Modeling Interactions Among Criteria in MCDM Methods: A Review

Ksenija Mandic(✉), Vjekoslav Bobar, and Boris Delibašić

Faculty of Organizational Sciences, University of Belgrade,
Jove Ilica 154, Belgrade, Serbia
ksenija.mandic@crony.rs, vbobar@gmail.com,
boris.delibasic@fon.bg.ac.rs

Abstract. This paper reviews approaches for modelling interactions and dependencies between criteria in multi-criteria decision-making (MCDM) methods. Traditionally, MCDM methods only allow the establishment of linear dependence between criteria, so they only allow for simplified models that are mostly inadequate for modelling real-life problems. Several methods have therefore been developed for modelling the interdependence between criteria and sub-criteria in MCDM. This paper makes a comparison between some popular methods that allow modelling of criteria interdependencies: Analytic Network Process (ANP), Decision Making Trial and Evaluation Laboratory (DEMATEL), Interpretive Structural Modelling (ISM), Fuzzy Measures and the Choquet Integral (CI) and Interpolative Boolean Algebra (IBA). These methods allow the establishment of interactions and comparisons between criteria using supermatrices, diagrams, fuzzy measures, fuzzy integrals and logical functions. This paper presents the MCDM approaches that include in their analysis the interdependencies and relation between criteria/sub-criteria and thus enable more efficient and realistic modelling of decision-making problems.

Keywords: MCDM · Interactions between criteria · ANP · DEMATEL · ISM · Fuzzy measures and the Choquet Integral · IBA

1 Introduction

Multi-criteria decision-making (MCDM) is probably the most popular decision-making discipline. It models decision-makers' subjective assessments of a large number of quantitative and qualitative criteria, which are often conflicting. The primary aim of MCDM is to develop a methodology that enables the aggregation of criteria/sub-criteria, which includes the preferences of decision-makers [46]. Achieving this goal requires the application of complex procedures. As MCDM generally handles a multitude of criteria and sub-criteria, most literature on the topic uses the weighted sum of criteria for criteria aggregation. It is therefore assumed that criteria are independent, which is most often not the case. On the other hand, there are several approaches found in the literature that model interrelationship between criteria.

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When evaluating a decision-making problem, it is necessary to take into account a large number of criteria/sub-criteria and determine their relative weights. The criteria are often interdependent and between them there are certain relations, so their individual weight is hard to determine. For this reason, many decision-making problems cannot be adequately translated into a flat or even hierarchical criteria structure. In addition, the artificial neglect of these interdependencies affects the obtained results, so that they do not reflect the problem realistically. Therefore, in order to make an accurate and flexible decision, it is necessary to include in the MCDM analysis the interactions between the decision-making criteria. Engaging the complex relationships between the elements of a problem certainly requires more time and effort, but provides more realistic results.

One of the most commonly used MCDM methods is the Analytic Hierarchy Process (AHP) [31]. This technique compares and evaluates the impact of various elements in relation to the goal. It is based on a hierarchical, yet linear, structure between criteria. This method is not adequate, however, for the representation of the problem in a case where there are various interactions between elements, because it only takes into account a one-way hierarchical relationship between decision-making levels. In such situations, when decomposing the problem into a hierarchy, significant interdependence between the elements can be lost. Therefore, such cases require a holistic approach. In the literature, several methods have been developed that have tried to solve the discrepancy that emerges as a consequence of the failure to include interrelations between criteria in the decision-making process.

Analytic Network Process (ANP) was proposed to allow AHP [30] to model the interrelation between various hierarchical levels of decision-making and criteria. The hierarchical structures that are inherent to AHP are replaced by networks, within which relations between the levels are not represented in the manner of higher/lower, dominant/subordinate, or direct/indirect [23]. ANP is a non-linear structure that handles dependencies within a cluster of criteria (internal dependence) and between different clusters (external dependence) [5].

