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Edited by Fausto Pedro García Márquez,
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Contributors

Love Ekenberg, Mats Danielson, Andreas Paulsson, Bernard Cadet, Abit Balin, Hayri Baracli, Fausto Pedro García Márquez

Notice

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Meet the editors

Prof. Fausto Pedro García Márquez is a Full Professor at UCLM (Spain), Honorary Senior Research Fellow at Birmingham University (UK), and recently he was a Senior Manager at Accenture. He is a director of the Ingenium Research Group, author of more than 150 papers, 25 books and 5 patents in Business Management. He is a Principal Investigator in 4 EU projects, 5 National Projects, 2 Regional and more than 145 for companies. He had been awarded with more than 10 international prizes.

Alberto Pliego received his European PhD in Engineering from the School of Industrial Engineers of Ciudad Real in 2016, with the maximum distinction. He is an industrial engineer and technical engineer in electricity from the University of Castilla-la Mancha (UCLM), Spain. He has several publications (journal papers, conference paper, book chapters and monographies) in the field of maintenance and decision making. Alberto has worked as a lecturer and researcher at the UCLM in Ciudad Real; as an associate professor at the University College of Financial Studies (CUNEF) in Madrid and; as an IT consultant in Everis Spain. He is currently an active member of the Ingenium Research group.

Dr. Mayorkinos Papaelias is an expert in Decision Making, NDT and condition monitoring. He is currently involved as project coordinator in several industrial collaborative research projects related to the wind power and railway sectors which are financially supported by the European Commission.

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Chapter 1

Introductory Chapter: An Overview to the Analytic Principles with Business Practice in Decision Making

Fausto Pedro García Márquez,
Alberto Pliego Marugán and Mayorkinos Papaelias

Additional information is available at the end of the chapter

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1. Decision making

Decision-Making is a book based on contributions by different authors. The book synthesizes the analytic principles with business practice of decision-making [1]. The book provides an interface between the main disciplines of engineering/technology and the organizational, administrative, and planning abilities of decision-making. It is complementary to other sub-disciplines such as economics, finance, marketing, decision and risk analysis, etc.

Decision-making can be understood as a method to select an option into a set. The method can be exact or not, quantitative/qualitative, and so on, and therefore, the option can be optimal or not [2]. These operations are done for anyone every day in anywhere. The decisions can be classified according to the period as politic (very long period), strategic (long period), and operational (short period).

The scientific advances, together with the competitiveness in the market, have led that this concept will be very important nowadays, generating a large number of research publications, new software, specific profiles in the human resources, etc., in every industry field.

Nowadays the industry is employing the new technologies and information system in decision-making. Business analytics employs data to build quantitative models to manage decisions due to the unknown future. The methods are based on statistical analysis, management science, operational research, etc. [3, 4].

It requires advanced methods for advanced analytics [5–8]. Triantaphyllou showed a paradox on what decision-making method should be used to choose the best decision-making method [9]. A state-of-the-art survey of multiple attribute decision-making is discussed in Refs. [6, 10].

New methods are being presented [11–13], where the artificial intelligence is being one of the most important [14–16]. This book presents also several methods for different case studies.

Charnes et al. [17] presented a research work on measuring the efficiency of decision-making units. Linear and nonlinear programming methods were presented. This study also considered the engineering and economic connections to decision-making.

The chapters introduce and demonstrate a decision-making theory to practice case studies. It demonstrates key results for each sector with diverse real-world case studies. The theory is accompanied by relevant analysis techniques, with a progressional approach building from a simple theory to complex and dynamic decisions with multiple data points, including big data, lot of data, etc. Computational techniques, dynamic analysis, probabilistic methods, and mathematical optimization techniques are expertly blended to support analysis of multi-criteria decision-making problems with defined constraints and requirements.

The book is focused on graduate students and professionals in business administration, industrial organization, operations management, applied microeconomics, and the decisions sciences, either studying decision-making analysis or who are required to solve large, specific, and complex multi-criteria decision-making problems as a part of their jobs. The work will also be of interest to industrial engineers and engineering designers working with optimization problems, but this is not the main audience and finally researches from the academia.

Author details

Fausto Pedro García Márquez[1]*, Alberto Pliego Marugán[1] and Mayorkinos Papaelias[2]

*Address all correspondence to: faustopedro.garcia@uclm.es

1 Ingenium Research Group, University of Castilla-La Mancha, Spain

2 School of Metallurgy and Materials, University of Birmingham, United Kingdom

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Chapter 2

A Multi-Criteria Decision-Making Methodology Suggestion for Turkey Energy Planning Based Type-2 Fuzzy Sets

Abit Balin and Hayri Baracli

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Abstract

Energy as an essential basis for the social development has a vital role for survival and development of humankind as an environmental factor. Energy consumption of Turkey has become an important problem through the exorbitant price increase in the fundamental energy source of the world and rapid development in the economy of Turkey. The necessity to create correct decision-making processes related to future in order to eliminate this problem has appeared as well. For that reason, views of decision-makers upon the relative importance of selection criteria were determined, using analytical hierarchy process (AHP) and technique for order preference by similarity to ideal solution (TOPSIS) based upon type-2 fuzzy sets (FSs) that were used in order to list the best energy alternatives.

Keywords: energy planning, strategy management, type-2 fuzzy sets, multi-criteria decision-making (MCDM), technique for order preference by similarity to ideal solution (TOPSIS), analytical hierarchy process (AHP)

1. Introduction

Energy system plays an important role in the economic and social development of a country and life quality of people. In order to encourage the use of sustainable energy and implementation of energy productivity precautions and technical changes, some new government policies have been adapted. Since the beginning of civilization, energy sources have become important for people [1, 2].

Furthermore, making a decision on energy planning based upon the energy demand includes balancing various ecological, social, technical and economic aspects on time and place. This balance is critical for the survival of nature and welfare of the population dependents to energy [3, 4].

When we try to select any energy alternatives using some criteria, we should regard the inconsistent points between the considered criteria. Making a selection among energy resource alternatives is a multi-criteria decision-making (MCDM) problem including several criteria conflicting with each other. We are obliged to evaluate some alternatives, considering the advantages and disadvantages in terms of selection criteria. Meanwhile, energy evaluations should cope with qualities and components that are hard to define and can include both qualitative and quantitative factors. Accordingly, this problem should be overcome through multi-criteria decision-making (MCDM) method. This method can present alternatives to overcome complicated energy management problems [5, 6].

In 1970s, it was popular to discuss energy problems through mono-criteria approaches aiming to define low-cost most productive energy supply choices. Moreover, in 1980s, common values changed due to the raising awareness on environment. The necessity of considering the environmental and social concerns while performing energy planning required use of multi-criteria approaches. Multi-criteria decision-making (MCDM) methods were commonly performed upon social, economic, industrial, ecological and biological systems besides the energy systems [7, 8].

Some methods have been suggested in order to overcome fuzzy multi-criteria group decision-making problems. Type-2 fuzzy sets (FSs) are more efficient than ordinary FSs in terms of coping with wrong and missing information in real-world practices. A type-2 FS is a membership function (MF) represented by a [0–1] interval FS. Type-2 FSs include membership functions with certain intervals used commonly for high-level FSs due to the relative simplicities [9–11]. Type-2 FSs qualified with primary and secondary membership are an extension of type-1 FSs [12, 13]. In the literature, some articles related to type-2 FSs can be encountered. Chen and Lee [14] suggested a type-2 fuzzy technique for the priority sequence close to an ideal solution (TOPSIS) aiming to overcome group decision-making problems based upon TOPSIS. Chen [15] suggested a beneficial method in order to decrease tolerance prejudice during the decision-making processes based upon type-2 interval FSs and to forecast the importance of criteria in multi-criteria decision-making (MCDM) process. Chen [16] suggested multi-criteria decision making (MCDM) method including fuzzy numbers generalized as intermediate value under incomplete weight. Chen et al. [17] developed a method to discuss multi-quality group decision-making problems depending upon the sequence of type-2 interval FSs. Chen [18] suggested a new method in order to overcome multi-criteria group decision-making problems depending upon type-2 interval FSs and to determine the targeted importance of criteria. Wang et al. [19] suggested multi-criteria decision making (MCDM) methods depending upon arithmetic operations of type-2 interval fuzzy sets and sequence values.

In this chapter, a fuzzy multi-criteria decision making (MCDM) methodology based upon type-2 FSs was suggested for the decision-making problem related to energy alternatives. The suggested methodology will be used in order to determine the most appropriate energy alternative for Turkey. In the first stage, criteria weights will be determined with type-2 interval analytical hierarchy process (AHP) method. Then, the sequence of all alternatives will be determined according to their priority determined by type-2 interval fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method. In order to meet realizable energy demands for best alternative or alternatives, it was aimed to reveal general energy alternatives of Turkey and to determine consistent strategies, using fuzzy MCDM methodology based upon type-2 interval FSs.

2. Decision-making methods

2.1. Type-2 fuzzy sets

During the decision-making process, because of the increasing complexity of the socio-economic environment and uncertainty of the immanent subjective nature of human thought, the information related to quality values is generally ambiguous, and fuzzy. This reality has caused many researchers to perform fuzzy set (FS) theory in order to model uncertainty and ambiguity during the decision-making processes [18, 19].

Some multi-criteria decision-making (MCDM) methods were suggested depending upon the type-1 FSs. Type-2 FSs include more uncertainty rather than the type-1 FSs. Those provide us more freedom level in order to represent the uncertainty and fuzziness of the real world. Type-2 FSs can be considered as an extension of type-1 FSs. Because type-2 interval FSs are used instead of traditional type-1 FSs in order to represent weights of the qualities and evaluation values, type-2 FSs provide us a more beneficial method for the solution of the fuzzy multi-criteria decision-making problems in a more flexible and intelligent way [20–24].

