1 > A_2 > A_4 > A_3$
C_{16}	265.385	$A_1 > A_2 > A_4 > A_3$
C_{17}	466.667	$A_1 > A_2 > A_4 > A_3$
C_{18}	275	$A_1 > A_2 > A_4 > A_3$
C_{19}	963.830	$A_1 = A_2 = A_3 = A_4$
C_{20}	963.830	$A_1 = A_2 = A_3 = A_4$
C_{21}	963.830	$A_1 = A_2 = A_3 = A_4$
C_{22}	627.273	$A_1 > A_2 > A_4 > A_3$
C_{23}	900	$A_1 > A_2 > A_4 > A_3$
C_{24}	661.905	$A_1 > A_2 > A_4 > A_3$

The most critical criterion in this numerical example using AHP was the fourth criterion (C_4) (i.e. "Market growth rate for 115–150 passengers") signified by the smallest value (bold number) in Table 7. This value represented the minimum percentage change required in the weight of the "Market growth rate for the 115–150 passengers" criterion to change the ranking of alternatives one and two ($A_1 > A_2$). A 19.255% decrease in its weight preferred the "United States" market region (A_1) to "Asia" market region (A_2).

The most critical criterion in this numerical example using PROMETHEE II was the fourth criterion (C_4) (i.e. "Market growth rate for 115–150 passengers"), signified by the smallest value (bold number) in Table 8. This value represented the minimum percentage change required in the weight of the "Market growth rate for 115–150 passengers" to change the ranking of alternatives one and two ($A_1 > A_2$). A 50.311% decrease in its weight preferred the "United States" market region (A_1) to "Asia" market region (A_2).

The most critical performance measures in this numerical example using AHP were (A_4C_{19}, A_4C_{20} & A_4C_{21}), signified by the smallest values (bold numbers) in Table 9. These values represented the minimum percentage change required in the value of their performance measures to change the ranking of alternatives three and four "Europe" and the "Middle East" ($A_3 > A_4$). A 25% decrease in the values of their performance measures changed the preference from the "Middle East" region to "Europe".

The most critical performance measures in this numerical example using PROMETHEE II were (A_1C_{19}, A_2C_{19} A_1C_{20}, A_2C_{20}, A_1C_{21} & A_2C_{21}), signified by the smallest values (bold numbers) in Table 10. These values represented the minimum percentage change required in the values of performance measures (A_1C_{19}), (A_2C_{19}), (A_1C_{20}), (A_2C_{20}), (A_1C_{21}) or (A_2C_{21}) to change the ranking of the alternatives one and two, "United states" and "Asia" ($A_1 > A_2$). A 1% increase in the value of their performance measures changed the preference from "Asia" to the "United States". A 1% decrease in the value of their performance measures changed the preference from "Asia" to the "United States".

This decisional problem provided examples of three scenarios listed in Section 2 and actions were considered to address them:

SCENARIO ONE: AHP and PROMETHEE II delivered the same outcome. AHP required a 19.255% decrease to the value of most critical criterion weight (i.e. "Market growth rate for 115–150 passengers") to alter the ranking of alternatives, while PROMETHEE II required a

Table 9
Minimum percentage change in performance measures for Boing strategic market decisions example using AHP.