Another effective way to establish dependencies between decision-making criteria is proposed by the Decision-Making Trial and Evaluation Laboratory (DEMATEL) method. It was originally created between 1972 and 1979 by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva [11], in order to study complex and intertwined groups. DEMATEL visualizes complicated structural and causal relationships using matrices or digraphs and has the capability to convert relationships of cause and effect between criteria into a unique structural model [9].

Another approach applied in order to present interrelations among multiple variables is Interpretive Structural Modelling (ISM). This technique represents an interactive learning process, within which a set of various directly or indirectly related criteria is structured in a comprehensive systematic model [32]. ISM is a computer-aided method for developing graphical representations of system composition and structure [3].

In addition to the previously mentioned methods, it is recognized that fuzzy measures and integrals can also model interactions between criteria in a certain way [35]. It was not formalized, however, until Murofushi & Soned [25] proposed an interaction index for a pair of criteria. Later, Grabish [14] proposed a generalization of the index to any subset of criteria. At the beginning of the 90 s, the Sugeno integral was used as a tool for aggregation to calculate the average global score, taking into account the importance of criteria expressed by a fuzzy measure [14]. Then, after the proposal of Murofushi & Sugeno [25], the application of the Choquet integral (CI) - an extension of the classical Lebesgue integral - was quickly entered into use.

A more recent approach, which is singled out as suitable for representation of logical interactions between the criteria/sub-criteria of decision-making, is Interpolative Boolean Algebra (IBA). It was proposed by Radojevic [29] as a consistent realization of fuzzy logic [44]. When using IBA, all the axioms and theorems of Boolean logic apply [28]. What makes this model more flexible for application is that all the structural transformations are taken into account before assigning numerical values, which is not the case in conventional fuzzy MCDM methods. In addition, the IBA approach treats contradiction differently (i.e. a negated variable is not transformed immediately into a value) and respects the law of the excluded middle. Therefore, using IBA allows the establishment of fuzzy logic in a Boolean frame [27].

This paper is intended to review the aforementioned MCDM methods which can handle the relationships and interdependencies between decision-making criteria. Section 2 contains a literature overview of the MCDM methods which take into account the interactions between elements when making a decision. Section 3 gives a brief description of each of the presented methods. Sections 4 and 5 provide discussion and concluding observations with possible directions for further research.

2 Literature Review

Keeney & Raiffa [19] were among the first authors to analyse the problem of interactions between attributes within multi-attribute utility theory (MAUT). They considered three model variants. These models include as a key term the sum of the weighted attribute utilities. The most general model proposed is the multi-linear model, which includes the sum of weighted attributes and interaction terms. The multiplicative model is derived from the multi-linear model by setting all coefficients to one constant. The additive aggregation model is also a derivative of the multi-linear model, by setting all interaction coefficients as equal to zero. All three model variants are additive in essence.

In the literature, we can find several review papers of recent date which elaborate the methods of MCDM [1, 39, 40]. However, these papers are mainly based on a review of all the MCDM approaches, as well as their application in various fields of research. This review paper differs from the aforementioned papers in its analysis and description only of the methods primarily involving relationships and dependencies between criteria. Authors often combine the aforementioned MCDM methods in order to take into account the mutual interactions and interdependencies between the criteria/sub-criteria. Some combinations of these methods are presented hereinafter.

Gürbüz & Albayrak [16] propose a hybrid approach that combines ANP and CI for evaluation of human resources. The interaction between different criteria is taken into consideration, which is not peculiar for methods that have so far been used for the evaluation of human resources. In addition, two different types of interaction are managed at the same time. The reason for using ANP is that the decision-making problem has several criteria, and these criteria demonstrate interdependencies most of the time. On the other hand, CI - a fuzzy integral - handles "conjunctive/disjunctive" interactions between criteria. The same combination of methods is applied to the ERP selection problem [17].

On the other hand, Nguyen et al. [26] developed a fuzzy MADM model and machine tool selection, taking into account the interaction between criteria. For the needs of this paper they used fuzzy ANP and COPRAS-G (Complex Proportional Assessment of Alternatives with Grey Relations). The FANP is used to cope with imprecise information arising from the evaluations of decision-makers. Furthermore, this method allows the modelling of interaction, feedback, relationships and interdependence between criteria, and thus determines the weights of criteria. COPRAS-G enables the representation of preference ratios for the alternative interval values in relation to each criterion and to calculate the weighted priorities of the machine alternatives.