Basic concepts and processes of type-2 FSs were presented below, and some definitions of type-2 FSs and type-2 interval FSs were analyzed shortly. The fuzziness of type-1 membership function shifting the points on the triangle to the right or left without the obligation of being at the same rate as in **Figure 1 (b)** was presented in **Figure 1 (a)**. Then, there is no even one residual value for the membership function in a specific value of "x" such as "x'". Instead of this, the membership function gains value at the point where vertical line intersects with the

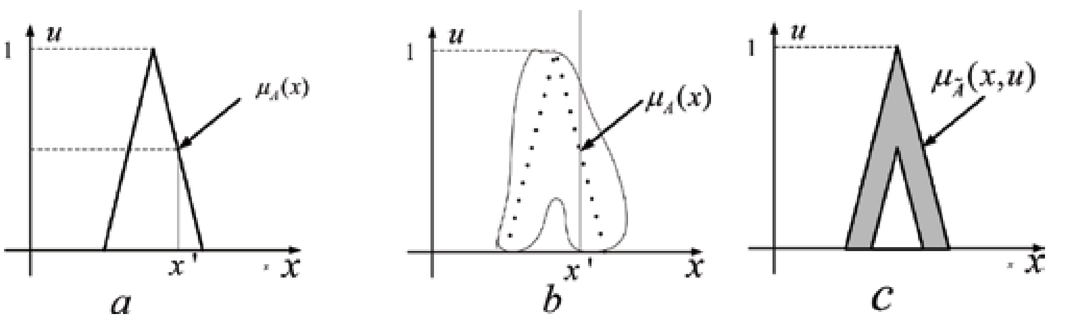

Figure 1. Type-1 and type-2 membership functions [26].

fuzziness. It is not necessary for these values to be weighted similarly. Accordingly, we can provide a width distribution for all these points. Implementing this to all $x \in X$, we create a three-sided membership function-a type-2 membership function- qualifying a type-2 fuzzy set [24, 25].

Let us assume $\tilde{A}$ as a type-1 FS $\tilde{A} = (a_1, a_2, a_3, a_4; H_1(A), H_2(A))$ with isosceles trapezium as shown in **Figure 2**. $H_1(A)$ indicated the membership value of, a_2 element, and $H_2(A)$ indicates the membership value of a_3 element. According to this, it is $0 \le H_1(A) \le 1$ and $0 \le H_2(A) \le 1$. If $a_2 = a_3$, the type-2 FS becomes $\tilde{A}$ triangle-shape type-1 FS [26].

Definition 1: In X universe of discourse, the type-2 FS $\tilde{\tilde{A}}$ can be represented with type-2 membership function $\mu_{\tilde{\tilde{A}}}$ as shown below [13, 25, 27]:

$$\tilde{\tilde{A}} = \left\{ \left((x,u), \mu_{\tilde{\tilde{A}}}(x,u) \right) \middle| \forall x \in X, \forall u \in J_X \subseteq [0,1], 0 \le \mu_{\tilde{\tilde{A}}}(x,u) \le 1 \right\}$$

Here, $0 \le \mu_{\tilde{\tilde{A}}}(x,u) \le 1$ and J_X indicates an interval in [0, 1]. Moreover, the type-2 FS $\tilde{\tilde{A}}$ can be represented as below:

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_X} \mu_{\tilde{\tilde{A}}}(x,u)/(x,u) = \int_{x \in X} \left[\int_{u \in \int_x} \mu_{\tilde{\tilde{A}}}(x,u)/u \right] / x$$

Here, $J_X \subseteq [0,1]$ and $\iint$ express all combination upon x and u. According to this, x is the primary variable, $J_X \subseteq [0,1]$ indicates the primary membership of x, u is the secondary variable, and $\int_{u \in \int_x} \mu_{\tilde{\tilde{A}}}(x,u)/u$ indicates the secondary membership function in x (MF). $\iint$ expresses all valid combination on x and u. For different discourse universes, $\sum$ takes place of $\int$.

Definition 2: Let us assume $\tilde{\tilde{A}}$ as a type-2 FS in X discourse universe represented with type 2 membership function $\mu_{\tilde{\tilde{A}}}$. If it is $\mu_{\tilde{\tilde{A}}}(x,u) = 1$, then $\tilde{\tilde{A}}$ is called type-2 interval fuzzy set. $\tilde{\tilde{A}}$ as a type-2 FS can be considered as a special type of type-2 FS indicated as below [13, 18, 25, 28].

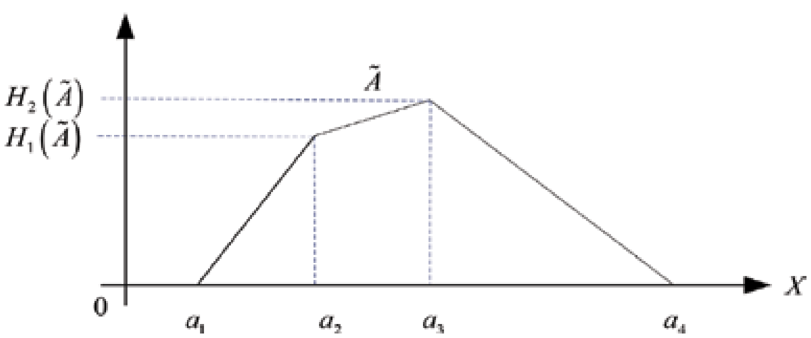

Figure 2. Isosceles trapezium shape type-1 FS [26].

$$\tilde{\tilde{A}} = \int_{x \in X} \int_{u \in J_X} 1/(x,u) = \int_{x \in X} \left[\int_{u \in j_x} 1/u \right] /x$$

Here, x is the primary variable, $J_X \subseteq [0,1]$ indicates the primary membership of x, u is the secondary variable, and $\int_{u \in j_x} 1/u$ is the second membership function in x.

Definition 3: In this chapter, we evaluated fuzzy MCDM problems using type-2 interval FSs. For the reference point, size of upper and lower membership functions related to type-2 interval FSs was used. Upper membership function and the lower membership function of such type-2 interval FS indicate type-1 membership function. This can be presented as below:

$$\tilde{\tilde{A}}_i = \left(\tilde{A}_i^U, \tilde{A}_i^L\right) = \left(\left(a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U; H_1\left(\tilde{A}_i^U\right), H_2\left(\tilde{A}_i^U\right)\right), \left(a_{i1}^L, a_{i2}^L, a_{i3}^L, a_{i4}^L; H_1\left(\tilde{A}_i^L\right), H_2\left(\tilde{A}_i^L\right)\right)\right)$$

Here, $\tilde{A}_i^U$ and $\tilde{A}_i^L$ are type-1 FSs, and a_{i1}^U, a_{i2}^U, a_{i3}^U, a_{i4}^U, a_{i1}^L, a_{i2}^L, a_{i3}^L ve a_{i4}^L are the reference points of the type-2 interval $\tilde{\tilde{A}}_i$. $H_j\left(\tilde{A}_i^U\right)$ expresses the membership value of $a_{i(j+1)}^U$ element in $\tilde{A}_i^U$, which is the upper isosceles trapezoid-shape membership function. According to this, $1 \le j \le 2$, $H_j\left(\tilde{A}_i^L\right)$ [13, 25].

Definition 4: $Rank\left(\tilde{\tilde{A}}_i\right)$ as the $\tilde{\tilde{A}}_i$ sequence value, which is type-2 interval FS in isosceles trapezoid shape is defined as below [13, 28].

$$\begin{aligned} Rank\left(\tilde{\tilde{A}}_i\right) &= M_1\left(\tilde{A}_i^U\right) + M_1\left(\tilde{A}_i^L\right) + M_2\left(\tilde{A}_i^U\right) + M_2\left(\tilde{A}_i^L\right) + M_3\left(\tilde{A}_i^U\right) + M_3\left(\tilde{A}_i^L\right) \\ &-\frac{1}{4}\left(S_1\left(\tilde{A}_i^U\right) + S_1\left(\tilde{A}_i^L\right) + S_2\left(\tilde{A}_i^U\right) + S_2\left(\tilde{A}_i^L\right) + S_3\left(\tilde{A}_i^U\right) + S_3\left(\tilde{A}_i^L\right) + S_4\left(\tilde{A}_i^U\right) + S_4\left(\tilde{A}_i^L\right)\right) \\ &+H_1\left(\tilde{A}_i^U\right) + H_1\left(\tilde{A}_i^L\right) + H_2\left(\tilde{A}_i^U\right) + H_2\left(\tilde{A}_i^L\right) \end{aligned}$$

Here, $M_p\left(\tilde{\tilde{A}}_i^j\right)$ indicates the average of a_{ip}^j and $a_{i(p+1)}^j$ elements, $M_p\left(\tilde{\tilde{A}}_i^j\right) = \left(a_{ip}^j + a_{i(p+1)}^j\right)/2, 1 \le p \le 3,$ indicates the standard deviation of a_{iq}^j and $a_{i(q+1)}^j$ elements, $S_q\left(\tilde{A}_i^j\right) = \sqrt{\frac{1}{2}\sum_{k=q}^{q+1}\left(a_{ik}^j - \frac{1}{2}\sum_{k=q}^{q+1} a_{ik}^j\right)^2}, 1 \le q \le 3,$ indicates the standard deviation of $S_4\left(\tilde{A}_i^j\right)$, $a_{i1}^j, a_{i2}^j, a_{i3}^j, a_{i4}^j$ elements, $S_4\left(\tilde{A}_i^j\right) = \sqrt{\frac{1}{4}\sum_{k=1}^{4}\left(a_{ik}^j - \frac{1}{4}\sum_{k=1}^{4} a_{ik}^j\right)^2}$ $H_p\left(\tilde{A}_i^j\right)$ indicates the membership value of $a_{i(p+1)}^j$ element in in $\tilde{A}_i^j$, $1 \le p \le 3, j \in \{U, L\},$ ve $1 \le i \le n.$ as an isosceles trapezoid shaped membership function; and **Figure 3** represents a type-2 interval FS in an isosceles trapezoid shape.

For the formation of type-2 interval FSs, $\tilde{A}_i^U$ as isosceles trapezoid shaped upper membership function and $\tilde{A}_i^L$ as isosceles trapezoid shaped lower membership function were used. $\tilde{\tilde{A}}$ created using type-2 interval FS is as below [13, 25, 30].