Performance measure	Percentage change	New ranking
A_1C_1	N/F	–
A_2C_1	N/F	–
A_3C_1	57	$A_2 > A_1 > A_3 > A_4$
A_4C_1	N/F	–
A_1C_2	N/F	–
A_2C_2	N/F	–
A_2C_2	N/F	–
A_3C_2	N/F	–
A_4C_2	N/F	–
A_1C_3	N/F	–
A_2C_3	N/F	–
A_3C_3	−82	$A_1 > A_2 > A_4 > A_3$
A_4C_3	N/F	–
A_1C_4	71	$A_1 > A_2 > A_4 > A_3$
A_2C_4	−30	$A_1 > A_2 > A_4 > A_3$
A_3C_4	65	$A_2 > A_1 > A_3 > A_4$
A_4C_4	−41	$A_2 > A_1 > A_3 > A_4$
A_1C_5	N/F	–
A_2C_5	−59	$A_1 > A_2 > A_4 > A_3$
A_3C_5	N/F	–
A_4C_5	N/F	–
A_1C_6	N/F	–
A_2C_6	−55	$A_1 > A_2 > A_4 > A_3$
A_3C_6	N/F	–
A_4C_6	N/F	–
A_1C_7	N/F	–
A_2C_7	N/F	–
A_3C_7	N/F	–
A_4C_7	N/F	–
A_1C_8	N/F	–
A_2C_8	N/F	–
A_2C_8	N/F	–
A_3C_8	N/F	–
A_4C_8	N/F	–
A_1C_9	N/F	–
A_2C_9	N/F	–
A_3C_9	N/F	–
A_4C_9	N/F	–
A_1C_{10}	N/F	–
A_2C_{10}	N/F	–
A_3C_{10}	N/F	–
A_4C_{10}	N/F	–
A_1C_{11}	N/F	–
A_2C_{11}	N/F	–
A_3C_{11}	N/F	–
A_4C_{11}	N/F	–
A_1C_{12}	N/F	–
A_2C_{12}	N/F	–
A_3C_{12}	N/F	–
A_4C_{12}	N/F	–
A_1C_{13}	N/F	–
A_2C_{13}	N/F	–
A_3C_{13}	N/F	–
A_4C_{13}	N/F	–
A_1C_{14}	N/F	–
A_2C_{14}	N/F	–
A_3C_{14}	N/F	–
A_4C_{14}	N/F	–
A_1C_{15}	N/F	–
A_2C_{15}	N/F	–
A_3C_{15}	N/F	–
A_4C_{15}	N/F	–
A_1C_{16}	N/F	–
A_2C_{16}	N/F	–
A_3C_{16}	N/F	–
A_4C_{16}	N/F	–
A_1C_{17}	N/F	–
A_2C_{17}	N/F	–
A_3C_{17}	N/F	–
A_4C_{17}	N/F	–
A_1C_{18}	N/F	–
A_2C_{18}	N/F	–
A_3C_{18}	N/F	–
A_4C_{18}	N/F	–
A_1C_{19}	39	$A_1 > A_2 > A_4 > A_3$
A_2C_{19}	−32	$A_1 > A_2 > A_4 > A_3$
A_3C_{19}	30	$A_2 > A_1 > A_3 > A_4$
A_4C_{19}	**−25**	$A_2 > A_1 > A_3 > A_4$
A_1C_{20}	39	$A_1 > A_2 > A_4 > A_3$
A_2C_{20}	−32	$A_1 > A_2 > A_4 > A_3$
A_3C_{20}	30	$A_2 > A_1 > A_3 > A_4$
A_4C_{20}	**−25**	$A_2 > A_1 > A_3 > A_4$
A_1C_{21}	39	$A_1 > A_2 > A_4 > A_3$
A_2C_{21}	−32	$A_1 > A_2 > A_4 > A_3$
A_3C_{21}	30	$A_2 > A_1 > A_3 > A_4$
A_4C_{21}	**−25**	$A_2 > A_1 > A_3 > A_4$
A_1C_{22}	N/F	–
A_2C_{22}	N/F	–
A_4C_{22}	N/F	–
A_1C_{23}	N/F	–
A_2C_{23}	N/F	–
A_3C_{23}	N/F	–
A_4C_{23}	N/F	–
A_1C_{24}	N/F	–
A_2C_{24}	N/F	–
A_3C_{24}	N/F	–
A_4C_{24}	N/F	–

50.311% decrease to the value of the most critical criterion weight (i.e. “Market growth rate for 115–150 passengers”) to alter the ranking of alternatives. PROMETHEE II was 2.613 times less sensitive to changes in the value of the most critical criterion weight than AHP. Decision makers often prefer a method that is resilient to changes in criteria weights and often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. PROMETHEE II would be recommended for this decisional problem when decision makers were uncertain of criteria weights or anticipated a risk factor of high severity that could affect criteria weights.

SCENARIO TWO: AHP required a 25% increase to the values of most critical performance measures to alter the ranking of the alternatives. PROMETHEE II required a 1% change to the values of the most critical performance measures to alter the ranking of the alternatives. AHP was 25 times less sensitive than PROMETHEE II to changes in the values of the most critical performance measures. Decision makers often prefer a method that is less sensitive to changes in the values of the performance measures and often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. AHP would be recommended for this decisional problem when decision makers were uncertain of performance measures or anticipated a risk factor of high severity that could affect performance measures.

SCENARIO THREE: PROMETHEE II was less sensitive than AHP to changes in the value of the most critical criterion weight and required a 50.311% change to the value of the most critical criterion weight to change the ranking of the alternatives. AHP was less sensitive than PROMETHEE to changes in the values of the most critical performance measures and required a 25% change to the values of the most critical performance measures to change the ranking of the alternatives. The number of the most critical criteria and the most critical performance measures a method has for a decisional problem provides guidance about the number of risk factors the method is vulnerable towards. The higher the number of the most critical criteria and the most critical performance measures, the higher the number of risk factors a method is sensitive towards that might change the final outcome. Moreover, the lower the minimum percentage change required in the most critical criteria and the most critical performance measure, the higher the

Table 10
Minimum percentage change in performance measures for Boing strategic market decisions example using PROMETHEE II.