Mehregan et al. [24] studied the interaction between sustainability criteria in the selection of suppliers and to do so they used ISM and fuzzy DEMATEL (FDEMATEL) methods for the first time. They applied ISM to determine the interaction between sustainable supplier evaluation criteria, while the use of FDEMATEL allowed them to determine the intensity of these interdependencies. They illustrated how the integrated ISM-FDEMATEL model can be a significant management tool for evaluating and analyzing interactions between criteria. This approach has been used in Iranian gas engineering and in the development of companies.

Tadic et al. [38] have proposed a FDEMATEL-FANP-FVIKOR model for the selection of city logistics concepts. For the analysis of interdependences between factors and criteria fuzzy ANP was used, for determining interdependences between the groups of factors the fuzzy DEMATEL method was used, while the ranking of alternatives was done by FVIKOR technique. In the first phase, FDEMATEL and FANP are combined, providing a weight for each criterion. These weights are used in the next step, applying the FVIKOR method to rank the alternatives.

Another more recent approach that is singled out as an efficient tool for establishing a logical interaction between criteria/sub-criteria is IBA. Mandic et al. [22] have combined IBA and the classical MCDM method TOPSIS to conduct the selection of suppliers. IBA enables the presentation of logical dependencies between criteria with the help of Boolean algebra and in compliance with Boolean laws. In this study IBA has been used in order to present logical interdependences between the elements of decision-making, while TOPSIS was used to produce the ranking of alternatives.

The main criterion for the selection of sources cited within this section is the application of MCDM methods that involve interactions between criteria for solving real problems of decision-making. In the paper, works of recent date are quoted to indicate the topicality of analyzed themes.

3 Description of the Methods that Include Interaction Between the Elements of Decision-Making

3.1 Analytic Network Process - ANP

MCDM methods such as AHP and ANP are able to generate priority weights of criteria and alternatives, using a pair-wise comparison matrix of expert's decisions. However, ANP [30] is an expansion of AHP because it takes into account the relationships between higher-level and lower-level elements. ANP is used to model the interaction, dependence and feedback within groups of elements and between groups [26]. The groups of elements include the goals, criteria and sub-criteria in the decision making process. ANP is more advanced than AHP because it includes the relationships between elements within the structure.

Network structures are integral to ANP. In the network structure, a node is a cluster of associated elements; the lines within the structure suggest interaction between clusters, while the inner loop represents dependencies between the elements within a cluster. There are two types of influences/dependencies between elements considered in ANP: internal and external. Internal influences are dependencies of one element on another element within a cluster. External influences are the effect that elements from one cluster have on the elements of another [16]. The advantage of ANP is that it is able to determine the priority of clusters and their elements. In addition to considering the interdependencies of elements it also takes into account the independent elements themselves [41].

With ANP, interactions between elements are established by applying a supermatrix. Within MCDM a supermatrix includes three types of relations [17]: (1) independence from successive criteria/sub-criteria, (2) interdependence between criteria/sub-criteria and (3) interdependence between the levels of criteria and sub-criteria. ANP can be implemented in six steps as presented in Fig. 1:

