Chapter 2
A Discourse of Multi-criteria Decision Making (MCDM) Approaches

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Abstract During a decision making process, decision makers often need to handle large amount of information in order to reach a rational decision. Such information can be incomplete, uncertain and even contradictory to each other. Multi-criteria decision making (MCDM) methods provide effective and popular solutions to aid decisions under uncertainty. Well-established MCDM methodologies such as AHP, TOPSIS, VIKOR, ELECTRE, and PROMETHEE are reviewed with particular reference to their standard frameworks in this chapter to provide a holistic knowledge base on their applications individually and/or collectively in the other chapters in this book.

Keywords MCDM • AHP • TOPSIS • VIKOR • ELECTRE • PROMETHEE • Fuzzy set • Evidential Reasoning

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P.T.-W. Lee, Z. Yang (eds.), *Multi-Criteria Decision Making in Maritime Studies and Logistics*, International Series in Operations Research & Management Science 260,
DOI 10.1007/978-3-319-62338-2_2

1 Introduction

MCDM methods can be defined as structured frameworks that deal with the process of making decisions in the presence of multiple objectives (Pohekar and Ramachandran 2004). They are used to find the best opinion from all of the feasible alternatives in the presence of multiple, usually conflicting, decision criteria (Pomerol and Romero 2000).

A MCDM process typically defines objectives, chooses the criteria to measure the objectives, specifies alternatives, transforms the criterion scales into commensurable units, assigns weights to the criteria that reflect their relative importance, selects, and applies a mathematical algorithm for ranking and choosing an alternative (Ananda and Herath 2009). During a decision making process, objectives can be uncertain, complex and even conflicting; criteria can be cardinal or ordinal; and information can be exact or fuzzy. MCDM methods are considered to be an important tool as they allow decision-makers to select a solution by tackling all above mentioned difficulties and complexity.

Uncertainty is an important aspect to be addressed in MCDM. It is defined as a situation in which a person does not have appropriate quantitative and qualitative information to describe, prescribe or predict deterministically and numerically a system, its behaviour or other characteristics (Zimmermann 2000). Uncertainty in principle is originated from failures, assumptions, unavailability or incompleteness of data.

There are a large number of MCDM methods established in the literature. They differ from each other in terms of the required quality and quantity of additional information, the methodologies, the user-friendliness of the methods and their associated software, the sensitivity tools used, and the mathematical properties (Zavadskas and Turskis 2011). However, it is noteworthy that none of them is considered suitable under all MCDM environments and therefore hybrid approaches are often developed to deal with complex scenarios involving different types of uncertainties.

2 Analytical Hierarchy Process (AHP)

AHP was developed by Saaty (1980). As one of the most widely used MDCM approaches, AHP is capable of assisting criteria selection, criteria importance analysis and alternative evaluation. The best decision can be made when qualitative and quantitative aspects of a decision are included (Saaty 1990). AHP uses the concept of pair-wise comparisons to improve the efficiency of synthesising qualitative and quantitative evaluations in a decision process. It contains different alternatives and criteria for judging the alternatives. The approach allows decision makers to express their opinions by comparing two alternatives at a time rather than simultaneously on all the alternatives. It simplifies and expedites a decision making process on complex issues. The visibility and easiness characteristics of AHP contribute to its popularity across different industries. Vaidya and Kumar (2006) revealed that the AHP method has been used in nearly 150 applications. Examples of using AHP in the shipping and maritime sectors include, port choice and competitiveness evaluation (Lam and Dai 2012; Yeo et al. 2010; Yeo et al. 2014), vessel selection (Yang et al. 2009b; Xie et al. 2008), port allocation (Carlos Perez-Mesa et al. 2012), risk estimation of ship operations (Ung et al. 2006), design support evaluation for the offshore industry (Sii and Wang 2003), port service quality ranking (Ugboma et al. 2004), maritime regulation implementation (Karahalios et al. 2011), ship operational energy efficiency (Beşikçi et al. 2016), choice of ship flag (Chou and Ding 2016), assessment of the maritime labour convention compliance (Akyuz et al. 2015) and marine accident analysis (Sahin and Senol 2015).

AHP uses a mathematical process to handle subjective judgements of an individual or a group in a decision making process. It consists of four steps: (1) establishing the hierarchy of criteria and alternatives, (2) making pair-wise comparisons of the criteria, and estimating the weights of the criteria and the relative performance values of the alternatives with respect to each criterion, (3) aggregating the weights and performance values for alternative priority, and (4) checking the consistency of the judgements to verify the result.

Step 1 Establish the hierarchy of criteria and alternatives

Hierarchy is the base of AHP. In order to conduct an AHP study, a hierarchy of clear criteria and alternatives need to be constructed. Figure 2.1 shows an example of hierarchy with defined criteria and alternatives.

Step 2 Make a pair-wise comparison decision matrix (M).

A pair-wise comparison matrix (M) is constructed for all the criteria (Eq. (2.1). a in the matrix represents a quantified judgement on a pair of criteria (e.g. a_{12} represents the importance of *Criterial 1(C1)* over *Criterial 2 (C2)*). A scale of "1" to "9" is adopted to conduct non-quantitative pair-wise comparisons of two elements (Saaty 1980). Judgements are given verbally as indicated in Table 2.1 before corresponding score is allocated.

$$M = \begin{array}{c} \\ C_1 \\ C_2 \\ \vdots \\ C_j \\ \vdots \\ C_n \end{array} \begin{array}{c} \begin{array}{cccccc} C_1 & C_2 & \dots & C_i & \dots & C_n \end{array} \\ \begin{bmatrix} a_{11} & a_{21} & \dots & a_{i1} & \dots & a_{n1} \\ a_{12} & a_{22} & \dots & a_{i2} & \dots & a_{n2} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{1j} & a_{2j} & \dots & a_{ij} & \dots & a_{nj} \\ \vdots & \vdots & & \vdots & & \vdots \\ a_{1n} & a_{2n} & \dots & a_{in} & \dots & a_{nn} \end{bmatrix} \end{array} \tag{2.1}$$

Step 3 Normalize the decision matrix and calculate the priorities of this matrix to obtain the weights of criteria $w_1, w_2, \ldots$ *and* w_n.