Performance measure	Percentage change	New ranking
A_1C_1	N/F	–
A_2C_1	N/F	–
A_3C_1	N/F	–
A_4C_1	N/F	–
A_1C_2	N/F	–
A_2C_2	N/F	–
A_2C_2	N/F	–
A_3C_2	N/F	–
A_4C_2	N/F	–
A_1C_3	N/F	–
A_2C_3	N/F	–
A_3C_3	N/F	–
A_4C_3	N/F	–
A_1C_4	47	$A_1 > A_2 > A_4 > A_3$
A_2C_4	−44	$A_1 > A_2 > A_4 > A_3$
A_3C_4	N/F	–
A_4C_4	99	$A_1 > A_2 > A_4 > A_3$
A_1C_5	N/F	–
A_2C_5	−63	$A_1 > A_2 > A_4 > A_3$
A_3C_5	N/F	–
A_4C_5	N/F	–
A_1C_6	N/F	–
A_2C_6	−72	$A_1 > A_2 > A_4 > A_3$
A_3C_6	N/F	–
A_4C_6	N/F	–
A_1C_7	N/F	–
A_2C_7	N/F	–
A_3C_7	N/F	–
A_4C_7	N/F	–
A_1C_8	N/F	–
A_2C_8	N/F	–
A_2C_8	N/F	–
A_3C_8	N/F	–
A_4C_8	N/F	–
A_1C_9	N/F	–
A_2C_9	N/F	–
A_3C_9	N/F	–
A_4C_9	N/F	–
A_1C_{10}	N/F	–
A_2C_{10}	N/F	–
A_3C_{10}	N/F	–
A_4C_{10}	N/F	–
A_1C_{11}	N/F	–
A_2C_{11}	N/F	–
A_3C_{11}	N/F	–
A_4C_{11}	N/F	–
A_1C_{12}	N/F	–
A_2C_{12}	N/F	–
A_3C_{12}	N/F	–
A_4C_{12}	N/F	–
A_1C_{13}	N/F	–
A_2C_{13}	N/F	–
A_3C_{13}	N/F	–
A_4C_{13}	N/F	–
A_1C_{14}	N/F	–
A_2C_{14}	N/F	–
A_3C_{14}	N/F	–
A_4C_{14}	N/F	–
A_1C_{15}	N/F	–
A_2C_{15}	N/F	–
A_3C_{15}	N/F	–
A_4C_{15}	N/F	–
A_1C_{16}	N/F	–
A_2C_{16}	N/F	–
A_3C_{16}	N/F	–
A_4C_{16}	N/F	–
A_1C_{17}	N/F	–
A_2C_{17}	N/F	–
A_3C_{17}	N/F	–
A_4C_{17}	N/F	–
A_1C_{18}	N/F	–
A_2C_{18}	N/F	–
A_3C_{18}	N/F	–
A_4C_{18}	N/F	–
A_1C_{19}	**1**	$A_1 > A_2 > A_4 > A_3$
A_2C_{19}	**−1**	$A_1 > A_2 > A_4 > A_3$
A_3C_{19}	N/F	–
A_4C_{19}	N/F	–
A_1C_{20}	**1**	$A_1 > A_2 > A_4 > A_3$
A_2C_{20}	**−1**	$A_1 > A_2 > A_4 > A_3$
A_3C_{20}	N/F	–
A_4C_{20}	N/F	–
A_1C_{21}	**1**	$A_1 > A_2 > A_4 > A_3$
A_2C_{21}	**−1**	$A_1 > A_2 > A_4 > A_3$
A_3C_{21}	N/F	–
A_4C_{21}	N/F	–
A_1C_{22}	N/F	–
A_2C_{22}	N/F	–
A_3C_{22}	N/F	–
A_4C_{22}	N/F	–
A_1C_{23}	N/F	–
A_2C_{23}	N/F	–
A_3C_{23}	N/F	–
A_4C_{23}	N/F	–
A_1C_{24}	N/F	–
A_2C_{24}	N/F	–
A_3C_{24}	N/F	–
A_4C_{24}	N/F	–

sensitivity of the final outcome of a method to changes in the inputs (i.e. risk and uncertainty). In this case a best compromise between minimum percentage change required in the most critical performance measures and the most critical criteria should be made. Recommending AHP for this decisional problem would provide a more robust outcome with less vulnerability to risk and uncertainty.

3.3. Numerical example 3 (Corporate relocation decision)

This numerical example considered ways to determine the best city in the United States of America to relocate a corporation. A set of six criteria were identified and five cities met the minimum requirements identified by the analysts.

The set of criteria were:

- C_1: Financial Considerations
- C_2: Employee Availability
- C_3: Support Services
- C_4: Cultural Opportunities
- C_5: Leisure Activities
- C_6: Climate; Seasonal, and Year Round

The set of alternatives were:

- A_1: New York City
- A_2: Washington D.C.
- A_3: Atlanta, Georgia
- A_4: Los Angeles, California
- A_5: Portland, Oregon

Criteria weights and performance measures for all the alternative with respect to all the criteria are shown as a decision matrix in Table 11.

The Novel MCDM Methods Selection Framework was applied to this decisional problem as shown in Fig. 2. A screen shot of the structured MCDM methods selection framework is shown in Fig. 3. The group of candidate methods that were suitable for this decisional problem were the same as for Examples 1 and 2.

AHP and PROMETHEE II were selected for this numerical example. AHP provided the following ranking of alternatives:

Table 11
Decision matrix for corporate relocation decision example.

Alternative criteria	A_1 N.Y.C.	A_2 Washington D.C.	A_3 Atlanta	A_4 L.A.	A_5 Portland
C_1: Financial Considerations = 0.428	0.313	0.119	0.176	0.346	0.046
C_2: Employee Availability = 0.207	0.064	0.098	0.168	0.493	0.177
C_3: Support Services = 0.207	0.416	0.062	0.116	0.284	0.122
C_4: Cultural Opportunities = 0.041	0.300	0.215	0.105	0.307	0.073
C_5: Leisure Activities = 0.063	0.060	0.107	0.160	0.315	0.359
C_6: Climate = 0.053	0.082	0.082	0.173	0.442	0.220

$A_4 > A_1 > A_3 > A_5 > A_2$, with a global score of alternatives: $A_1 = 0.264$, $A_2 = 0.107$, $A_3 = 0.158$, $A_4 = 0.358$ and $A_5 = 0.112$. PROMETHEE II provided the same ranking of alternatives: $A_4 > A_1 > A_3 > A_5 > A_2$, with a net flow of alternatives: $\Phi(A_1) = 0.865$, $\Phi(A_2) = 0.132$, $\Phi(A_3) = -0.124$, $\Phi(A_4) = -0.276$and $\Phi(A_5) = -0.596$.