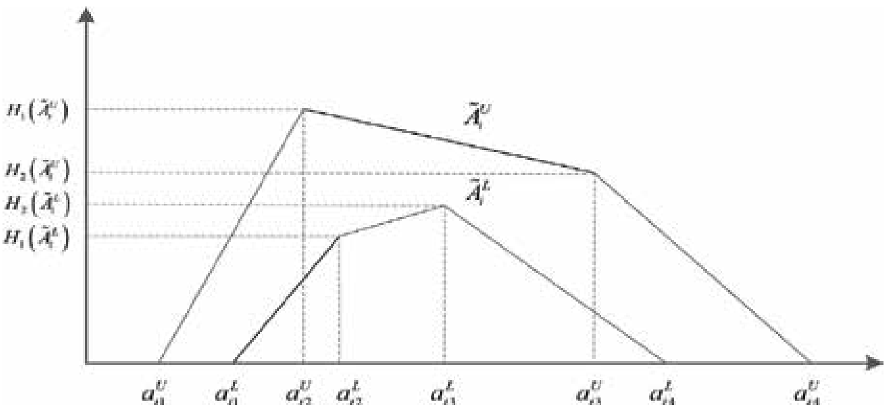

Figure 3. Isosceles trapezoid shaped membership function of the type-2 interval FS $\tilde{\tilde{A}}$ [29].

Addition:

$$\tilde{\tilde{A}}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right)$$

$$\tilde{\tilde{A}}_2 = \left(\tilde{A}_2^U, \tilde{A}_2^L\right) = \left(\left(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1\left(\tilde{A}_2^U\right), H_2\left(\tilde{A}_2^U\right)\right), \left(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1\left(\tilde{A}_2^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right)$$

$$\tilde{A}_1 \oplus \tilde{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \oplus \left(\tilde{A}_2^U, \tilde{A}_2^L\right)$$

$$= \begin{pmatrix} \left(a_{11}^U + a_{21}^U, a_{12}^U + a_{22}^U, a_{13}^U + a_{23}^U, a_{14}^U + a_{24}^U; \min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), \min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right)\right), \\ \left(a_{11}^L + a_{21}^L, a_{12}^L + a_{22}^L, a_{13}^L + a_{23}^L, a_{14}^L + a_{24}^L; \min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), \min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right) \end{pmatrix}$$

Subtraction:

$$\tilde{A}_1 \Theta \tilde{A}_2 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) \Theta \left(\tilde{A}_2^U, \tilde{A}_2^L\right)$$

$$= \begin{pmatrix} \left(a_{11}^U - a_{21}^U, a_{12}^U - a_{22}^U, a_{13}^U - a_{23}^U, a_{14}^U - a_{24}^U; \min\left(H_1\left(\tilde{A}_1^U\right), H_1\left(\tilde{A}_2^U\right)\right), \min\left(H_2\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_2^U\right)\right)\right), \\ \left(a_{11}^L - a_{21}^L, a_{12}^L - a_{22}^L, a_{13}^L - a_{23}^L, a_{14}^L - a_{24}^L; \min\left(H_1\left(\tilde{A}_1^L\right), H_1\left(\tilde{A}_2^L\right)\right), \min\left(H_2\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right) \end{pmatrix}$$

Multiplication:

$$\tilde{\tilde{A}}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right)$$

$$\tilde{\tilde{A}}_2 = \left(\tilde{A}_2^U, \tilde{A}_2^L\right) = \left(\left(a_{21}^U, a_{22}^U, a_{23}^U, a_{24}^U; H_1\left(\tilde{A}_2^U\right), H_2\left(\tilde{A}_2^U\right)\right), \left(a_{21}^L, a_{22}^L, a_{23}^L, a_{24}^L; H_1\left(\tilde{A}_2^L\right), H_2\left(\tilde{A}_2^L\right)\right)\right)$$

Arithmetic operation:

$$\tilde{\tilde{A}}_1 = \left(\tilde{A}_1^U, \tilde{A}_1^L\right) = \left(\left(a_{11}^U, a_{12}^U, a_{13}^U, a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \left(a_{11}^L, a_{12}^L, a_{13}^L, a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right)\right)$$

$$k\tilde{\tilde{A}}_1 = \begin{pmatrix} \left(k \times a_{11}^U, k \times a_{12}^U, k \times a_{13}^U, k \times a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \\ \left(k \times a_{11}^L, k \times a_{12}^L, k \times a_{13}^L, k \times a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right) \end{pmatrix}$$

$$\frac{\tilde{\tilde{A}}_1}{k} = \begin{pmatrix} \left(\frac{1}{k} \times a_{11}^U, \frac{1}{k} \times a_{12}^U, \frac{1}{k} \times a_{13}^U, \frac{1}{k} \times a_{14}^U; H_1\left(\tilde{A}_1^U\right), H_2\left(\tilde{A}_1^U\right)\right), \\ \left(\frac{1}{k} \times a_{11}^L, \frac{1}{k} \times a_{12}^L, \frac{1}{k} \times a_{13}^L, \frac{1}{k} \times a_{14}^L; H_1\left(\tilde{A}_1^L\right), H_2\left(\tilde{A}_1^L\right)\right) \end{pmatrix}$$

Here, k > 0.

2.2. Type-2 fuzzy analytic hierarchy process (AHP) methodology

Analytic Hierarchy Process (AHP) is an analysis instrument related to decision making used commonly to model non-structured problems in real life. AHP depending upon binary comparison values for a target set is performed in order to reveal a similar priority vector representing the preferences. Due to the difficulty in determining the numerical preferences for scoring the forecasts, uncertainty at a specific amount will identify with all or some of the paired comparison values in an AHP problem. A priority vector created with paired comparisons within uncertainties expresses fuzzy AHP problems. The primary task of fuzzy AHP method is to make a decision related to the relative importance of each factor pair in the same hierarchy [24, 29, 31].

In this chapter, AHP method was developed to overcome multi-criteria decision-making (MCDM) problems depending upon type-2 interval FSs for determining the weight matrix of the criteria. Fuzzy AHP stages depending upon type-2 FSs are shortly as below tip-2 [18, 24]:

Stage 1: Type-2 interval fuzzy paired comparison matrixes are created among all criteria in the hierarchical structure.

$$\tilde{\tilde{M}} = \begin{pmatrix} 1 & \tilde{\tilde{a}}_{12} & \cdots & \tilde{\tilde{a}}_{1n} \\ \tilde{\tilde{a}}_{21} & 1 & \cdots & \tilde{\tilde{a}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ \tilde{\tilde{a}}_{n1} & \tilde{\tilde{a}}_{n2} & \cdots & 1 \end{pmatrix} = \begin{pmatrix} 1 & \tilde{\tilde{a}}_{12} & \cdots & \tilde{\tilde{a}}_{1n} \\ 1/\tilde{\tilde{a}}_{12} & 1 & \cdots & \tilde{\tilde{a}}_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ 1/\tilde{\tilde{a}}_{1n} & 1/\tilde{\tilde{a}}_{2n} & \cdots & 1 \end{pmatrix} \tag{1}$$

Here,

$$1/\tilde{\tilde{a}}_{ij} = \left(\frac{1}{\tilde{\tilde{a}}_{ij4}^U}, \frac{1}{\tilde{\tilde{a}}_{ij3}^U}, \frac{1}{\tilde{\tilde{a}}_{ij2}^U}, \frac{1}{\tilde{\tilde{a}}_{ij1}^U}; H_1\left(\tilde{\tilde{a}}_{ij}^U\right), H_2\left(\tilde{\tilde{a}}_{ij}^U\right)\right), \left(\frac{1}{\tilde{\tilde{a}}_{ij4}^L}, \frac{1}{\tilde{\tilde{a}}_{ij3}^L}, \frac{1}{\tilde{\tilde{a}}_{ij2}^L}, \frac{1}{\tilde{\tilde{a}}_{ij1}^L}; H_1\left(\tilde{\tilde{a}}_{ij}^L\right), H_2\left(\tilde{\tilde{a}}_{ij}^L\right)\right)$$

Stage 2: Geometrical average technique is used as below in order to find the fuzzy geometric average:

$$\tilde{\tilde{r}}_i = \left(\tilde{\tilde{a}}_{i1} \otimes \tilde{\tilde{a}}_{i2} \otimes \cdots \otimes \tilde{\tilde{a}}_{in}\right)^{1/n} \tag{2}$$

Here,

$$\sqrt[n]{\tilde{\tilde{a}}_{i1}} = \left(\left(\sqrt[n]{\tilde{\tilde{a}}^U_{ij4}}, \sqrt[n]{\tilde{\tilde{a}}^U_{ij3}}, \sqrt[n]{\tilde{\tilde{a}}^U_{ij2}}, \sqrt[n]{\tilde{\tilde{a}}^U_{ij1}}; H_1\left(\tilde{\tilde{a}}^U_{ij}\right), H_2\left(\tilde{\tilde{a}}^U_{ij}\right)\right), \left(\sqrt[n]{\tilde{\tilde{a}}^L_{ij4}}, \sqrt[n]{\tilde{\tilde{a}}^L_{ij3}}, \sqrt[n]{\tilde{\tilde{a}}^L_{ij2}}, \sqrt[n]{\tilde{\tilde{a}}^L_{ij1}}; H_1\left(\tilde{\tilde{a}}^L_{ij}\right), H_2\left(\tilde{\tilde{a}}^L_{ij}\right)\right)\right)$$

Stage 3: Type-2 interval fuzzy weight of each criteria is calculated using the equation below:

$$\tilde{\tilde{w}}_i = \tilde{\tilde{r}}_i \otimes \left(\tilde{\tilde{r}}_1 \oplus \tilde{\tilde{r}}_2 \oplus \cdots \oplus \tilde{\tilde{r}}_n\right)^{-1} \tag{3}$$

2.3. Type-2 fuzzy TOPSIS methodology

Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method is a technique used for a priority sequence close to an ideal solution. TOPSIS method is a popular approach related to MCDM and has been commonly performed in the literature. TOPSIS method was firstly revealed by Yoon and Hwang [32]. The leading feature of this method is selected alternatives' having the closest distance to the positive ideal solutions, and the furthest distance to negative ideal solutions [32]. Fuzzy TOPSIS method was revealed aiming to eliminate or minimize the deficiencies in traditional TOPSIS method using oral variables called as fuzzy numbers for the comparison of alternatives and weighing of criteria [18]. A fuzzy TOPSIS method provides an opportunity to cope with uncertainty related to a decision-making problem. In this chapter, TOPSIS method was also used in order to overcome MCDM problems depending upon type-2 interval FSs.