In order to calculate the weight of each criterion, the comparison matrix has to be normalized. This can be done by summing each set of column values; then each value is divided by its corresponding summed value. The relative weight of the k^{th} criteria is obtained through averaging the values of the k^{th} row in the matrix. This can be presented by using Eq. (2.2).

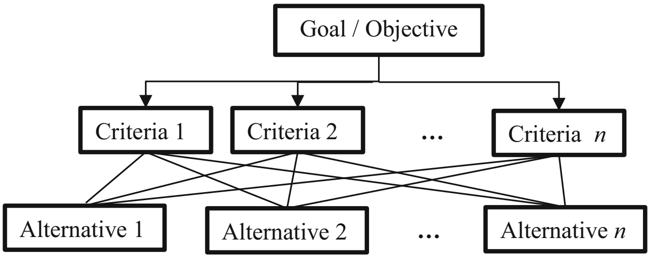

Fig. 2.1 Hierarchy of criterial and alternatives

Table 2.1 Judgement scores in AHP (Saaty 1980)

Score	Judgment	Explanation
1	Equally	Two activities contribute equally to the objective
3	Moderately	Experience and judgment slightly favor one activity over another
5	Strongly	Experience and judgment strongly favor one activity over another
7	Very strongly	An activity is strongly favored and its dominance demonstrated in practice
9	Extremely	The evidence favoring one activity over another is of the highest possible order of affirmation
2,4,6,8	Intermediate values between two adjacent judgments	When compromise is needed

$$w_k = \frac{1}{n}\sum_{j=1}^{n}\frac{a_{kj}}{\sum_{i=1}^{n} a_{ij}}, \quad k = (1, 2, \ldots n) \tag{2.2}$$

where, a_{ij} is the entry of row i and column j in a comparison matrix of order n and w_k is the weight of a specific criterion k in the pairwise comparison matrix.

Step 4 Check consistency of the judgements to verify the result

In order to derive meaningful weights, a minimal consistency is required and a test must be done. The consistency of the comparison matrices is tracked by a Consistency Ratio (CR). CR index in AHP is used in order to maintain consistency in decision making of the responders. CR can be defined as follows:

$$CR = \frac{CI}{RI} \tag{2.3}$$

CI is the consistency index and RI is the random index. CI can be defined as follows:

$$CI = \frac{\lambda_{max} - n}{n - 1} \tag{2.4}$$

where λ_{max} defined as the maximum eigenvalue can be approximately calculated in Eq. (2.5).

$$\lambda_{max} = \frac{\sum_{j=1}^{n} \frac{\sum_{k=1}^{n} w_k a_{jk}}{w_j}}{n} \quad j = (1, 2, \ldots n), k = (1, 2, \ldots n) \tag{2.5}$$

where w_j and w_k are the weights of criteria obtained in Step 2.

According to Saaty (1995), CR should be less than or equal to 10% to be acceptable. Higher CR value indicates the need of adjustment of the judgements.

The rating for each alternatives against each criterion can be obtained by following a similar procedure. The decision alternatives can then be priorities by using the weighted average rating.

3 Analytical Network Process (ANP)

The AHP has some advantages over other methods because of its simplicity and its ability to rank parts of a multi-criteria problem in a hierarchical structure (Chen and Lin 2006). However it lacks the ability to model the interdependencies among the criteria, which constrains its applications in complex systems such as transport networks. Analytical Network Process (ANP) (Saaty 1990) was developed to complement the AHP in a way that the criteria are presented in a network (instead of hierarchy) structure.

ANP, being capable of modelling interdependency among the decision factors, becomes a useful MCDM tool since its development. It is an extension of AHP and allows the consideration of interdependence among and between levels of criteria and alternatives. ANP uses a network without the need to specify levels as in hierarchy. It provides a logical way of dealing dependency. Networks in ANP include clusters of elements that may influence each other. A pairwise comparison matrix is established for all elements (Eq. (2.6). The respondents need to answer the questions such as: "Given an element and its upper level objective, which of the two elements influences the given element more with respect to the upper level objective, and how much more influence it has than another element?" The responses are presented numerically, scaled on the basis of Saaty's 1–9 scale (see Table 2.1), where 1 presents indifference between the two elements and 9 stands for overwhelming dominance of the element under consideration (in the row of the matrix) over the comparison element (in the column of the matrix). The local weights for all the elements are then generated by using Eq. (2.7. The local weights derived from the pairwise comparison matrices become a part of the inputs of a supermatrix. A supermatrix with its general entry matrices is shown as Eqs. (2.8) and (2.9). The weighted supermatrix is obtained through multiplying the priority vectors of each element in the un-weighted supermatrix with the priority vectors of the corresponding clusters. The global weights are then obtained through raising the weight supermatrix to limiting power.

$$A = a_{(ij)} = \begin{array}{c} \\ e_1 \\ e_2 \\ \vdots \\ e_i \\ \vdots \\ e_m \end{array} \begin{array}{c} \begin{array}{cccccc} e_1 & e_2 & \cdots & e_j & \cdots & e_m \end{array} \\ \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1j} & \cdots & a_{1m} \\ a_{21} & a_{22} & \cdots & a_{2j} & \cdots & a_{2m} \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{i1} & a_{i2} & \cdots & a_{ij} & \cdots & a_{im} \\ \vdots & \vdots & \vdots & \vdots & \ddots & \vdots \\ a_{m1} & a_{m2} & \cdots & a_{mj} & \cdots & a_{mm} \end{bmatrix} \end{array} \tag{2.6}$$

where $a_{(ij)} = 1$ if $i = j$; $a_{(ij)} = \frac{1}{a_{ji}}$, $i = (1, 2, \ldots m)$ and $j = (1, 2, \ldots m)$.