Although AHP and PROMETHEE II methods delivered the same ranking of alternatives, sensitivity analysis was conducted on both methods' outcomes to recommend a method that best suited this decisional problem and provided the most robust outcome. Minimum percentage change required to alter the ranking of alternatives for the most critical criterion weight and the most critical performance measure were calculated. Results are shown in Tables 12, 13, 14 and 15. N/F shown in Tables 14 and 15 stands for a non-feasible value where ± 100% change in the value of that performance measure did not affect the original ranking of the alternatives.

The most critical criterion in this numerical example using AHP was the first criterion (C_1) (i.e. "Financial Considerations") signified by the smallest value (bold number) in Table 12. This value represented the minimum percentage change required in the weight of the "Financial Considerations" criterion to change the ranking of alternatives two and five ($A_2 > A_5$). A 10.514% increase in its weight preferred "Washington D.C." to "Portland".

The most critical criterion in this numerical example using PROMETHEE II was the first criterion (C_1) (i.e. "Financial Considerations") signified by the smallest value (bold number) in Table 13. This value represented the minimum percentage change required in the weight of the "Financial Considerations" criterion to change the ranking of alternatives three and five "Atlanta" and "Portland" ($A_5 > A_3$). Where a 25.234% decrease in its weight preferred "Portland" to "Atlanta".

The most critical performance measure in this numerical example using AHP was (A_2C_1), signified by the smallest value (bold number) in Table 14. This value represented the minimum percentage change required in the value of performance measure (A_2C_1) to change the ranking of alternatives two and five, "Washington D.C." and "Portland" ($A_2 > A_5$). A 10% increase in its value preferred "Washington D.C." to "Portland".

The most critical performance measure in this numerical example using PROMETHEE II was (A_3C_1), signified by the smallest value (bold number) in Table 15. This value represented the minimum percentage change required in the value of performance measure (A_3C_1) to change the ranking of alternatives three and five, "Atlanta" and "Portland" ($A_5 > A_3$). A 29% decrease in its value preferred "Portland" to "Atlanta".

Table 12
Minimum percentage change in criteria weights for corporate relocation decision example using AHP.

Criteria	Percentage change	New ranking
C_1: Financial Considerations = 0.428	**10.514**	$A_4 > A_1 > A_3 > A_2 > A_5$
C_2: Employee Availability = 0.207	−29.952	$A_4 > A_1 > A_3 > A_2 > A_5$
C_3: Support Services = 0.207	−45.411	$A_4 > A_1 > A_3 > A_2 > A_5$
C_4: Cultural Opportunities = 0.041	112.195	$A_4 > A_1 > A_3 > A_2 > A_5$
C_5: Leisure Activities = 0.063	−33.333	$A_4 > A_1 > A_3 > A_2 > A_5$
C_6: Climate = 0.053	−86.792	$A_4 > A_1 > A_3 > A_2 > A_5$

Table 13
Minimum percentage change in criteria weights for corporate relocation decision example using PROMETHEE II.

Criteria	Percentage change	New ranking
C_1: Financial Considerations = 0.428	**−25.234**	$A_4 > A_1 > A_5 > A_3 > A_2$
C_2: Employee Availability = 0.207	78.744	$A_4 > A_3 > A_1 > A_5 > A_2$
C_3: Support Services = 0.207	−80.676	$A_4 > A_3 > A_1 > A_5 > A_2$
C_4: Cultural Opportunities = 0.041	582.927	$A_4 > A_1 > A_3 > A_2 > A_5$
C_5: Leisure Activities = 0.063	201.587	$A_4 > A_1 > A_5 > A_3 > A_2$
C_6: Climate = 0.053	428.302	$A_4 > A_1 > A_5 > A_3 > A_2$

Table 14
Minimum percentage change in performance measures for corporate relocation decision example using AHP.

Performance measure	Percentage change	New ranking
A_1C_1	57	$A_4 > A_1 > A_3 > A_2 > A_5$
A_2C_1	**10**	$A_4 > A_1 > A_3 > A_2 > A_5$
A_3C_1	−51	$A_4 > A_1 > A_5 > A_3 > A_2$
A_4C_1	−43	$A_1 > A_4 > A_3 > A_5 > A_2$
A_5C_1	−25	$A_4 > A_1 > A_3 > A_2 > A_5$
A_1C_2	N/F	–
A_2C_2	35	$A_4 > A_1 > A_3 > A_2 > A_5$
A_3C_2	N/F	–
A_4C_2	30	$A_4 > A_1 > A_3 > A_2 > A_5$
A_5C_2	−20	$A_4 > A_1 > A_3 > A_2 > A_5$
A_1C_3	45	$A_4 > A_1 > A_3 > A_2 > A_5$
A_2C_3	47	$A_4 > A_1 > A_3 > A_2 > A_5$
A_3C_3	N/F	–
A_4C_3	88	$A_4 > A_1 > A_3 > A_2 > A_5$
A_5C_3	−23	$A_4 > A_1 > A_3 > A_2 > A_5$
A_1C_4	N/F	–
A_2C_4	63	$A_4 > A_1 > A_3 > A_2 > A_5$
A_3C_4	N/F	–
A_4C_4	N/F	–
A_5C_4	N/F	–
A_1C_5	N/F	–
A_2C_5	70	$A_4 > A_1 > A_3 > A_2 > A_5$
A_3C_5	N/F	–
A_4C_5	42	$A_4 > A_1 > A_3 > A_2 > A_5$
A_5C_5	−22	
A_1C_6	N/F	–
A_2C_6	N/F	–
A_3C_6	N/F	–
A_4C_6	83	$A_4 > A_1 > A_3 > A_2 = A_5$
A_5C_6	−51	$A_4 > A_1 > A_3 > A_2 > A_5$