The stages of the suggested method are as below [13]:

Stage 1: Y_p decision matrix and $\overline{Y}$ average matrix of the p$^{\text{th}}$ decision maker are created as shown below.

$$Y_p = \left(\tilde{\tilde{f}}^p_{ij}\right)_{m\times n} = \begin{array}{c} \\ f_1 \\ f_2 \\ \cdots \\ f_m \end{array} \overset{\begin{array}{cccc} x_1 & x_2 & \dots & x_n \end{array}}{\begin{bmatrix} \tilde{\tilde{f}}^p_{11} & \tilde{\tilde{f}}^p_{12} & \dots & \tilde{\tilde{f}}^{p\ \ p}_{1n} \\ \tilde{\tilde{f}}^p_{21} & \tilde{\tilde{f}}^p_{22} & \dots & \tilde{\tilde{f}}^p_{1n} \\ \dots & \dots & \dots & \dots \\ \tilde{\tilde{f}}^p_{m1} & \tilde{\tilde{f}}^p_{m1} & \dots & \tilde{\tilde{f}}_{mn} \end{bmatrix}} \tag{4}$$

$$\overline{Y} = \left(\tilde{\tilde{f}}_{ij}\right)_{m\times n}$$

Here,

$\tilde{\tilde{f}}_{ij} = \left(\dfrac{\tilde{\tilde{f}}^1_{ij} \oplus \tilde{\tilde{f}}^2_{ij} \oplus \dots \oplus \tilde{\tilde{f}}^k_{ij}}{k}\right), \tilde{\tilde{f}}_{ij}$, is a type-2 interval FS; $1 \le i \le m, 1 \le j \le n, 1 \le p \le k$ and k express the number of decision makers.

Stage 2: W_p weighting matrix and $\overline{W}$ average weighting matrix of p[th] decision maker are created as shown below:

$$W_p = \left(\tilde{\tilde{w}}_i^p\right)_{1\times m} = \begin{matrix} f_1 & f_2 & \dots & f_m \\ \left[\tilde{\tilde{w}}_1^p\right. & \tilde{\tilde{w}}_2^p & \dots & \left.\tilde{\tilde{w}}_m^p\right] \end{matrix} \tag{5}$$

$$\overline{W} = \left(\tilde{\tilde{w}}_i\right)_{1\times m}$$

Here, $\tilde{\tilde{w}}_i = \left(\frac{\tilde{\tilde{w}}^1{}_i \oplus \tilde{\tilde{w}}^2{}_i \oplus \dots \oplus \tilde{\tilde{w}}^k{}_i}{k}\right)$, $\tilde{\tilde{w}}_i$ is a type-2 interval FS; and $1 \le i \le m$, $1 \le p \le k$ and k expresses the number of decision makers.

In this chapter, the weights of criteria were determined using type-2 interval fuzzy AHP.

Stage 3: Weighting decision matrix of $\overline{Y}_w$ is created.

$$\overline{Y}_w = \left(\tilde{\tilde{v}}_{ij}\right)_{m\times n} = \begin{matrix} f_1 \\ f_2 \\ \dots \\ f_m \end{matrix} \begin{bmatrix} \tilde{\tilde{v}}_{11} & \tilde{\tilde{v}}_{12} & \dots & \tilde{\tilde{v}}_{1n} \\ \tilde{\tilde{v}}_{21} & \tilde{\tilde{v}}_{22} & \dots & \tilde{\tilde{v}}_{2n} \\ \dots & \dots & \dots & \dots \\ \tilde{\tilde{v}}_{m1} & \tilde{\tilde{v}}_{m2} & \dots & \tilde{\tilde{v}}_{mn} \end{bmatrix} \tag{6}$$

Here, $\tilde{\tilde{v}}_{ij} = \tilde{\tilde{w}}_i \otimes \tilde{\tilde{f}}_{ij}$, $1 \le i \le m \;\; ve \; 1 \le j \le n$

Stage 4: Based on Definition 4, $\tilde{\tilde{v}}_{ij}$ as the sequence level of type-2 fuzzy set $\tilde{\tilde{v}}_{ij}$ in which $1 \le j \le n$ is calculated. $\overline{Y}^*{}_w$ as the decision matrix weight listed according to the sequence is created.

$$\overline{Y}^*{}_w = \left(Rank\left(\tilde{\tilde{v}}_{ij}\right)\right)_{m\times n} \tag{7}$$

Here, $1 \le i \le m \;\; ve \; 1 \le j \le n$

Stage 5: $x^+ = \left(v_1^+, v_2^+, \dots, v_m^+\right)$ as the positive ideal solution and $x^- = \left(v_1^-, v_2^-, \dots, v_m^-\right)$ negative ideal solution are found.

Here,

$$v_i^+ = \begin{cases} \underset{1\le j\le n}{Max} \left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & \text{if } f_i \in F_1 \\ \underset{1\le j\le n}{Min} \left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & \text{if } f_i \in F_2 \end{cases} \tag{8}$$

$$v_i^- = \begin{cases} \underset{1\le j\le n}{Min} \left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & \text{if } f_i \in F_1 \\ \underset{1\le j\le n}{Max} \left\{Rank\left(\tilde{\tilde{v}}_{ij}\right)\right\}, & \text{if } f_i \in F_2 \end{cases} \tag{9}$$

Here, F_1 indicates the set of advantage qualities and F_2 indicates the set of disadvantage qualities; and $1 \le i \le m$.

Stage 6: $d^+(x_j)$ distance between each alternative x_j and positive ideal x^+ is calculated as shown below:

$$d^+(x_j) = \sqrt{\sum_{i=1}^{m} \left(Rank(\tilde{\tilde{v}}_{ij}) - v_i^+\right)^2} \tag{10}$$

Here, it is $1 \leq j \leq n$. $d^+(x_j)$ distance between each alternative x_j and negative ideal x^- is calculated as shown below:

$$d^-(x_j) = \sqrt{\sum_{i=1}^{m} \left(Rank(\tilde{\tilde{v}}_{ij}) - v_i^-\right)^2} \tag{11}$$

Here, it is $1 \leq j \leq n$.

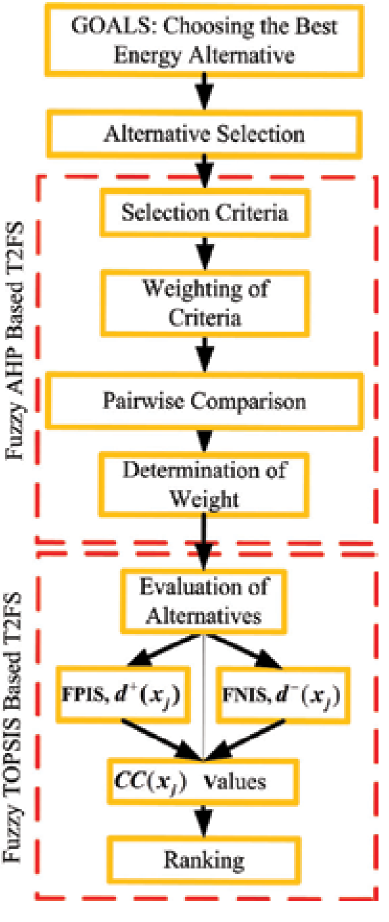

Figure 4. Suggested type-2 fuzzy AHP-TOPSIS hybrid methodology.

Stage 7: $CC(x_j)$ as the relative distance according to x^+ positive and negative ideal solution of x_j is calculated as below:

$$CC(x_j) = \frac{d^-(x_j)}{d^-(x_j) + d^+(x_j)} \tag{12}$$

Here, it is $1 \le j \le n$.

Stage 8: The values of $CC(x_j)$ are sequenced from small to large where $1 \le j \le n$. As the value of $CC(x_j)$ increases, x_j preference grades of the alternatives increases, and here it is $1 \le j \le n$.

Suggested fuzzy methodology:

In this chapter, fuzzy TOPSIS and AHP depending upon MCDM methodology were developed according to type-2 FSs. The steps of the suggested methodology were presented in **Figure 4**.

3. An implementation of related to decision-making on energy alternatives in Turkey

Energy is one of the most important inputs of economy affecting the development level of countries as in any stages of life. Although Turkey has several energy resources, those resources have not been adequately used up to now. Turkey that has recently been dependent on outside for energy as in the past meets nearly one-third of the energy demand from domestic production. Because fossil fuel energy has gradually decreased, within the following 10 years, Turkey most probably will encounter with problems such as high energy prices, energy insecurity, and energy shortage. For those reasons, in Turkey, it is necessary to plan all energy resources within the framework of a specific policy. In order to manage these resources, developing necessary technologies and providing to popularize the use of those will be vital for the economic development of the country. The results revealed in this study suggest the perspectives related to future and provide an opportunity to produce new energy policies appropriate for the conditions of today.

In details, Turkey needs to provide its energy requirement using its energy resources. The aforementioned energy resources are as below: geothermal energy (A1), solar energy (A2), wind energy (A3), hydraulic energy (A4), bioenergy (A5), hydrogen energy (A6), nuclear energy (A7), petrol (A8), natural gas (A9), and coal-lignite (A10). The hierarchy of the decision-making problem related to the energy planning mentioned in this study was presented in **Figure 5**.