Suppose there are m elements to be compared in a matrix, let $e_1, e_2, \ldots, e_m$ denote the different elements, where $a_{(ij)}$ represents the level of influences that the respondent believes when element e_i is compared with e_j. When scoring is conducted for a pair, a reciprocal value is automatically assigned to the reverse comparison within the matrix.

$$w_k = \frac{1}{m} \sum_{j=1}^{m} \frac{a_{kj}}{\sum\limits_{i=1}^{n} a_{ij}} \qquad k = (1, 2, \ldots m) \tag{2.7}$$

where, w_k is the priority vector of the k^{th} element in the pairwise comparison matrix. Its value is a part of the supermatrix in the later steps. Literately, it repeats the ANP procedure in Sect. 3.

$$\begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \\ e_{11} \cdots e_{1m_1} & \cdots & e_{j1} \cdots e_{jm_j} & \cdots & e_{n1} \cdots e_{nm_n} \end{array}$$

$$W = \begin{array}{cc} & \\ C_1 & \begin{array}{c} e_{11} \\ e_{12} \\ \vdots \\ e_{1m_1} \end{array} \\ \vdots & \\ C_i & \begin{array}{c} e_{i1} \\ e_{i2} \\ \vdots \\ e_{im_i} \end{array} \\ \vdots & \\ C_n & \begin{array}{c} e_{n1} \\ e_{n2} \\ \vdots \\ e_{nm_n} \end{array} \end{array} \begin{bmatrix} W_{11} & \cdots & W_{1j} & \cdots & W_{1n} \\ \vdots & & \vdots & & \vdots \\ W_{i1} & \cdots & W_{ij} & \cdots & W_{in} \\ \vdots & & \vdots & & \vdots \\ W_{n1} & \cdots & W_{nj} & \cdots & W_{nn} \end{bmatrix} \tag{2.8}$$

where C_n denotes the nth cluster (top level objective), e_{nm} represents the m^{th} element in the n^{th} cluster, and W_{ij} is the principal eigenvector of the influence of the elements in the j^{th} cluster compared to the i_{th} cluster. If the j^{th} cluster has no influence on the j^{th} cluster, then $W_{ij} = 0$. W_{ij} (Eq. (2.9) represents the values of priority vectors of elements from the cluster C_i in relation to elements from the cluster C_j.

$$W_{ij} = \begin{vmatrix} w_{i1}^{j1} & w_{i1}^{j2} & \cdots & w_{i1}^{jm_j} \\ w_{i2}^{j1} & w_{i2}^{j2} & \cdots & w_{i2}^{jm_j} \\ \vdots & \vdots & \vdots & \vdots \\ w_{im_i}^{j1} & w_{im_i}^{j2} & \cdots & w_{im_i}^{jm_j} \end{vmatrix} \tag{2.9}$$

ANP can be used to model a problem that needs to be presented by a hierarchic or a network structure and then establish a pairwise comparison relationship within the structure. It allows for dependence and includes independence. It has the ability to prioritize groups or clusters of elements. It can handle interdependence better than AHP and "can support a complex, networked decision-making with various intangible criteria" (Tsai et al, 2010, p. 3884). However, ANP has two disadvantages: firstly, it is difficult to provide correct network structure among criteria even for experts, and different structures lead to different results. Secondly, to form a supermatrix all criteria have to be pair-wise compared with regard to all other criteria, which is difficult and also unnatural (Yu and Tzeng 2006).

4 Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS)

TOPSIS, as one of the classical decision making methods for solving MCDM problems, was developed by Hwang and Yoon (1981). The method is based on the principle that the chosen alternative should have the farthest Euclidean distance from the negative ideal solution (NIS), and the shortest from the positive ideal solution (PIS). More specifically the solution that maximizes the benefit criteria and minimizes the cost criteria will be selected as the best (Zouggari and Benyoucef 2012). TOPSIS can be sometimes used to replace AHP in the process of ranking the alternatives. In other words, it is often the case that the AHP is used to assign the weight of the selection criteria while the TOPSIS is applied to prioritise the selection alternatives. The procedure of the TOPSIS method contains six steps.

Step1 Identify alternatives and criteria to establish a decision making matrix

A decision matrix D can be established to record data and it can be expressed as below:

$$D = \begin{array}{c} \\ A_1 \\ \vdots \\ A_i \\ \vdots \\ A_m \end{array} \begin{array}{c} \begin{array}{ccccc} C_1 & \cdots & C_j & \cdots & C_n \end{array} \\ \begin{bmatrix} x_{11} & \cdots & x_{12} & \cdots & x_{1n} \\ \vdots & & \vdots & & \vdots \\ x_{i1} & \cdots & x_{ij} & \cdots & x_{in} \\ \vdots & & \vdots & & \vdots \\ x_{m1} & \cdots & x_{mj} & \cdots & x_{mn} \end{bmatrix} \end{array} \tag{2.10}$$

$$W = \left[w_1 \ldots w_j \ldots w_n \right]$$

where each A_i represent alternative i considered; C_j is the criterion used to measure the performance of each alternative; and x_{ij} is the rating of the i^{th} alternative with respect to the j^{th} criterion. w_j is the subjective importance estimation of the j^{th} criterion which is defined by the decision makers.