This decisional problem provided specific examples of three scenarios listed in Section 2 and actions were considered to address them:

SCENARIO ONE: AHP required a 10.514% increase to the value of most critical criterion weight to alter the ranking of alternatives, while PROMETHEE II required a 25,234% decrease to the value of the most critical criterion weight to alter the ranking of alternatives. Both methods delivered the same outcomes. PROMETHEE II was 2.4 times

Table 15
Minimum percentage change in performance measures for corporate relocation decision example using PROMETHEE II.

Performance measure	Percentage change	New ranking
A_1C_1	−35	$A_4 > A_3 > A_1 > A_5 > A_2$
A_2C_1	40	$A_4 > A_1 > A_5 > A_3 > A_2$
A_3C_1	**−29**	$A_4 > A_1 > A_5 > A_3 > A_2$
A_4C_1	−56	$A_1 > A_4 > A_3 > A_5 > A_2$
A_5C_1	N/F	–
A_1C_2	N/F	–
A_2C_2	N/F	–
A_3C_2	−58	$A_4 > A_1 > A_5 > A_3 > A_2$
A_4C_2	N/F	–
A_5C_2	−60	$A_4 > A_1 > A_3 > A_2 > A_5$
A_1C_3	−61	$A_4 > A_3 > A_5 > A_1 > A_2$
A_2C_3	N/F	–
A_3C_3	N/F	–
A_4C_3	N/F	–
A_5C_3	N/F	–
A_1C_4	N/F	–
A_2C_4	N/F	–
A_3C_4	N/F	–
A_4C_4	N/F	–
A_5C_4	N/F	–
A_1C_5	N/F	–
A_2C_5	N/F	–
A_3C_5	N/F	–
A_4C_5	N/F	–
A_5C_5	N/F	–
A_1C_6	N/F	–
A_2C_6	N/F	–
A_3C_6	N/F	–
A_4C_6	N/F	–
A_5C_6	N/F	–

less sensitive to changes in the value of the most critical criterion weight than AHP. Decision makers often prefer a method that is resilient to changes in criteria weights and often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. PROMETHEE II would be recommended for this decisional problem when decision makers were uncertain of criteria weights or anticipated a risk factor of high severity that could affect criteria weights.

SCENARIO TWO: AHP required a 10% increase to the value of most critical performance measure score to alter the ranking of alternatives, while PROMETHEE II required a 29% decrease to the value of the most critical performance measure score to alter the ranking of alternatives. PROMETHEE II was 2.9 times less sensitive to changes in the value of the most critical performance measure than AHP. Decision makers often prefer a method that is less sensitive to changes in the values of the performance measures and often apply MCDM methods to aid them in delivering strategic decisions and long-term planning [29]. A robust method provides more stable outcomes with less sensitivity to risk and uncertainties. PROMETHEE II would also be recommended for this decisional problem when decision makers were uncertain of performance measures or anticipated a risk factor of high severity that could affect performance measures.

SCENARIO THREE: The number of the most critical criteria and the most critical performance measures a method has for a certain decisional problem provides guidance about the number of risk factors the method is vulnerable. The higher the number of the most critical criteria and the most critical performance measures, the higher the number of risk factors a method is sensitive that might change the final outcome of the method. Moreover, the lower the minimum percentage change required in the most critical criteria and the most critical performance measure, the higher the sensitivity of the final outcome of a method to changes in the inputs (i.e. risk and uncertainty). PROMETHEE II was less sensitive than AHP to changes in the values of the both criteria weights and performance measures. Recommending PROMETHEE II for this decisional problem would provide a more robust outcome with less vulnerability to risk and uncertainty.

In all three scenarios, PROMETHEE II would be preferred for this problem.

4. Discussion

This paper considered three numerical examples described in Expert Choice Sample models. Numerical example one used a U.S. coast guard officer evaluation model, the second example used a Boeing strategic marketing decision model and the third numerical example used a corporate relocation decision model.

Different methods might provide different outputs when applied to the same decisional problem, this was because methods deal differently with performance measures, and criteria weights often have different impact from one method to another, moreover in MCDM problems a *"correct"* result does not exist [46]. If two methods delivered significantly different results then, at least one method was invalid [15]. MCDM methods deliver a best compromise solution. Work presented in this paper did not compare the outcome of AHP and PROMETHEE II but compared the stability of the outcome of AHP and PROMETHEE II when uncertainty affected both criteria weights and performance measures.