The criteria used in this study are as below [24]:

Productivity (C1): productivity is the amount of beneficial energy obtained from an energy resource. Namely, a stable productivity development by means of the reliability of a big power plant and inexpensiveness of the raw material depends upon its being economical and deriving profits.

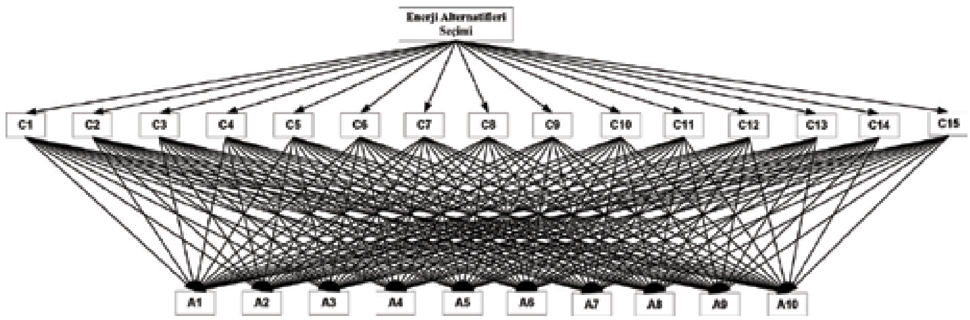

Figure 5. Hierarchical structure of selecting energy alternatives.

Exergy productivity (C2): energy productivity is calculation of the productivity according to the second thermodynamic law of a process. The energy including the heat change generally runs to waste.

Investment cost (C3): the investment cost includes the purchase of mechanical tools, installment of technological instruments, construction of roads, connection of roads to the international lines, engineering studies, and additional operation processes.

Cost of operation and maintenance (C4): operating and maintenance costs include two items: the first is the money spent on wages of employees and energy. The second is the operation cost including raw materials and services necessary for operating the power plant.

NOx release (C5): it is a general term referring to NOx, NO and NO2, it has a direct effect upon the health of people, and indirectly affects the social status of the society.

CO2 release (C6): carbon dioxide gas without color, odor, and the taste is nearly 1.5 times more intense than air under normal pressure and temperature conditions.

Required area (C7): the surrounding and panorama of the areas where power plants are built totally affect the area where they have been built. Moreover, the areas where power plants will be built have the same standards.

Social acceptability (C8): social acceptability is determining the perception assumed of the projects by the society revising the views of consumers. In other words, this term refers to a summary of local people's views related to the power plants.

Employment creation (C9): economic development and welfare of the local people in areas where power plants have been established depend upon this power plant for decades. Long-term power plants providing employment for the society and stabilizing local people to a more desirable life standard are more convenient.

Net current profit (C10): NCP can be explained as a current profit of the time interval when cash flow is maintained. It is a typical method used to find the value of time-based money in long-term energy studies.

Risk (C11): this choice represents the number of distinguishable problems during the implementation of energy policy.

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Reliability (C12): this criterion evaluates the technological adequacy for implementing the energy policy. The implemented technology can be the one tested only in the laboratory, performed just in pilot factories, or not developed exactly.

Implementation period (C13): this choice reveals the minimum cost purposed monthly or annual applicable minimum status of an applicable alternative energy policy.

Waste disposal reliability (C14): this choice tries to decrease damage to nature. It expresses the studies carried out to rectify a situation through a sustainable study.

Compatibility to energy policies (C15): this criterion presented the distance of suggested policy targets to international energy policy or state policy.

After determining the set of criteria and alternatives, stages of developed type-2 FS AHP algorithm is implemented to the criteria. In order to determine the relative importance of each evaluation criterion, experts used a nine-item scale presented in **Table 1**.

Seven-item scale represented in **Table 2** reveals the oral expressions used by the energy planning experts for creating an alternative criteria matrix.

Oral terms	**Type-2 fuzzy sets**											
Absolutely strong (AS)	((4.00,	5.00,	5.00,	6.00;	1.00	1.00),	(4.50,	5.00,	5.00,	5.50;	1.00	1.00))
Very strong (VS)	((3.00,	4.00,	4.00,	5.00;	1.00	1.00),	(3.50,	4.00,	4.00	4.50;	1.00	1.00))
Fairly strong (FS)	((2.00,	3.00,	3.00,	4.00;	1.00	1.00),	(2.50,	3.00,	3.00,	4.50;	1.00	1.00))
Semi-strong (SS)	((1.00,	2.00,	2.00,	3.00;	1.00	1.00),	(1.50,	2.00,	2.00,	3.50;	1.00	1.00))
Equal (E)	((1.00,	1.00,	1.00,	1.00;	1.00	1.00),	(1.00,	1.00,	1.00,	1.00;	1.00	1.00))
Semi-weak (SW)	((0.33,	0.50,	0.50,	1.00;	1.00	1.00),	(0.29,	0.50,	0.50,	0.67;	1.00	1.00))
Fairly weak (FW)	((0.25,	0.33,	0.33,	0.50;	1.00	1.00),	(0.22,	0.33,	0.33,	0.40;	1.00	1.00))
Very weak (VW)	((0.20,	0.25,	0.25,	0.33;	1.00	1.00),	(0.22,	0.25,	0.25,	0.29;	1.00	1.00))
Absolutely weak (AW)	((0.17,	0.20,	0.20,	0.25;	1.00	1.00),	(0.18,	0.20,	0.20,	0.22;	1.00	1.00))

Table 1. Fuzzy values used for the paired comparison of the criteria.

Oral terms	**Type-2 fuzzy sets**											
Very low: (VL)	((0.00,	0.00,	0.00,	0.10;	1.00,	1.00),	(0.00,	0.00,	0.00,	0.05;	0.90	0.90))
Low: (L)	((0.00,	0.10,	0.10,	0.30;	1.00,	1.00),	(0.05,	0.10,	0.10,	0.20;	0.90	0.90))
Mid-low: (ML)	((0.10,	0.30,	0.30,	0.50;	1.00,	1.00),	(0.20,	0.30,	0.30,	0.40;	0.90	0.90))
Medium: (M)	((0.30,	0.50,	0.50,	0.70;	1.00,	1.00),	(0.40,	0.50,	0.50,	0.60;	0.90	0.90))
Mid-high: (MH)	((0.50,	0.70,	0.70,	0.90;	1.00,	1.00),	(0.60,	0.70,	0.70,	0.80;	0.90	0.90))
High: (H)	((0.70,	0.90,	0.90,	1.00;	1.00,	1.00),	(0.80,	0.90,	0.90,	0.95;	0.90	0.90))
Very high:(VH)	((0.90,	1.00,	1.00,	1.00;	1.00,	1.00),	(0.95,	1.00,	1.00,	1.00;	0.90	0.90))

Table 2. Fuzzy values used for the paired comparison of the alternatives.

		C1	C2	C3	C4	…	C12	C13	C14	C15
C1	**D1**	1	FW	FW	FW	…	FW	FW	AW	E
	D2	1	SW	SW	VW	…	FW	FW	VW	SS
	D3	1	SW	SW	VW	…	FW	FW	AW	E
C2	**D1**	FS	1	E	SW	…	E	E	FW	FS
	D2	SS	1	E	FW	…	SW	SW	FW	FS
	D3	SS	1	E	FW	…	SW	SW	VW	SS
C3	**D1**	FS	E	1	SW	…	E	E	FW	FS
	D2	SS	E	1	FW	…	SW	SW	FW	FS
	D3	SS	E	1	FW	…	SW	SW	VW	SS
…	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…
C13	**D1**	FS	E	E	SW	…	E	1	FW	FS
	D2	FS	SS	SS	SW	…	E	1	SW	VS
	D3	FS	SS	SS	SW	…	E	1	FW	FS
C14	**D1**	AS	FS	FS	SS	…	FS	FS	1	AS
	D2	VS	FS	FS	E	…	SS	SS	1	AS
	D3	AS	VS	VS	SS	…	FS	FS	1	AS
C15	**D1**	E	FW	FW	VW	…	FW	FW	AW	1
	D2	SW	FW	FW	AW	…	VW	VW	AW	1
	D3	E	SW	SW	VW	…	FW	FW	AW	1

Table 3. Oral expression of the paired comparison matrix for the evaluation criteria.

Table 3 present the results of the paired comparison of oral expressions related to the evaluation criteria performed by three energy planning experts.

It has been mentioned that AHP method suggests a consistency index for determining whether there is an inconsistency in each comparison matrix. The inconsistency rate (CR) value is accepted to be lower than 10%, and it means consistency. Inconsistency analysis performed for this study, CR value was obtained as (0.084), and it was concluded that the evaluations were acceptable and consistent.

When **Table 4** was considered, influence grade of all criteria upon our energy resources and policies to be created were very close to each other. When the results in this table are analyzed, we can conclude that all determined criteria are essential for us and the determined criteria are selected accurately. Although all criteria were very important, the criteria mostly affecting the energy alternative selection or our energy policy were "CO_2" C6 (4.594), "Waste Disposal Reliability" C14 (4.581), and "NOx" C5 (4.491), respectively. On the other hand, the criteria

	$\tilde{\tilde{W}}$	BNP
C1	((0.32,0.41,0.41,0.58;1,1),(0.31,0.41,0.41,0.48;0.9,0.9))	3.927
C2	((0.6,0.8,0.8,1.14;1,1),(0.62,0.8,0.8,1.02;0.9,0.9))	4.051
C3	((0.6,0.8,0.8,1.13;1,1),(0.61,0.8,0.8,1.02;0.9,0.9))	4.048
C4	((1.35,1.91,1.91,2.53;1,1),(1.6,1.91,1.91,2.56;0.9,0.9))	4.396
C5	((1.62,2.22,2.22,2.83;1,1),(1.92,2.22,2.22,2.89;0.9,0.9))	4.491
C6	((1.83,2.55,2.55,3.23;1,1),(2.2,2.55,2.55,3.35;0.9,0.9))	4.594
C7	((0.95,1.33,1.33,1.83;1,1),(1.06,1.33,1.33,1.72;0.9,0.9))	4.213
C8	((0.49,0.66,0.66,0.94;1,1),(0.5,0.66,0.66,0.83;0.9,0.9))	4.005
C9	((1.24,1.76,1.76,2.35;1,1),(1.44,1.76,1.76,2.31;0.9,0.9))	4.346
C10	((0.38,0.49,0.49,0.69;1,1),(0.38,0.49,0.49,0.59;0.9,0.9))	3.952
C11	((0.49,0.67,0.67,0.96;1,1),(0.5,0.67,0.67,0.84;0.9,0.9))	4.007
C12	((0.78,1.12,1.12,1.61;1,1),(0.85,1.12,1.12,1.51;0.9,0.9))	4.149
C13	((0.76,1.1,1.1,1.58;1,1),(0.84,1.1,1.1,1.48;0.9,0.9))	4.143
C14	((1.82,2.51,2.51,3.17;1,1),(2.17,2.51,2.51,3.27;0.9,0.9))	4.581
C15	((0.29,0.37,0.37,0.52;1,1),(0.29,0.37,0.37,0.43;0.9,0.9))	3.914

Table 4. Results of type-2 fuzzy AHP method implemented for determining the weights.

affecting our energy policy or energy alternative selection as the least were “Compatibility to energy policies” C15 (3.914), “Productivity” C1 (3.927), and “Net current profit” C10 (3.952), respectively.