Step 2 Normalize the decision making matrix

The decision making matrix can be normalized through Eq. (2.11).

$$R_{ij} = \overline{x_{ij}} \Big/ \sqrt{\sum_{k=1}^{n} x_{ik}^2}, (i = 1, 2, \ldots m), (k = 1, 2, ..j..n) \tag{2.11}$$

Step 3 Construct weighted normalized fuzzy decision matrix

The weighted normalized decision matrix can be constructed by multiplying the normalized decision matrix R_{ij} with the associated weights w_j as follows:

$$V_{ij} = w_j R_{ij} \tag{2.12}$$

Step 4 Determine PIS and NIS

The PIS and NIS can be expressed as:

$$\begin{aligned} V^* &= \left\{ \left(\sum \max V_{ij}, j \in B \right), \left(\sum \min V_{ij}, j \in C \right) \right\} \\ &= \left\{ V_1^*, V_2^*, \ldots V_n^* \right\} \\ V^- &= \left\{ \left(\sum \min V_{ij}, j \in B \right), \left(\sum \max V_{ij}, j \in C \right) \right\} \\ &= \left\{ V_1^-, V_2^-, \ldots V_n^- \right\} \end{aligned} \tag{2.13}$$

where B and C indicate the sets of benefit and cost criteria respectively. V^* stands for the values of PIS, whereas V^- is for NIS.

Step 5 Obtain the separation measures

The separation of each alternative from the PIS and NIS can be represented by the Euclidean distance using the following equations.

$$\begin{aligned} S^* &= \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^* \right)^2} \qquad (i = 1, 2, \ldots, m) \\ S^- &= \sqrt{\sum_{j=1}^{n} \left(V_{ij} - V_j^- \right)^2} \qquad (i = 1, 2, \ldots, m) \end{aligned} \tag{2.14}$$

Step 6 Determine the relative closeness of the investigated alternatives to the PIS

$$P_i = S^- / (S^* + S^-) \tag{2.15}$$

Once the values for relative closeness of all alternatives are obtained, they can then be ranked based on the P_i in descending order. The higher the P_i value, the closer an alternative is to the PIS.

TOPSIS is a popular method due to its simplicity and the ability to identify the best alternative quickly. It is also useful for both qualitative and quantitative data. The output can be a preferential ranking using both negative and positive criteria (Aly et al. 2013). However there are some disadvantages of the traditional TOPSIS method. For example, the Euclidean distance algorithm it uses does not consider the correlation of attributes. The weight coefficients acquired by expert judgements have arguably subjective bias (Wang et al. 2015).

5 VIsekriterijumska optimizacija i KOmpromisno Resenje (VIKOR)

VIKOR[1] stands for **VI**sekriterijumska optimizacija i **KO**mpromisno **R**esenje in Serbian language developed by Serafim Opricovic, who called it the compromise ranking method. VIKOR is an outranking method for a finite set of alternative actions to be ranked and selected among criteria and solves a discrete multi-criteria problem with non-commensurable and conflicting criteria. As Opricovic and Tzeng (2003: p.228) and Opricovic (2011, p.12984) stated, the origin of the VIKOR method should be credited to Duckstein and Opricovic (1980) who started to develop it with the help of L_p-metric that Yu (1973) introduced in the compromise programming method (Zeleny 1973). In other words, it focuses on asking and selecting the best from a set of alternatives, and determines compromise solutions to a problem with conflicting criteria, which can help the decision makers to reach a final decision. The compromise solution is a feasible solution which is the closest to the ideal. However, most literature of VIKOR indicated that the method is rooted in Opricovic's book (1998) published in Serbian (Visekriterijumska optimizacija sistema u gradjevinarstvu), implying that it was written in English by quoting it as 'Multicriteria Optimization of Civil Engineering Systems" in their publications. As a result, it causes as if the book would be easily available in English for latecomers' reference. VIKOR as one of the MCDA methods has been further popularized by Opricovic and Tzeng (2004 and 2007). An extension of VIKOR to determine fuzzy compromise solution for multicriteria is presented in Opricovic (2007).

Both the VIKOR and the TOPSIS methods are distance-based. However, a compromise solution in VIKOR is determined based on mutual concessions, while, in TOPSIS, the best solution is determined by the shortest distance from the PIS and the farthest distance from the NIS, without the consideration of relative importance of these distances (Opricovic and Tzeng 2007). A detailed comparative analysis of TOPSIS and VIKOR can be found in Opricovic and Tzeng (2004). Assuming that there are m alternatives, denoted as $A_1, A_2, \ldots, A_m$. For an alternative A_i, the merit of the j^{th} aspect is denoted by $x_{ij}, j = 1,2, \ldots, n$. Then, the procedure of traditional VIKOR for compromise-ranking can be described as the following steps:

Step 1 Determine the best x_j^* and the worst x_j^- values of all criterion functions, where $j = 1,2, \ldots, n$;

[1]Not a few of its acronyms and full names in the existing literature have typos. The last author of this chapter has confirmed them from Opricovic by email.

$$\begin{gathered} x_j^* = \max\left[\left(x_{ij}\right)|j = 1, 2, \ldots, n\right],\ x_j^- = \min\left[\left(x_{ij}\right)|j = 1, 2, \ldots, n\right], \\ \text{if the } j^{th} \text{ criterion represents a benefit;} \\ x_j^* = \min\left[\left(x_{ij}\right)|j = 1, 2, \ldots, n\right], x_j^- = \max\left[\left(x_{ij}\right)|j = 1, 2, \ldots, n\right], \\ \text{if the } j^{th} \text{ criterion represents a cost.} \end{gathered} \tag{2.16}$$

Step 2 Compute the values of S_i and R_i, where, $i = 1,2,\ldots,m$, by the relations

$$S_i = \sum_{j=1}^{n} w_j \frac{x_j^* - x_{ij}}{x_j^* - x_j^-} \tag{2.17}$$

$$R_i = \max\left[w_j \frac{x_j^* - x_{ij}}{x_j^* - x_j^-} | j = 1, 2, \ldots, n\right] \tag{2.18}$$

where, w_j is the weight of the j^{th} criterion. S_i and R_i denote the utility measure and the regret measure, respectively, for the alternative A_i.