Analysing the results from case studies and the results of numerical examples 1, 2 and 3, and results from other problems, a set of propositions have been suggested.

In each case the following method was used:

1 Qualitative and quantitative risk analysis should be conducted first.
2 The novel MCDM Methods Selection Framework applied to that problem to provide a subset of candidate methods suitable for that problem.
3 Conduct sensitivity analysis on the subset of candidate methods.
4 Results from sensitivity analysis and risk analysis should be used to recommend a method that is least sensitive to factors highlighted by the qualitative and quantitative risk analysis.
5 A MCDM method might be recommended for a decisional problem even though it was highly sensitive to changes in a certain factor, but that factor might not be highlighted during the risk analysis. Also a MCDM method might be excluded from the subset of candidate methods if it was sensitive to factors highlighted by the risk analysis.

Some potential generalized MCDM scenarios were presented in this paper. From these scenarios a new set of propositions can be stated:

- **Propositions for Uncertainty in inputs:**

PROPOSITION ONE – Uncertainty in Criteria Weights: If decision makers are uncertain of criteria weights and / or anticipate a risk factor of high severity that could affect criteria weights, then a method that is less sensitive to changes in criteria weights should be recommended for the decisional problem. If methods had the same sensitivity to uncertainty in criteria weights, then the method that had fewer critical criteria should be recommended to the decisional problem.

PROPOSITION TWO - Uncertainty in Performance Measures: If decision makers are uncertain of performance measures and / or anticipate a risk factor of high severity that could affect performance measures, then a method that is less sensitive to changes in performance measures should be recommended for the decisional problem. If methods had the same sensitivity to uncertainty in performance measures, then the method that had fewer critical performance measures should be recommended for the decisional problem.

PROPOSITION THREE – Uncertainty in Inputs: If decision makers are uncertain and / or anticipate a risk factor of high severity that could affect both criteria weights and performance measures, then a method that is least sensitive to changes in criteria weights and performance measures should be recommended for the decisional problem. If methods had the same sensitivity to uncertainty in criteria weights and / or performance measures, then the method that had fewer critical criteria weights and /or performance measures should be recommended for the decisional problem and a best compromise between these factors would be recommended.

PROPOSITION FOUR – The Most Critical Criterion: The higher the weight of the criterion the higher the probability that it is the most critical criterion and the higher the probability that it is the most critical performance measure with respect to that criterion.

- **Propositions for Ranking of Alternatives:**

PROPOSITION FIVE – Indifference Proposition: Whenever two or more alternatives are indifferent in the outcome of a MCDM method, the state of these alternatives might be considered as a state of equilibrium, where any change in any performance measure of the alternative with respect to any criteria might prefer one alternative to the others, and / or any change in any criterion weight might prefer one alternative to the others. Using pseudo criteria, the change required in the performance measures to prefer one alternative to the others must be large enough not to be filtered by the indifference thresholds.

PROPOSITION SIX – When an Alternative will be Ranked First: For an alternative to be ranked first, the alternative must score highest on all criteria. If the MCDM method used allow a compensation between good and poor performances of alternatives with respect to criteria, an alternative might be ranked first if it scored highest on the most important criterion or criteria (i.e. highest weight criterion or criteria) and did not have poor performances for other criteria (i.e. it didn't score significantly lower than other alternatives).

PROPOSITION SEVEN - Equal Criteria Weights: In a decisional problem where all criteria had the same weights, an alternative will be ranked first if:

- Using a method that allowed compensation between good and poor performances with respect to criteria, then the alternative that scored the highest sum when aggregating all performance measures with respect to all criteria will be ranked first.
- Using a method that applied did not allow compensation between good and poor performances with respect to criteria, appropriate indifference and preference thresholds and all criteria had the same type, then the alternative that scored highest on all criteria, or the alternative that scored higher on larger number of criteria (i.e. scored higher on more criteria) will be ranked first.

5. Conclusions

The large number of existing MCDM methods confuses potential decision makers, resulting in inappropriate pairing of methods and problems. The authors were not suggesting that one MCDM method was better than another, but that one MCDM method could deliver a more robust outcome than another for a specific problem. To recommend a single method for a decisional problem, risk and uncertainty factors needed to be considered. Both performance measures and criteria weights were studied, and sensitivity analysis applied to performance measures and criteria weights to give a recommendation.

This paper presented a new framework and methods to recommend a MCDM method that delivered the most robust output from a variety of existing MCDM methods, each having its own advantages, disadvantages and limitations. Considering a number of potential generalized scenarios for MCDM problems, a new set of general propositions were created and are presented.

Applying sensitivity analysis to one input factor at a time may not be enough and Monte-Carlo simulation might model the uncertainty of more than one input factor at a time. Uncertainty could be modelled using different approaches and for example, applying PROMETHEE II with different criteria types could provide a more stable outcome. PROMETHEE II could also be improved using Veto thresholds.

Other factors were not considered when selecting a MCDM method, for example the level of compensation allowed between good and poor performances of alternatives with respect to criteria, type of value function representing criteria or interaction between criteria. PROMETHEE II Indifference, Preference and Veto thresholds could be used to provide a more robust outcome and enhance the stability of the outcome of PROMETHEE II method.