The subsequent stage is to determine the best energy alternatives developing TOPSIS method for the solution of fuzzy multi-criteria decision-making problems based upon type-2 interval FSs method. **Table 5** represented paired comparison matrix performed with the oral expression of alternatives criteria matrix carried out by energy planning experts. The experts evaluated the energy alternatives according to each criterion using **Table 2**. The experts also assumed all criteria as beneficial while evaluating the alternatives.

In the subsequent stage, evaluation matrix is created calculating the arithmetic average of the scores related to the evaluation results obtained by the experts. After this stage, a weighted type-2 fuzzy decision matrix is obtained.

After creating fuzzy weighted decision table, fuzzy positive ideal solutions (FPIS, d_i^+) and fuzzy negative ideal solutions (FNIS, d_i^-) are obtained as shown in **Table 6**. Finally, correlation coefficient (CC_i) of each alternative is calculated.

According to **Table 6**, evaluation of appropriate energy alternatives was carried out, and the sequence was determined as A3-A2-A4-A1-A5-A9-A8-A10-A7 and A6. It was revealed that the best energy alternative with investment priority was wind. The priority sequence of the rest alternatives was solar energy, hydraulic energy, geothermal energy, bioenergy, natural gas, petrol, coal-lignite, nuclear energy, and hydrogen energy.

		C1	C2	C3	C4	…	C12	C13	C14	C15
A1	**D1**	H	M	M	M	…	M	MH	MH	H
	D2	MH	M	MH	MH	…	MH	M	MH	VH
	D3	H	MH	MH	M	…	H	M	H	VH
A2	**D1**	MH	VH	H	MH	…	H	H	VH	VH
	D2	M	MH	MH	M	…	VH	H	VH	VH
	D3	M	MH	H	H	…	VH	M	H	VH
A3	**D1**	H	L	H	H	…	MH	H	VH	VH
	D2	MH	ML	H	M	…	H	ML	H	H
	D3	H	MH	MH	MH	…	H	M	VH	VH
…	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…
	…	…	…	…	…	…	…	…	…	…
A8	**D1**	M	M	M	ML	…	M	M	ML	ML
	D2	MH	MH	H	H	…	MH	M	M	M
	D3	M	MH	M	M	…	MH	M	ML	ML
A9	**D1**	M	M	M	ML	…	M	M	ML	ML
	D2	VH	H	H	MH	…	M	M	M	ML
	D3	MH	MH	M	ML	…	M	M	ML	ML
A10	**D1**	ML	L	ML	L	…	M	ML	VL	MH
	D2	M	M	MH	M	…	M	MH	ML	VH
	D3	ML	ML	M	ML	…	M	M	ML	VH

Table 5. Oral expression matrix for evaluation results of the alternatives.

Alternatives	$d^{+}(x_j)$	$d^{-}(x_j)$	$CC(x_j)$
Geothermal energy (A1)	1.4622	1.6557	0.5310
Solar energy (A2)	0.7137	2.1241	0.7485
Wind energy (A3)	0.3499	2.5486	0.8793
Hydraulic energy (A4)	1.4593	1.6908	0.5367
Bioenergy (A5)	1.5981	1.6925	0.5143
Hydrogen energy (A6)	2.6897	0.3579	0.1174
Nuclear energy (A7)	3.1515	0.8478	0.2120
Petrol (A8)	2.4740	1.0384	0.2956
Natural gas (A9)	2.3925	1.1328	0.3213
Coal-lignite (A10)	3.0036	0.8270	0.2159

Table 6. The results obtained through fuzzy multi-criteria decision-making method based upon type-2 interval FSs.

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4. Conclusion and suggestions

Energy is one of the fundamental inputs of social and economic development all around the world; the importance of energy has increased day by day, and its strategic place in the world is considered to be maintained for long years. This fact highlighted the necessity for all countries to use their energy resources they have productively. While actualizing this, it should adopt being more qualified, more productive, more reliable, more efficient, cheaper, more environment-friendly, more uninterrupted, and sustainable as a principle.

When considering all these aforementioned situations, it is necessary for the energy sector to be developed for all energy resources. In order for the companies and investors to compete in energy markets, policies should be established to restructure the energy sector.

For that purpose;

- Wind energy and solar energy should be focused on short and long-term energy planning to be made by Turkey in order to meet increasing energy demand by 9% on average every year. In order to meet the energy need in the system, Turkey should provide incentives putting these two energy resources on top of the list. When considering the parameters such as risk minimization, waste disposal reliability, and CO_2 and NOX release as the expectations of the society for short and long-term planning, the necessity got evaluating the wind energy and solar energy as the leading emerges.
- In long-term energy planning, technological investment should also be provided on hydraulic energy, geothermal energy, and bioenergy resources besides the wind and solar energy, and these energy resources should be put into use carrying out private sector encouragement studies.
- Bioenergy on the fifth-rank should be encouraged from investor "raw material producer to bioenergy user" through government supports and incentives creating appropriate strategies and action plans in order to maximize the use of "biogas, biofuel, and biomass."

In future, the suggested method can also be performed to the other decision-making problems related to the issues such as the selection of suppliers, selection of facility area, selection of material, and selection of software. In addition to these, the subsequent study should be carried out upon evaluating regional energy resource tendency of Turkey and revealing the demand. In accordance with the obtained results, it can also be revealed, which energy resource in which area should be invested as more advantageously.

Author details

Abit Balin[1]* and Hayri Baracli[2]

*Address all correspondence to: abitbalin@hotmail.com

1 Faculty of Transportation and Logistics, Istanbul University, Istanbul, Turkey

2 Department of Industrial Engineering, Yildiz Technical University, Istanbul, Turkey

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Chapter 3

Decision-Making in Complex Dynamic and Evolutive Systems: The Need for a New Paradigm

Bernard Cadet

Additional information is available at the end of the chapter

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Abstract

For contemporary psychology, decision-making represents behaviours, which are very different from automatic responses. They are developed by implementing integrative cognitive functions adapted to the finalities sought and the situation to treat. Through the diversity of epistemological choices for instance, research in previous decades focused on the individual choices expressed by situations or contexts with a stable structure. The new problems of life in today's society lead to making decisions on societal problems (climate, energy, etc.), which bring into play systems and no longer variables. This chapter has four aspects. After having characterised the decision-making process as a cognitive behaviour (1), having recalled the best known traditional models (those of Economics and Psychology) (2), this chapter deals with the properties of complex systems (globality, interactivity, dynamism, and scalability), which render decision-making difficult (3), and concludes with the necessity of a change of paradigm by pointing to paths to follow (4).

Keywords: dynamic complex systems, cognition and complexity, complex decisions, errors of decision, paradigm change

1. Introduction

For a long time, before using electronic devices of navigation, sailors used to check their progresses using points of interest (POIs) as marks of their journey. These were particular points rich in information (a cape, an island ….) allowing the sailors to reduce uncertainty about its position. This is a typically cognitive process which allowed the sailors to mark out their route and see how they were progressing. Metaphorically, the term may be used in the study of decision-making to describe the cognitive work of the decision maker watching out for indications to ensure that his line of thought progresses in such a way as to enable him to make a final choice: that of deciding the course of action to be embarked upon.[1]

This chapter sets out to analyse several strategies or several models drawn up to give an insight into the decision-making process which, by definition (since several choices are possible), always takes place in a context of uncertainty. A large part of the cognitive activity of the decision maker is directed at lessening this, by processing the information available in various ways. It is structured in four parts. The first part presents decision-making as a form of conduct and behaviour, so enabling it to be studied from the point of view of psychology. The second part, for the benefit of readers who are unfamiliar with these questions, analyses two commonly used decision-making models which, notwithstanding their differences, have this much in common: they make it possible to give an account of individual decisions. The third part, in a more innovative way, undertakes to study a very particular type of super-individual decision that concerning groups of human beings exposed to risk situations. How do those responsible for safety, whatever their particular role, take their decisions to avoid the generalisation of harmful consequences? Their ways of approach, very different from individual strategies, open up new perspectives. Situations like this have two advantages for researchers: (1) substantive (i.e. do the actions carried out lead to satisfactory responses to the critical case?); (2) epistemological (i.e. how does one represent or conceptualise these situations?). The fourth part attempts to analyse the consequences of a development of this kind. The epistemological questions they give rise to are so important that they radically change the traditional decision-making models. This being so, there is a need for a changed paradigm amounting to no less than a "scientific revolution" of the kind described in Kuhn's famous work.