Step 3 Compute the value Q_i, where, $i = 1,2,\ldots,m$, by the relations

$$Q_i = v\left(\frac{S_i - S^*}{S^- - S^*}\right) + (1 - v)\left(\frac{R_i - R^*}{R^- - R^*}\right) \tag{2.19}$$

$$\begin{aligned} S^* &= \min[(S_i)|i = 1, 2, \ldots, m], S^- = \max[(S_i)|i = 1, 2, \ldots, m]; \\ R^* &= \min[(R_i)|i = 1, 2, \ldots, m], R^- = \max[(R_i)|i = 1, 2, \ldots, m] \end{aligned} \tag{2.20}$$

where, v is the weight for the strategy of maximum group utility and 1-v is the weight of the individual regret. v is usually set to 0.5 (Opricovic 1998).

Step 4 Rank the alternatives, sorting by the S, R and Q values in a decreasing order. The results are three ranking lists. The less the value of Q_i is, the better decision of the alternatives A_i is.

Step 5 Propose a compromise solution, the alternative ($A^{'}$) which is ranked the best by the minimum value of Q, if the following two conditions are satisfied:

C1. "Acceptable advantage": $Q(A^{''}) - Q(A^{'}) \geq D$, where $A^{''}$ is the alternative with second position in the ranking list by Q; $DQ = 1/(m - 1)$ and m is the number of alternatives.

C2. "Acceptable stability in decision making": The alternative $A^{'}$ should also be the best in terms of S and/or R value (The lower the value of S/R is, the better).

If one of these conditions is not satisfied, it is not possible to select directly the best solution of the set but a subset of preferable options can be defined, which consists of (Opricovic and Tzeng 2007):

1. Alternatives $A^{'}$ and $A^{''}$ if only the condition C2 is not satisfied, or
2. Alternatives $A^{'}, A^{''}, \ldots, A^{(M)}$ if the condition C1 is not satisfied, where $A^{(M)}$ is determined by the relation $Q(A^{M}) - Q(A^{'}) < DQ$ for maximum M.

The VIKOR calculates the ratio of positive and negative ideal solution, and thus proposes a compromise solution with an advantage rate. Therefore, it is particular helpful in a situation where the decision maker is not able to express their preference at the beginning of decision-making process. It has been applied for dealing with MCDM problems in various fields including design and manufacturing, marketing, supply chain management, and risk management, to name just a few (Yazdani and Graeml 2014).

6 Elimination Et Choix Traduisant la REalité (ELECTRE)

The acronym of ELECTRE stands for ELimination Et Choix Traduisant la REalité (ELimination and Choice Expressing the REality) (Benayoun et al. 1966). As a family member of MCDM methods, the ELECTRE method was originated in the mid-1960s at the European consultancy company SEMA for commercial reasons (Sevkli 2010). It was initially devised for choosing the best action from a given set of alternatives, and was later referred to as ELECTRE I. This approach has evolved into a number of variants, such as ELECTRE II (Roy and Bertier 1973), ELECTRE III (Roy 1978), and ELECTRE TRI (Yu 1992), for the purpose of different types of problems being addressed, such as choosing, ranking or sorting. Figueira et al. (2005) stated more detailed introduction of different ELECTRE methods, as well as their history, developments, and main features. ELECTRE is based on the study of outranking relations between alternatives, taking two at a time. Concordance and discordance indexes are used to analyse such relations, which can be viewed as the measures of satisfaction and dissatisfaction of a decision maker when choosing one alternative over the other. Assume there are m alternatives and n decision criteria for a MCDM problem, and each alternative is evaluated with respect to n criteria. The decision matrix can be donated as the same by Eq. (2.10) (in Sect. 4). Then, the ELECTRE method can be summarised as follows.

The decision matrix $D = (x_{ij})_{m \times n}$ is firstly normalised through Eq. (2.11). A weighted normalized decision matrix $V = (v_{ij})_{m \times n}$ can then be constructed by multiplying the normalized one with the associated weights using Eq. (2.12). The procedures for normalizing and weighting a decision matrix exactly follow the first three steps in the TOPSIS method, detailed information on how to obtain a weighted normalized decision matrix is no longer repeated in this section.