Proposition five suggested that any change in the criteria weights or in the performance measures of the indifferent alternatives will break the indifference relation proposed by (Roy, 1981).

6. Future work

The authors are now comparing the Weighted Sum Model (WSM), the Weighted Product Model (WPM), the Weighted Aggregated Sum Product ASsessment (WASPAS) method, Additive Ratio ASessment method (ARAS), Complex PRoportional ASsessment (COPRAS) method, the Multiplicative Exponent Weighting (MEW) method, Simple Additive Weighting (SAW) method, AHP and PROMETHEE II using different values of λ for WASPAS and different types of preference functions: U-shaped criterion, V-shaped criterion, Level criterion, V-shape with indifference criterion, and Gaussian criterion for PROMETHEE II. Future work will consider different MCDM methods such as ELECTRE family methods and WASPAS method.

Perfect consistency in real life problems is often hard to achieve. To investigate this, the authors intend to apply the new MCDM methods selection framework to other decisional problems with inconsistent pairwise comparisons in various uncertain, fuzzy and risky environments [8–10,30,31,37,40] and to use the techniques to decide on direction for powered wheelchairs [38,39,41,42].

The authors have no competing interests to declare.

Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.orp.2018.10.003.

References

[1] Ballestero E, Romero C. Multiple criteria decision making and its applications to economic problems. Netherlands: Kluwer Academic Publishers; 1998.
[2] Butler J, Jia J, Dyer J. Simulation techniques for the sensitivity analysis of multi-criteria decision models. *Eur J Operat Res* 1997;103:531–46.
[3] Durbach I, Stewart T. An experimental study of the effect of uncertainty representation on decision making. *Eur J Operat Res* 2011;214:380–92.
[4] Durbach I, Stewart T. Modeling uncertainty in multi-criteria decision analysis. *Eur J Operat Res* 2012;223:1–14.
[5] Eldarandaly K, Ahmed A, AbdelAziz N. An expert system for choosing the suitable MCDM method for solving a spatial decision problem. Proceedings of the 9th Int. Conf. on Production Engineering, Design and Control. 2009.
[6] French S. Modelling making inferences and making decision: The roles of sensitivity analysis. Sociedadde Estadísticae Investigación Operativa (TOP) 2003;11:229–51.
[7] Grechuk B, Zabarankin M. Direct data-based decision making under uncertainty. *Eur J Operat Res* 2018;267:200–11.
[8] Gegov A, Sanders D, Vatchova B. Complexity management methodology for fuzzy systems with feedforward rule bases. *Intern J Knowledge-Based Intell Eng Syst* 2015;19:83–95. 310.
[9] Gegov AE, Sanders DA, Vatchova B. Mamdani fuzzy networks with feedforward rule bases for complex systems modelling. *J Intell Fuzzy Syst* 2016;30(5):2623–37.
[10] Gegov A, Sanders D, Vatchova B. Aggregation of inconsistent rules for fuzzy rule base simplification. *Intern J Knowledge-Based Intell Eng Syst* 2017;21(3):135–45.
[11] Gregory R, Failing L, Harstone M, Long G, McDaniels T, Ohlson D. Structured decision making – A practical guide to environmental management choices (1st ed.). Wiley Blackwell; 2012.
[12] Grenshon M. Ph.D. dissertation. Arizona, USA: Sys. And Ind. Eng. University of Arizona; 1981.
[13] Guitouni A, Martel JM. Tentative guidelines to help choosing an appropriate MCDM method. *Eur J Operat Res* 1997;109:501–21.