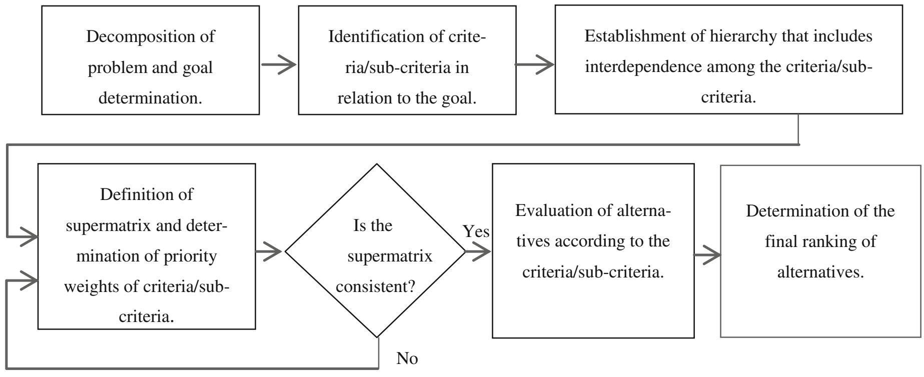

Fig. 1. The steps of ANP

3.2 Decision Making Trial and Evaluation Laboratory - DEMATEL

DEMATEL was developed between 1972 and 1979 by the Science and Human Affairs Program of the Battelle Memorial Institute of Geneva [11]. The goal of DEMATEL is to convert the causal relationships between elements from a complex system to an understandable structural model [21]. DEMATEL is helpful in visualizing the structure of complex causal relationships between evaluation criteria through the use of matrices or digraphs [4].

This method involves two groups - causal and effect. The causal group affects the effect group and thus are determined the weights of criteria [7]. This technique allows decision-makers better comprehension of the structural relationship between elements of a system [45]. This method is applied to analyze and outline the relationship of cause and effect between the evaluation criteria [43] or to reveal interrelationship between factors [21]. Phases of the DEMATEL method can be presented as in the following Fig. 2:

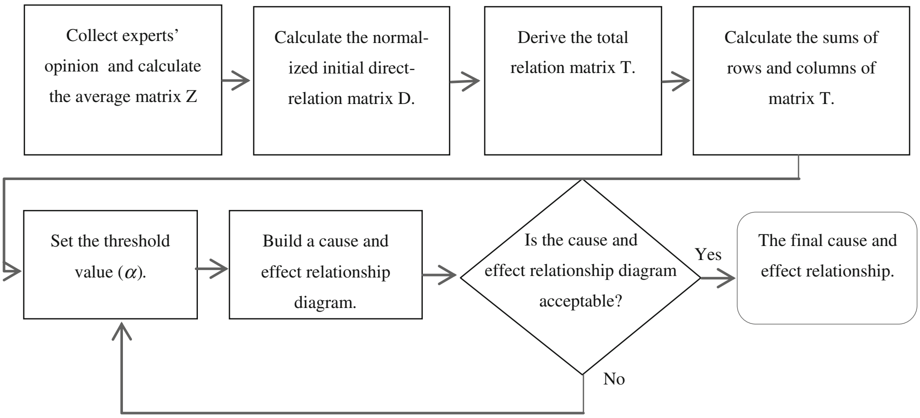

Fig. 2. The steps of DEMATEL (Source: [37])

DEMATEL analyzes the structure of components within each criterion, as well as the intensity of direct and indirect relationships between the defined components, causal relationships, and the strength of influence [20]. Structural matrices and causal diagrams are used to present the causal relationships and levels of impact between criteria in a complex system.

3.3 Interpretive Structural Modelling - ISM

ISM is proposed by Warfield [42] for the analysis of complex social and economic systems. ISM presents a computer-assisted learning process that allows individuals or groups to develop a map of the intricate relationships between the different elements that are involved in a complex situation [3]. The basis of this technique is to use the practical knowledge of experts to decompose a complicated system into several sub-systems, i.e. to create a structural model which consists of several levels (Fig. 3).