After that, concordance and discordance sets are determined. For each pair of alternatives A_p and A_q ($p, q = 1, 2, \ldots$,m and, $p \neq q$), the set of criteria is divided into two distinct subsets. In terms of the criteria against which alternative A_p is preferred to alternative A_q, the concordance set is composed as

$$C(p, q) = \{j | v_{pj} > v_{qj}\} \tag{2.21}$$

$C(p, q)$ is the collection of attributes where A_p is better than, or equal, to A_q. On completing $C(p, q)$, the discordance set $D(p, q)$, as a complement of $C(p, q)$, is obtained by investigating the criteria against which A_p is better than A_q. it can be presented as

$$D(p, q) = \{j | v_{pj} < v_{qj}\} \tag{2.22}$$

The concordance index of $C(p, q)$ is generated by adding the values of weights of concordance set elements, defined as

$$C_{pq} = \sum_{j^*} w_{j^*} \tag{2.23}$$

where j^* are the attributes contained in the concordance set $C(p, q)$. The discordance index $D(p, q)$ represents the degree of disagreement in $A_p \rightarrow A_q$ (it means that alternative A_p outranks A_q, which indicates a situation where performance values of A_p are better or at least equal than those offered by A_q in respect of the majority of criteria) in Eq. (2.24):

$$D_{pq} = \frac{\sum_{j^+} | v_{pj^+} - v_{qj^+} |}{\sum_{j} | v_{pj} - v_{qj} |} \tag{2.24}$$

where j^+ are the attributes contained in the discordance set $D(p, q)$. This method implies that A_p outranks A_q when $C_{pq} \geq \bar{C}$ and $D_{pq} \leq \bar{D}$, where, threshold values $\bar{C}$ and $\bar{D}$ are usually set by decision makers (Sevkli 2010).

One main weakness of ELECTRE methods is that threshold values for the concordance and discordance indices are usually decided according to decision makers' opinion, which brings in subjectivity. However, as important members belonging to family of outranking methods, ELECTRE methods are still popular despite its existence for more than four decades, and its application can be seen in, for example, energy management (Mousavi et al. 2017), supply chain management (Fahmi et al. 2016), and risk assessment (Govindan and Jepsen 2016).

7 Preference Ranking Organization METHods for Enrichment Evaluation (PROMETHEE)

ROMETHEE is a popular MCDM outranking method dealing with the evaluation problems, originally introduced by Brans (1982). Brans et al. (1984) elaborated the method as a new family member of outranking methods in multi-criteria analysis.

Brans and Vincke (1985) further developed it with sophisticated mathematical reasoning and published their work in *Management Science*. Brans and Mareschal (1994) introduced a decision support system and visual software, named as PROMCALC & GAIA, showing some examples and requisites to demonstrate the applications of PROMETHEE in reality.

The PROMETHEE method contains PROMETHEE I for partial ranking of alternatives, PROMETHEE II for complete ranking, PROMETHEE III for ranking based on interval, and PROMETHEE IV for ranking in continuous viable solutions. Other members include PROMETHEE V (Brans and Mareschal 1992), PROMETHEE VI (Brans and Mareschal 1995), PROMETHEE GDSS (Macharis et al. 1998), and visual interactive module GAIA (Geometrical Analysis for Interactive Aid) for graphical representation (Brans and Mareschal 2005), and etc. On a review paper on PROMETHEE (Behzadian et al. 2010), 217 papers using the method were investigated from 100 journals in the period of 1985–2009.

The core idea of PROMETHEE is the pairwise comparison of alternatives along each recognized criterion, taking the inner relationships of each evaluation facts into account. It derives a (partial or complete) ranking of a finite set of feasible alternatives based on a positive outranking flow, a negative outranking flow and a net outranking flow. PROMTHEE is capable of addressing decision-makers' evaluation problems through reasonable normalization, thus avoiding inconsistent ranking results with the characteristic functions, and providing them with visual software so as to easily deal with the evaluation problems and sensitive analysis. Given its structure, this method allows a direct operation on the variables included in a decision matrix, without requiring any normalization. PROMETHEE II, which presents the fundamental to the implementation of other PROMETHEE methods, consists the following steps (Behzadian et al. 2010):

Step 1 Evaluate the alternatives with respect to the criteria (assuming there m alternatives and n criteria), and determine the deviations based on pair-wise comparisons:

$$d_j(a,b) = g_j(a) - g_j(b) \tag{2.25}$$

where, a and b are two alternatives, and $d_j(a,b)$ denotes the difference between the evaluations of a and b on each criterion.

Step 2 Calculate the preference between the alternatives a and b via function:

$$P_j(a,b) = F_j\left[d_j(a,b)\right],\ \ j = 1,2,\ \ldots,n \tag{2.26}$$

where $P_j(a,b)$ denotes the reference of alternative a with regard to alternative b against the j^{th} criterion, as a function of $d_j(a,b)$. F_j is a preference function, which translates the difference between the evaluations of alternatives a and b on the j^{th} criterion into a preference degree ranging from 0 to 1. There are six basic types of preference functions as proposed by Brans and Vincke (1985) including usual criterion, U-shape criterion, V-shape criterion, level criterion, V-shape with indifference criterion and Gaussian criterion.

Step 3 Calculate the overall or global preference index

$$\pi(a,b) = \sum_{j=1}^{n} P_j(a,b) w_j \tag{2.27}$$

where, w_j is the weight of the j^{th} criterion, and $\pi(a,b)$ of a over b is defined as the weighted sum of $p(a,b)$ for each criterion.

Step 4 Calculated the positive and negative outranking flows

$$\phi^+(a) = \frac{1}{m-1} \sum_{x \in A} \pi(a,x) \tag{2.28}$$

$$\phi^-(a) = \frac{1}{m-1} \sum_{x \in A} \pi(x,a) \tag{2.29}$$

where A is a collection of alternatives. The partial outranking can be obtained from the two ranks induced by ϕ^+ (positive outranking flow) and ϕ^-(negative outranking flow). a outranks b if $\phi^+(a) \geq \phi^+(b)$ and $\phi^-(a) \leq \phi^-(b)$. Otherwise, it will result to an indifference relation or incomparability of the two alternatives.

Step 5 Calculate the net outranking flow and the complete ranking.

$$\phi(a) = \phi^+(a) - \phi^-(a) \tag{2.30}$$

where $\phi(a)$ denotes the net outranking flow for each alternative. The higher the net flow is, the better the alternative.