2. Taking a decision: a complex and integrated form of conduct

For psychologists, more than just behaviour—a term which might suggest a certain automatism of response—decision-making is a specific form of conduct. First of all, the choice of this term underlines the fact that such processes must not be reduced to the extremely visible and observable aspects of the explicit choice of one course of action in preference to other (often many other) possible ones. Secondly, it introduces a constructivist option. The decision is constructed progressively and that which marks its culmination (the choice of the course of action to be embarked upon) is necessarily preceded and justified (sometimes in an approximate or erroneous way) by phases implying cognitive information-processing activities (perception, attention, memory, etc.) which "explain" the choice arrived at. Decision-making is also a process which presupposes freedom of choice, which is defined in time and consists of several stages. The two principal operations are the search for information and the assessment of its importance, which we will call weighting.

[1]For stylistic reasons and to simplify writing, the masculine form is used in this chapter. This does not imply preference or discrimination. What is said is equally applicable to male and female decision makers.

2.1. An initial definition

One of the best known definitions of the entire process of decision-making is that of MacCrimmon [1], characterised by the accumulation of stages identified in his account of the subject. A decision maker "observes a gap between an existing state and a desired state and has the motivation as well as the potential to reduce this gap, while more than one possibility of action exists which may not be immediately available, a kind of action requiring an irreversible allocation of resources [cognitive in this case], and while the benefits [consequences] associated with each choice are completely uncertain" [1]. Each choice consists, according to him, of resolving a problem (MacCrimmon uses the expression "decision problem").

2.2. Different perspectives

A definition is rarely neutral, and this one, formulated with members of the managerial class in mind, is characterised by a series of operations to be carried out successively, therefore presupposing the existence of a (meta-) process of control and integration, and of verification by retrospective loops, not mentioned in the formulation but nonetheless indispensable to ensure the validity of the whole construct.

It is not surprising that MacCrimmon's definition does not totally suit psychologists who are more interested in the previous stage: knowledge of the mental processes and the choice of the strategies planned by the decision makers. Among them, there are some who will criticise this definition for being too segmental, cumulative and prescriptive, and for its failure to give a more important place to the conditions of the time (in economics), the physical environment of the time (in the determination of risk-management strategies), social dimensions (judicial decisions), the pressures of the world of the time (political decisions) which have a determining influence on choices. Strictly focused on rationality, a definition of this kind leaves little room for motivation, sensitivity, desire, emotions, not to mention pleasure, and so on.

2.3. Constructing a decision: what are the processes?

We will consider two principles as being justified both by the evidence and by observations so that the analytic processes may continue to have an acceptable level of general applicability. Decision-making takes place: (1) in an environment or context which is an integral part of the problem but of which the role is too often minimised if not totally hidden; (2) epistemologically, decision-making is constructivist in nature, which means that it progressively develops and becomes more refined on the basis of representations of the world which become all the more operative as the occasions multiply and the information becomes more diverse. Decision-making in this perspective is therefore an illustrative example of a type of conduct resulting from the putting into play of dynamic processes [2].

2.4. Managing the decisional space

We owe the introduction of the topological dimension in decision-making to Lewin (1890–1947) and his field theory [3, 4]. The characteristics present in the field are a component to be taken into consideration, and this leads to a very broad view of the decision which cannot be limited to dealing with certain intangible visible indications or to reproducing learning processes. In elaborating any concrete decision, the information is extracted from a context, and some of this information, according to its nature or intensity, will be accepted as valid by the decision maker on a cognitive basis. Each piece of information used must be assessed in accordance with the context and, where applicable, with the framework in which it happens to be inserted [5]; these two characteristics give it a “salience” [6] of variable intensity. As Lewin has shown, the field which contains all these pieces is not homogenous; it has hills or rough areas which are characteristic points because they are the cause of certain dynamisms.

3. Two traditional models of decision-making

With regard to decision-making, the two most well-known models (among the various existing) are summarised here: that of the economic decision and that of the behavioural decision [7].

3.1. Economics

Economics was the first discipline to formalise decision-making in the full meaning of the term, that is, by establishing a binding axiomatised system [8]. We shall limit ourselves here to indicate in a summary way the salient elements of a branch of study which is still extremely active. The economist’s problem consists of assessing among **n** mutually exclusive actions $\{\mathbf{a}_1 \ldots\ldots \mathbf{a}_n\}$ that will give the greatest satisfaction in a given situation, on the one hand, and to a specified decision maker, on the other hand. Therefore, the objective consists of ordering the outcomes (**1**) according to the preferences of the decision maker ($a_3 > a_8 > a_1$, etc.). To do this, the decision maker constructs a “decision tree” containing “routes” and “stages” (called knots) which represent possible pathways to be followed. At each knot, the decision maker must opt for a way which will bring him to the next stage and so on to the end (to the “leaves”) which indicates the expected consequences of each action. (For a more complete presentation, see [7] Chapter 2). Each of the end points is evaluated numerically taking its frequency into account [assessment of the probability (p) that it will take place taking uncertainty into account] and the subjective value (i.e. for the decision maker concerned) of the utility **u** of the consequences attached to it. It should be noted that, even though the context is that of economics, the consequences are not determined in monetary amounts (objective references) but in subjective units of utility (u) [the satisfaction it can afford]. The value attached to the same sum of money varies in fact according to the individual fortune already possessed so that utility is a more general reference than monetary value. The two indices are combined in a multiplied form, that is, p*u. The outcome (leaf) which has the highest p*u numerical value is that deemed to constitute the best consequence. Climbing the tree in reverse therefore makes it possible to determine the “best” action to be executed. This model, known as subjective expected utility (SEU), therefore refers to a numerical validation criterion ultimately obtained by the observance of axiomatic properties.

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3.2. Psychology

Psychology was the second discipline to set itself the task of modelling decision-making. Although it took the preceding concepts as a basis, this school of thought has led to a very different model form. In 1953–1954, the psychologist Ward Edwards [9, 10], applying the validation methods used in psychology, in particular predictive validity, installed a team of researchers in a Las Vegas casino to study the decision-making of professional players. These persons who live off gambling takings consequently on decisions made in a context defined clearly by rules (those of the game) but where chance also plays a part represented an appropriate sample of decision makers who have, in a short time to decide and to assume the effects of their choices. The initial objective of the team of psychologists was to verify the SEU theory, but it became apparent that the players' decisions were not based on any of the axiomatic elements necessary for the determination of p*q and consequently were not related to the SEU criterion. The decisions taken were based on behavioural information processing in which knowledge, learning and intuition seemed to play an important role. A new investigational pathway was therefore opened up under the name of Behavioural Decision-Making (BDT) [11].

Very soon, Simon [12] underlined the fundamental differences existing between these two conceptions of decision-making, that of economics, which is axiomatic and organised with a view to attaining an end (maximise p*u), and that of psychology, which also identifies an objective to be achieved but sets out to achieve it in a procedural way (implement relevant information-processing procedures). These procedures, which would later be called cognitive, were to lead to new modelling forms [13] used even in economics with behavioural economics [14]. The frontiers between the disciplines had therefore become permeable, a very welcome development.

3.3. Managing an intermediate system

Schematically, the decision-making process consists of transforming all kinds of semantic units present at the mechanism entry point into behavioural forms of action choosing which mark the outcome of the process. Between these two extreme points, there is an organised network of information which will undergo processing. Seen from the topological point of view only, the decision consists of processing an intermediate system which is a generalisation of the notion of intermediate variable (or intervening variable or mediating variable) often used in psychology and defined as "a hypothetical variable postulated to account for the way in which a set of independent variables control a set of dependent variables".[2] The notion of an intermediate system is nothing other than the generalisation of that of the intermediate variable with the retention of the epistemological notions of postulated and hypothetical entities (based on the decision maker's knowledge), on the one hand, and causality, on the other hand (i.e. the incoming variables influence the outgoing ones and so produce effects). Functionally, this intermediate system, which from the methodological point of view is a construct, constitutes a reserve of informational resources organised in the form of networks or "dormant" information clusters. When judiciously activated by the decision maker, these networks make more effective decision-making possible.

[2]Collins English, 12th edition 2014, Harper Collins Publishers.

This is demonstrated by work in the area of Management Science on the complex entities constituted by enterprises in which the "right" decisions make it possible to achieve competitive advantages and the blossoming of the company. It has been shown in [15] that the management of an intermediate system in American small and medium enterprises (SME) enables this enviable objective to be achieved. At this point in our account, we may consider the decision maker as an agent who picks and processes information from a system at a half-way point between perception and action, a kind of reservoir holding pertinent indications drowned in a mass of information items most of which have no causal relationship with the question under consideration. Such a task can only be difficult.

3.4. The cognitive difficulties of decision makers and their reactions

There are many works dealing with the difficulties, mistakes, false ideas, shortcuts and approximations affecting the action choices of decision makers [6, 13, 16], leading them to making poor-quality decisions. Therefore, as not to over-encumber this account, we will not list all these but rather classify them under three headings: structural difficulties, information-picking difficulties and processing difficulties, each category being illustrated by a single commentary.

Structural difficulties are those corresponding to inaccurate or erroneous mental representations of the global organisation of the intermediate system, more often than not implicitly considered as being simpler than it is in reality. This is the case when the decision maker (cognitively) elaborates a decision tree which is not exhaustive and when (in the actual situation) he finds himself confronted with the task of implementing real eventualities but ones not forming part of the initial plan. The decision tree has two functions, one to classify, and the other to predict. Used principally in Economics and Biology [17], it is the forerunner of classification algorithms and has a predictive value with regard to the choice of action, for any new observation.

Information-picking difficulties are frequent. The information items of use for decision-making are not, in real situations, isolated and salient as they might be in a laboratory experiment. To use them, the decision maker is obliged to search for them on the basis of their salience (or saliency), which therefore entails the necessity of a prior mental representation. Salience is a function of the purposes assigned to the action. The point is to pick salient information for a very specific decision and not to decide by using the most obtrusive (visible) elements in a given field. This latter strategy leads to a decision bias called salience bias [6–13] consisting of processing extremely visible information items but ones not relevant to the question under consideration.