[14] Haddad M. A framework that uses sensitivity analysis to select multi criteria decision making methods. J Comp Syst Eng 2017;18:413–9.
[15] Haddad M, Sanders D, Bausch N, Tewkesbury G, Gegov A, Hassan M. Learning to make intelligent decisions using an expert system for the intelligent selection of either PROMITHEE II or the Analytical Hierarchy Process. IEEE Proceedings of the SAI Conference on Intelligent Systems. 2018. p. 662–8. Also selected for publication in *Volume 868* of *Advances in Intelligent Systems and Computing* to be published by Springer.
[16] Ishizaka A, Siraj S. Are multi-criteria decision-making tools useful? An experimental comparative study of three methods. *Eur J Operat Res* 2018;264:462–71.
[17] Kornyshova E, Salinesi C. MCDM techniques selection approaches: state of the art. Proceedings of the 2007 IEEE Symposium on Computational Intelligence in Multicriteria Decision Making (MCDM 2007). 2007.
[18] Laaribi A. SIG et analyse multicitere. Paris, France: Hermes Science Publication; 2000.
[19] MacCrimmon K. An overview of the multiple objective decision making in multiple criteria decision making. Columbia: The University of South Carolina Press; 1973.
[20] Miettinen K, Salminen P. Decision-aid for discrete multiple criteria decision making problems with imprecise data. *Eur J Operat Res* 1999;119:50–60. 1999.
[21] Miller G. The magical number seven, plus or minus two: Some limits on our capacity for processing information. *Psychol Rev* 1956;21:81–97.
[22] Mota P. Ph.D. dissertation. Lisbon, Porugal: Elec. and Comp. Eng. Uni. Nova De Lisboa; 2013.
[23] Olson D, Mechitov A, Moshkovich H. Learning aspects of decision aids. Proceedings of the 15th Int. Conf. on MCDM'00, IEEE Symposium on Computational Intelligence in Multicriteria Decision Making (MCDM 2007). 2007.
[24] Ozernoy V. Choosing the best multiple criteria decision making method. INFOR 1992;30(2):159–71.
[25] Poyhonen M, Hamalainen R. On the convergence of multiattribute weighting methods. *Eur J Operat Res* 2001;129:569–85.
[26] Project Management Institute. Risk management plan in a guide to the project management body of knowledge (PMBOK). 6th ed Pa, USA: Newtown Square; 2004.
[27] Raju K, Kumar D. Irrigation planning using genetic algorithms. *Water Resource Manag* 2004;18:163–76.
[28] Razaei J. Best –worst multi-criteria decision-making method. Omega 2015;53:49–57.
[29] Razmak J, Aouni B. Decision support system and multi-criteria decision aid: a state of the art and perspectives. *J Multi-Crit. Decis Anal* 2015;22:101–17.
[30] Robinson D, Sanders D, Mazharsolook E. Sensor-based ambient intelligence for optimal energy efficiency. *Sensor Rev* 2014;34(2):170–81.
[31] Robinson DC, Sanders DA, Mazharsolook E. Ambient intelligence for optimal manufacturing and energy efficiency. *Assemb Automat J* 2015;35(3):234–48. https://doi.org/10.1108/AA-11-2014-087.
[32] Roy B, Slowinski R. Questions guiding the choice of a multicriteria decision aiding method. *Eur J Decis Proc* 2013;1:69–97.
[33] Saaty T, Ergu D. When is a decision making method trustworthy? Criteria for evaluating multi-criteria decision making methods. *Intern J Inform Technol Decis Mak* 2015;14(6). https://doi.org/10.1141/S021962201550025X.
[34] Saaty T. Decision making – the analytical hierarchy and network processes (AHP/ANP). *J Syst Sci Syst Eng* 2004;13(1):1–35.
[35] Salo A, Hamalainen R. Preference assessment by imprecise ratio statements. *Operat Res* 1992;40:1053–61.
[36] Saltelli A, Tarantola S, Campolongo F. Sensitivity analysis as an ingredient of modelling. *Stat Sci* 2000;15(4):377–95.
[37] Sanders D, Gegov A. AI tools for use in assembly automation journal and some examples of recent applications. *Assemb Automat J* 2013;33(2):184–94.
[38] Sanders DA. Using self-reliance factors to decide how to share control between human powered wheelchair drivers and ultrasonic sensors. IEEE Trans Neural Syst Rehab Eng 2017;25(8):1221–9.
[39] Sanders D. Non-model-based control of a wheeled vehicle pulling two trailers to provide early powered mobility and driving experiences. IEEE Trans Neural Syst Rehab Eng 2018;26(1):96–104.
[40] Sanders D, Bergasa-Suso J, Khusainov R, Gegov A, Chester S, Bausch N. Introducing dead bands within two-dimensional clusters of user data to improve data classification. Proceedings of the 9th International Conference on Human Systems Interaction (HSI). IEEE; 2016. p. 14–20.
[41] Sanders DA, Gegov A, Haddad M, Ikwan F, Wiltshire D, Tan YV. A rule-based expert system to decide on direction and speed of a powered wheelchair. IEEE Proceedings of the SAI Intelligent Systems Conference. 2018. p. 426–33.
[42] Sanders DA, Robinson DC, Hassan M, Haddad M, Gegov A, Ahmed N. Making decisions about saving energy in compressed air systems using ambient intelligence and artificial intelligence. IEEE Proceedings of the SAI Intelligent Systems Conference. 2018. p. 1313–6. Also selected for publication in *Volume 869* of *Advances in Intelligent Systems and Computing* to be published by Springer.
[43] Scholten L, Schuwirth N, Reichert P, Lienert J. Tackling uncertainty in multi-criteria decision analysis–An application to water supply infrastructure planning. *Eur J Operat Res* 2015;242:243–60.
[44] Stewart T. Dealing with uncertainties in MCDA (multi-criteria decision analysis). In: Figueira J, Greco S, Ehrgott M, editors. Multiple criteria decision analysis state of the art annotated surveys, 78. New York: Springer; 2005. p. 445–70.
[45] Traintaphyllou E, Sanchez A. A sensitivity analysis approach for some deterministic multi-criteria decision-making methods. *Decis Sci* 1997;28(1).
[46] Tscheikner-Gratl F, Egger P, Rauch W, Kleidorfer M. Comparison of multi-criteria decision support methods for integrated rehabilitation prioritization. Water 2017;9(68).
[47] Ulengin F, Topcu Y, Sahin S. An artificial neural network approach to multicriteria method selection. *Proceedings of the 15th Int. Conf. on MCDM'00*, IEEE Symposium on Computational Intelligence in Multicriteria Decision Making (MCDM 2007). 2007. 2007.
[48] Vincke P. A short note on a methodology for choosing a decision-aid method. In: Pardalos PM, Siskos Y, Zopoundis C, editors. Adv Multicrit Anal 1995:3–76.
[49] Wolters W, Mareschal B. Novel types of sensitivity analysis for additive MCDM methods. *Eur J Operat Res* 1995;81:281–90.