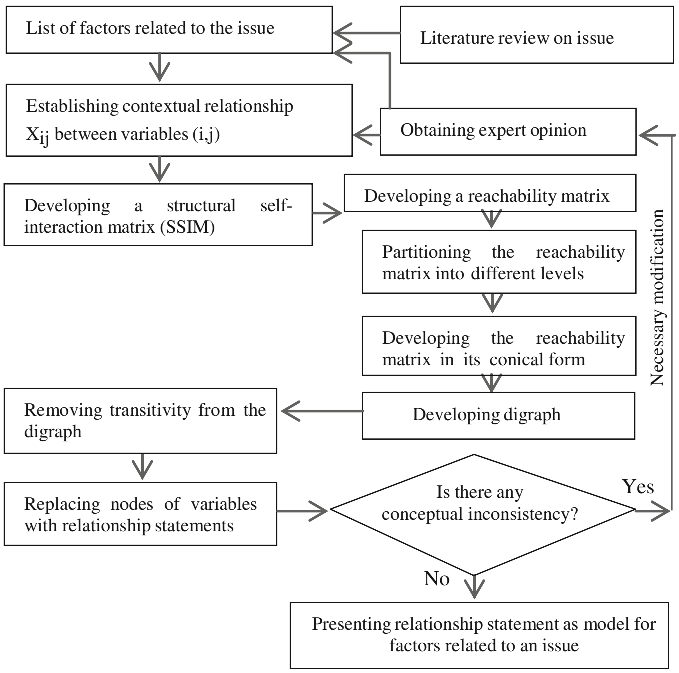

Fig. 3. The steps of ISM (Source: [3])

The interpretive (I) represents the judgment of a group of experts in relation to the area of research. Estimates made by the group of experts are collected and it is decided whether and how the variables are interrelated. Structural (S) refers to the overall structure extracted from a complex set of variables that interact with each other. Modelling (M) illustrates the specific relationships of the variables and overall structure of the system under consideration [12].

3.4 Fuzzy Measures and the Choquet Integral - CI

Fuzzy measures are set functions with monotonicity, which aren't necessarily additive [34]. In other words, they are an extension of a measure in the sense that the additivity of the measure is replaced with a weaker condition, monotonicity. Sugeno [36] also suggests the fuzzy integral, which is an integral with respect to fuzzy measures. The CI is suggested within the fuzzy measure community by Murofushi & Sugeno [25], while the fuzzy integral was put forward by Choquet [6] and encompasses interactions between k out of n criteria of the problem, which is called the k-additivity property.

The CI is an approach that is closely related to fuzzy measures. Fuzzy integrals are used to present the interactions between criteria. They allow simple translation of a decision-maker's requests into coefficients of the fuzzy measure. The idea is that super-additivity of the fuzzy measure implies synergy between the criteria, and subadditivity implies redundancy [14]. Most real applications of fuzzy measures deal with MCDM problems, where fuzzy measures are defined on the finite set of criteria, and model the relative importance of criteria as well as their interaction [13]. Furthermore, Grabish & Roubens [15] have proposed an axiomatic basis for the interaction index, giving a consistent basis for dealing with the notion of interaction.

3.5 Interpolative Boolean Algebra - IBA

Since conventional fuzzy set theory does not satisfy all Boolean axioms and laws, methods for the consistent realization of fuzzy logic have been developed. Consistent generalization of fuzzy logic is enabled by using Interpolative Boolean Algebra (IBA), as proposed by Radojevic [29]. IBA is a real valued, and/or [0,1] value realization of Boolean algebra [8]. This approach includes all logical functions, interpolative operators and generalized product operators [27]. Under IBA, all Boolean axioms and theorems apply [28].

IBA has a finite number of elements and it is atomic algebra. IBA clearly separates the structure and value of the elements of Boolean algebra. It consists of two levels: (a) symbolic and (b) valued [27]. At the symbolic level, one of the basic concepts is the structure of elements in IBA. The principle of structural functionality indicates that the structure of any combined element in IBA can be directly calculated based on the structure of its components. The valued level is a concrete symbolic level in terms of value. An element from the symbolic level preserves all its characteristics at the value level, as described by Boolean axioms and laws [28].

IBA is technically based on the generalized Boolean polynomial – GBP [29]. GBP is a polynomial of which the variables are elements of Boolean algebra, and thus it allows for the processing of the corresponding element of Boolean algebra into the value of the real interval [0,1] using operators such as classical (+), classical (−) and generalized product ($\otimes$) [27].