PROMETHEE does not provide the possibility to really structure a decision problem, which may increase the difficulty for the decision maker to obtain a clear view of the targeted problem. However, it has unique advantages when important elements of the decision are difficult to quantify or compare, as criteria scores can be expressed in their own units. Moreover, it needs much less inputs compared to other MCDM methods (Gavade 2014). Its extensive application in fields such as environment management, business management, and logistics and transportation has been discussed by Behzadian et al. (2010).

8 Evidential Reasoning (ER)

The theory of evidence was first generated by Dempster (1967) and further developed by Shafer (1976). The Dempster-Shafer theory of evidence or D-S theory was originally used for information aggregation in expert systems as an approximate reasoning tool (Buchanan and Shortliffe 1984; Mantaras 1990) and then used in decision making under uncertainty and risk in contrast to Bayes decision theory (Yager 1992; Yager 1995). ER is developed on the basis of the D-S theory. The use of ER as a decision making tool has been widely reported in the literature. An important achievement of applying ER to decision analysis is to incorporate it into traditional MCDM methods for addressing the degree of belief associated with subjective judgements. The lack of data, the inability of assessors to provide precise judgements, or the failures of some assessors to provide judgements in group decision-making can result in an incomplete assessment (Yang and Xu 2002). An ER based decision making approach for MCDM problems with both qualitative and quantitative criteria under uncertainty was developed in the early 1990's (Yang and Singh 1994; Yang and Sen 1994). The kernel of such an approach is an ER algorithm, which was generated by Yang and Singh (1994), later updated by Yang and Sen (1994) and further modified by Yang (2001) and Yang and Xu (2002). ER is applied for ranking alternatives or selecting the best compromise alternative in a process, in which both quantitative and qualitative attributes are simultaneously satisfied as much as possible (Yang and Singh 1994). Several applications of this approach are addressed in the maritime related literature (Yang 2001; Sii et al. 2001; Yang et al. 2005; Yang et al. 2009a; Yang et al. 2014).

The utilization of the ER algorithm with belief structure can be explained as follows.

Suppose there is a two level hierarchy structure, a top level attribute E consists of L attributes at the lower level which include all the attributes influencing the assessment of the E. Lower level attributes can be represented as:

$$E = (e_1, e_2, \ldots e_i, \ldots e_L).$$

The weight of each attributes can be expressed as $w = (w_1, w_2, \ldots w_i \ldots w_L)$. w_i is the normalized relative weight for the i^{th} attribute (e_i) where $0 \leq w_i \leq 1$.

Suppose there are N evaluation grades, each H_n ($n = 1, 2, \ldots N$) is a standard grade for assessing an attribute. Without loss of generality, it is assumed that $H_{(n+1)}$ is preferred to H_n. A given assessment for e_i ($i = 1, 2, \ldots L$) of an alternative can be represented as:

$$S(e_i) = \left\{ \left(H_n, \beta_{n,i}\right), n = 1, 2, \ldots N \right\} \tag{2.31}$$

where $\beta_{n,i} \geq 0$ and denotes to the degree of belief associated with the evaluation grade H_n for the attribute e_i. An assessment $S(e_i)$ is complete if $\sum_{n=1}^{N} \beta_{n,i} = 1$ and incomplete if $\sum_{n=1}^{N} \beta_{n,i} < 1$.

The basic probability assignments for each attribute can then be calculated as below.

Let $m_{n,i}$ be a basic probability mass representing the degree to which the i^{th} attribute supports the hypothesis that the top level attribute is assessed to the n^{th} evaluation grade. Then $m_{n,i}$ can be obtained as follows:

$$m_{n,i} = w_i \beta_{n,i} \qquad (n = 1, 2, \ldots N) \tag{2.32}$$

Let $m_{H,i}$ be the remaining probability mass unassigned to any individual grade after e_i has been assessed. $m_{H,i}$ can be calculated as follows:

$$m_{H,i} = 1 - \sum_{n=1,}^{N} m_{n,i} = 1 - w_i \sum_{n=1}^{N} \beta_{n,i} \quad (i = 1, 2 \ldots L) \tag{2.33}$$

$m_{H,i}$ contains $\bar{m}_{H,i}$ and $\tilde{m}_{H,i}$, where $\bar{m}_{H,i}$ represents the remaining probability mass that other attributes (apart from the i^{th} attribute) contribute in the assessment. $\tilde{m}_{H,i}$ is the unassigned probability mass due to the possible incompleteness in the assessment. They can be expressed as follows:

$$\bar{m}_{H,i} = 1 - w_i \text{ and } \tilde{m}_{H,i} = w_i\left(1 - \sum\nolimits_{n=1}^{N} \beta_{n,i}\right) \tag{2.34}$$

$m_{H,i}$ can therefore be presented as:

$$m_{H,i} = \bar{m}_{H,i} + \tilde{m}_{H,i} \tag{2.35}$$

The probability assignment for an attribute can be combined as follows.

Let $m_{n,I(1)} = m_{n,1}$ $(n = 1, 2, \ldots N)$, $\bar{m}_{H,I(1)} = \bar{m}_{H,1}$, $\tilde{m}_{H,I(1)} = \tilde{m}_{H,1}$ and $m_{H,I(1)} = m_{H,1}$. A factor $K_{I(i+1)}$ is used to normalize $m_{n,I(i+1)}$ and $m_{H,I(i+1)}$ so that $\sum_{n=1}^{N} m_{n,i} + m_{H,I(i+1)} = 1$.

$$K_{I(i+1)} = \left[1 - \sum\nolimits_{t=1}^{N} \sum\nolimits_{\substack{j=1 \\ j \neq t}}^{N} m_{t,I(i)} m_{j,i+1}\right]^{-1} (i = 1, 2 \ldots L-1) \tag{2.36}$$

The combined probability assignment $m_{n,I(L)}$ $(n = 1, 2, \ldots N)$, $\bar{m}_{H,I(L)}$, $\tilde{m}_{H,I(L)}$ and $m_{H,I(L)}$ can be generated as follows.

$$\{H_n\} : m_{n,I(i+1)} = K_{I(i+1)}\left[m_{n,I(i)} m_{n,i+1} + m_{H,I(i)} m_{n,i+1} + m_{n,I(i)} m_{H,i+1}\right] \tag{2.37}$$

$$\begin{aligned}&\{H\}:m_{H,I(i)}=\tilde{m}_{H,I(i)}+\bar{m}_{H,I(i)}\\&\tilde{m}_{H,I(i+1)}=K_{I(i+1)}\left[\tilde{m}_{H,I(i)}\tilde{m}_{H,i+1}+\bar{m}_{H,I(i)}\tilde{m}_{H,i+1}+\tilde{m}_{H,I(i)}\bar{m}_{H,i+1}\right]\\&\bar{m}_{H,I(i+1)}=K_{I(i+1)}\left[\bar{m}_{H,I(i)}\bar{m}_{H,i+1}\right]\end{aligned}\tag{2.38}$$

The combined degrees of belief of all the lower level attributes for the assessment of the top level attribute can then be calculated. Let β_n denote a degree of belief that the top level attribute is assessed to the grade H_n, which is generate by combining the assessments for all the associated attribute e_i,$(i = 1, 2 \ldots L)$. β_n can be calculated by:

$$\begin{aligned}&\{H_n\}:\beta_n=\frac{m_{n,I(L)}}{1-\bar{m}_{H,I(L)}}\quad(n=1,2,\ldots N)\\&\{H\}:\beta_H=\frac{\tilde{m}_{H,I(L)}}{1-\bar{m}_{H,I(L)}}\end{aligned}\tag{2.39}$$

The overall assessment for the top level attribute E can be represented by Eq. (6.22).

$$S(E) = (H_n, \beta_n) \quad (n = 1, 2, \ldots N) \tag{2.40}$$

ER is capable of dealing with problems with both quantitative and qualitative criteria. It introduces the concepts of belief structure and belief decision matrix, which makes it possible to model uncertainties of various types of nature in a unified format for further analysis without resorting to sensitivity analysis. However there are some criticisms in the application of ER. Processing the data in a belief decision matrix by hand is rather difficult. But this issue is largely addressed through the development of the IDS software. In addition, interpreting the outcome represented by a belief structure is not as straight forward as interpreting a simple score (Xu 2012).

9 Fuzzy Logic

Fuzzy logic was first conceptualized by Zadeh in 1965 (Zadeh 1965). Recognizing the reality that many criteria involved in a decision making process are far from precise or clear, the idea of applying fuzzy logic into MCDM has been widely discussed for more than two decades. Fuzzy logic is a superset of conventional Boolean logic with extensions to account for imprecise information. Instead of crisp membership of a set, its membership is fuzzy or imprecise. Fuzzy logic permits vague information, knowledge and concepts to be used in an exact mathematical manner. Linguistic variables such as “definite”, “likely”, “average”, “unlikely” and “impossible” are necessary media used to describe continuous and overlapping states. This enables qualitative and imprecise reasoning statements to be incorporated with fuzzy algorithms or fuzzy rule bases producing simpler, more intuitive and better-behaved models. Fuzzy logic is based on the principle that every crisp value belongs to all relevant fuzzy sets to various extents, called the degrees of membership. Pure fuzzy logic has extremely limited applications in business (the only popularised application is the Sony Palmtop) and the main use of fuzzy logic is as an underlying logic system for fuzzy expert decision making systems (Pai et al. 2003). It has been successfully applied for a wide range of single and MCDM problems. For instance, Chou (2010) proposes a fuzzy MCDM methodology for solving the container transhipment hub port selection dilemma under fuzzy environment. Wang and Lee (2010) utilize a fuzzy MCDM method for evaluating the financial performance of container shipping companies based on extended fuzzy preference relation and using linguistic weights. The application of fuzzy logic in MCDM becomes more compelling when being combined with AHP, (Bulut et al. 2012; Hsu 2012; Chao and Lin 2011), TOPSIS (e.g. Yeh and Chang 2009; Durbach and Stewart, 2012; Yang and Wang 2013; Kannan et al. 2014), VIKOR (e.g. Kaya and Kahraman 2010; Shemshadi et al. 2011), ELECTRE (e.g. Sevkli 2010; Chen and Xu 2015), and PROMETHEE (e.g. Shirinfar and Haleh 2011; Gupta et al. 2012; Tavakoli et al. 2013).

10 Conclusion

This chapter has introduced eight most popular MCDM methods, which rank a finite set of alternatives with respect to their frameworks, algorithms, and advantages and disadvantages. It has also presented their applications in the literature mainly within the context of shipping, port and logistics. The readers can therefore have a better understanding of their own applicability and suitability. Having said that, this chapter has laid down a platform for the following chapters in this book, which focus on new applications of MCDM methods as well as their hybrid approach in maritime and logistics areas.

Acknowledgements The authors would like to thank the EU FP7 Marie Curie IRSES project “ENRICH” (612546) for its financial support to this research.

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Multi-Criteria Decision Making in Maritime Studies and Logistics
Applications and Cases
Lee, P.T.-W.; Yang, Z. (Eds.)
2018, XIX, 363 p. 91 illus., 54 illus. in color., Hardcover
ISBN: 978-3-319-62336-8