4 Discussion

In addition to the presented methods, it is necessary to mention the more recent approaches which include interactions between criteria in their analysis. Among them are the following:

MUSA (Multi-Criteria Satisfaction Analysis), proposed by Angiella et al. [2], represents a preference disaggregation approach that is based on the principle of ordinal regression analysis. MUSA finds an additive utility function that represents the level of satisfaction of users based on their preferences. By using this approach, users determine the comprehensive satisfaction level for each product/service, but the marginal satisfaction level for each criteria of the decision-making is also determined.

UTA (Utilites Additives) includes robust ordinal regression, and is proposed by Jacquet-Lagreze & Siskos [18]. UTA belongs to the utility/value function category of MCDM approaches. Slowinski et al. [33] have proposed an extended version of the UTA method for the assessment of strong or weak outranking relations and the problem of multi-criteria ranking. This method takes into account all compatible value functions at the stage of ranking.

Figueira et al. [10] have proposed an improved version of ELECTRE (Elimination and Choice Expressing the Reality) which involves the analysis of interactions between criteria. Specifically, it expands the concept of concordance and discusses three types of interactions designated as mutual strengthening, mutual weakening, and antagonistic.

From the techniques presented, it can be concluded that MCDM methods which include interactions between criteria use different tools for their presentation, for example: ANP - hierarchy structures and supermatrices; DEMATEL - structural matrices and cause/effect diagrams; ISM - structural self-interaction matrices; fuzzy measures and CI - fuzzy measures and integrals; and IBA - logical function Boolean operators, GBP and LA. The following table (Table 1) presents the basic advantages and disadvantages of the stated methods.

Table 1. Advantages and disadvantages of presented MCDM methods

Method	ANP	DEMATEL	ISM	Fuzzy measures and integrals	IBA	MUSA	UTA	ELECTRE
Advantages of methods	Takes into account dependent and independent criteria	Determines the direct and indirect relationships between criteria	Allows judging of differences between elements and understanding of what criteria are based on	Presents positive and negative interactions between criteria	Provides structural transformation rather than introducing numerical values	Considers qualitative form of customers' judgments and preferences	Complete ranking using one compatible value function	Takes into account three types of interaction: mutual strength, mutual weakness and antagonistic
Disadvantages of methods	Is unable to single out an element and identify its strengths and weaknesses	Mechanism which allows the integration of indirect /direct relation is unclear	Cannot consider a number of criteria and is not statistically validated	Evaluates all criteria on one scale	Decision-makers cannot always adequately set logical functions	Cannot present positive and negative synergies	Unrealistic hypothesis concerning preferential interdependence between criteria	Is not adequate for representing a large number of interactions between criteria

5 Conclusion

Many MCDM methods are effectively used for solving a large number of decision-making problems in different fields of research. However, some of the most famous MCDM methods such as AHP and TOPSIS only allow the establishment of linear relationships between elements of decision making. Considering the relationship between criteria/sub-criteria in linear form only, ignoring any mutual interaction or interdependence, has proven not to be adequate in practice.

Academics, therefore, began to develop holistic approaches involving interrelationships between the elements of decision-making. Some of the approaches discussed in this paper are ANP, DEMATEL, ISM, fuzzy measures and integrals, and IBA. Analysis of the presented methods demonstrates that they give more reliable results by viewing the aggregation of criteria as a non-linear structure where elements are interrelated. Most MCDM methods, in structuring complex decision-making models, viewed criteria as independent elements. In many complex real world decision problems, however, there are certain relationships and interdependencies between the criteria. Moreover, the value of the criteria for an appropriate action can be influenced by a number of factors that are external to the decision system and cannot be controlled by the decision-maker.

In this paper we would like to highlight the importance of modelling the interactions betwen criteria in decision-making, because otherwise it may lead to making bad decisions according to false assumptions of linearity and independence. As can be concluded from the presented research, all recently proposed MCDM methods are dealing with the inclusion of interactions between decision-making criteria. Therefore, with further research, we aim to identify all of the newly developed approaches, perform a comparison with existing methods, and determine which of these routes is most appropriate to establish relations between decision-making criteria.

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