Processing difficulties become sensitive at the junctions of the different cognitive operations implemented in succession to determine the action chosen. Three principal difficulties become evident: (1) the very poor cognitive capacities of human beings in assessing and processing uncertainty, an unavoidable element in decision-making situations. Seen as disconcerting and subversive, it is often excluded from the process, something which leads to an "over-confidence" bias [6]. This bias is noticeable in the assessment of risks (generally under-estimated) quite as much as, in the opposite direction the possibility (overestimated) of winning the jackpot in the lottery.

4. Decision-making in complex dynamic systems

4.1. Epistemological reductionism

The decisions presented in the preceding sections are characterised by having been taken in a stable, defined informational context, that is, invariable throughout cognitive processing and ending in the choice of a single action, a behaviour marking the end, satisfactory more often than not, of processing operations. These situations are modelled on a limited number of variables, the pertinence of which is based on laboratory studies, sometimes of an experimental kind, but which have always undergone epistemological reductionism [18] guaranteeing their permanence and high level of general applicability. All other variables, particular or inconstant, are removed from the model.

4.2. Complex and dynamic decisions

There are decisions of another kind, which one could describe as super-individual as they concern at one and the same time a great number of persons, which must be taken in very different conditions. They cannot be processed in a laboratory nor reduced to a few variables, so they must be considered as global in nature and their complexity must be taken into account. Unlike the laboratory strategy where variables are isolated, the entity being studied can only be seen in a global way and cannot be reduced epistemologically without distortions. Another distinctive feature: the entities under study become modified under the influence of the processing operations, giving rise to a temporal dimension (evolution capacity) and a high degree of lability in the choice of "active" variables liable to be used in taking the decision. In such cases, therefore, momentary characteristics are what one is trying to define.

One of the examples (and a very recurrent one in the summer period) which best illustrates this conjunction of complexity and dynamism can be found in the management of forest fires. These phenomena give rise to management difficulties linked to the difficulty of anticipating developments (uncertainty) and the unstable components of the fire (changes in intensity and direction). The decisions regarding the actions to be taken to contain and manage the fire and extinguish the flames are very difficult cognitively. A new element has been introduced into the situation: that of the interactions at all levels between different variables; interactions of a kind and extent which develop with time, the progress of the event and the measures undertaken at the previous stages by the action teams. The intensity of the wind, its direction, the degree of dryness of the ground, the nature of the forests, and so on determine the characteristics of the fire and the way it will develop. The interpretation in substantive terms (i.e. in terms of the present situation) of the interactions is cognitively difficult, and the decisions taken as a consequence may be qualitatively poor [19].

4.3. An epistemological turnaround

The finding of identical difficulties in very different contexts (political, legal, economic, environmental, technological decisions, etc.) where human beings perform poorly must lead one to consider the various perspectives applied to studies on decision-making. The necessary and legitimate search for the most efficient action to solve a problem, as discussed by MacCrimmon, has led researchers to design research plans inspired by the exact sciences (e.g. physics and chemistry) or disciplines, such as biology, which verify their hypotheses concerning certain very specific variables, in an appropriate place perfectly protected against external influences: the laboratory. The history of Science, in its present state, shows in fact that for certain situations (but not all), such a choice produces the safest information. Such an approach, while being perfectly scientific, cannot be implemented in a generalised way to all the psychological problems of decision-making. Certain very recent decisions, such as those concerning climate change (cf. Section 5.1) or the management of industrial or ecological disasters, cannot usefully be subjected to epistemological reduction, a crucial process in laboratory studies. In other words, it is no longer possible to isolate certain variables and manipulate them to verify their causal status.

Must one then search for other scientific approaches? If so, there will have to be a turnaround in epistemology too. The phenomena under review will have to be assessed as global entities (holistic option), to be considered in their natural state rather than in a laboratory, in the conditions in which they actually occur, and if possible in *statu nascendi* (at the moment in which they occur). The management of maritime disasters with the threat of pollution require urgent decisions. These two recommendations are in line with the principles defined by Gestalt psychology in the first half of the twentieth century [3]. These were advanced over and over again at the time but could never be measured or assessed for want of methodological options other than experimentation. The epistemological change which will make it possible, in part, to overcome this difficulty consists of conceptualising the situation being studied as a dynamic complex system.

4.4. Dynamic complex systems

In 1968, the biologist Ludwig von Bertalanffy (1901–1972) published a work in which he presented the notion of a "system" as a very extensive holistic entity [20]. "Systems everywhere around us," he observed. Only the analytical traditions inherited from previous centuries prevent us from seeing them and approaching research questions by including this aspect of globality rather than destroying it at the outset by concentrating on certain variables.

This original contribution, which highlights the potential richness of the systemic way of thinking, has been completed by the work of Cilliers on the functioning of systems [21] and on the epistemological characteristics arising out of them [22]. For this author, a complex system is an entity presenting ten specific characteristics [21]. Among the most important, we would instance the presence of numerous interacting variables where the interactions are not linear. This means that proportionality is no longer the rule so that even a very small variation introduced into the system may have major effects when exiting. This corresponds to the case found in 1972 by the meteorologist Lorenz known as the "butterfly effect", thus opening the way to new forms of non-Newtonian determinism.

Let us also consider certain characteristics of the system itself, independent of the decision maker who can only take note of them and include them in his decision. The system has a history, it is composed of networks which reflect it, it has resources available to it which in the absence of human intervention determine its "behaviour", it is usually open to the environment, has self-organisation capacities and can regulate itself because of the existence of control loops. One could say that it is endowed with an "epistemological personality", so that the decision maker is first of all an analyst and a manager of both the resources of and directions taken by the system, before being able to choose the appropriate action.

5. The necessity for and characteristics of a new paradigm

Up to the present day, very wide sectors of scientific psychology have chosen to apply the experimental paradigm in their research practices as a guarantee of the validity and replicability of their conclusions. This is, of course, not an erroneous choice, but it has now become apparent that its application is impossible in certain situations where nonetheless the intervention of psychologists is required.

5.1. Complex systems and psychology: the case of global warming

The most illustrative case of conceptualising psychological issues in terms of complex systems is that of climate change. Climate is a complex system, it possesses all the properties defined in [21] characterising this type of organisation. The global state of the system depends on multiple interacting variables most of which are nonlinear, climate evolves, "integrates" characteristics which cause it to organise itself, to change its "behaviour" and global configuration. Among these factors for change, the production of carbon dioxide by human beings is one of the best identified factors (even if still the subject of ideological disputes) in global warming. Although human beings have no variable available to them which would enable them to act directly (as would an independent variable) to limit the harmful effects of global warming as required, they must nonetheless take decisions to influence its future course, and with regard to this, the contributions of psychologists are welcome.

The very well-known American Psychological Association (APA) has set up a task force which in 2008–2009 worked on the problem of "global climate change" and all its individual and collective psychological consequences. The objective was therefore much broader than decision-making, as is shown in the final report on the work of this commission which appeared in a special number of the American Psychologist [23]. Questions concerning the forecasting of the development of climate and the perception of risks are considered but, although it underlies many points in this work, the complex system notion is not explicitly mentioned. The phrase "addressing a multi-faceted phenomenon and a set of challenges" present in the title is, however, entirely consistent with the spirit of complex systems.

5.2. Functions of the paradigm

Putting psychological objects into perspective by reference to complex systems opens up the way to a new paradigm. The old experimental-type paradigm, as we have seen, cannot account for certain important decisions. The new paradigm must enable a better understanding of them. It would seem that we are at present on the threshold of a "scientific revolution" [24, 25] made all the more apparent by this necessary change.

A paradigm is defined as "a philosophical and theoretical framework of a scientific school or discipline within which theories, laws and generalisations and the experience performed in support of them are formulated".[3] The function of a paradigm, as this definition highlights, consists of ensuring the required coherence of the research approach and verifying the compatibility between the different components necessary for scientific knowledge (the hypotheses, the data observed, the methodological tools applied to process them and the theories constructed on the basis of the results, respectively). A paradigm is the overall structure containing compatible entities.

5.3. Certain major properties characterising the new paradigm

As emphasised in [21], thinking in terms of complex systems implies avoiding the "reductionism" linked to the initial choice of certain variables forming part of a greater complex. In the experimental paradigm, only those initially considered relevant will be used and where applicable verified. This choice being initial, even if supported by hypotheses and observations, is a determining factor in the construction of knowledge. In addition, the said variables are tested in an isolated way one from the other and then put into use "artificially" outside their natural environment. This procedure eliminates from the field the knowledge produced by a great number of interactions, which could prove decisive. The paradigm of complex systems is a complete change of perspective. The decisions studied with a view to their consequences are studied globally, on the ground, in their natural environment and in specific circumstances. The importance of the results obtained is a function of the activity of networks which, as for the nervous system, become observation "units."

This approach does not set out to establish general conclusions (conclusions applicable in all circumstances) regarding decision-making, since to do this, it would be necessary to ignore many specific items of information, which exist and are active in the specific situation to be dealt with and which in fact are often decisive in the taking the decision.

5.4. The search for assessment indicators

How should one assess, measure, or quantify the activity of a complex system with a view to predicting its development and being able to decide accordingly? Physicists, the first to deal with this question when it had to be answered in their discipline, refer to the laws of thermodynamics (particularly the second law) regarding energy. This energy dimension, present in all systems, makes comparisons possible by calculating, for each system, its level of entropy. The size of the latter was for a long time interpreted as a degree of disorder, but, unlike in the experimental approaches which scrupulously avoid it, systemic disorder can here have a positive connotation. It is considered as a possible generator of further states differing one from the other while order, once it has been determined, is immutable and results in one state only.

The transposing of the laws of thermodynamics into psychology has made it possible to highlight their relevance but at a meta-psychological level: that of the global psychological development of human beings [25] and this direction is too general to characterise a particular

[3]Merriam Webster Dictionary.

system. Researchers should therefore direct their efforts to looking for multiple indicators. Since this work has been published, the needs for identifying patterns of information have been emphasised as a heuristic way to manage complex systems [26]. For instance, artificial intelligence and human cognition ("humanised computing") are articulated to create tools either for treating psychological disorders [27] or allowing recognition of psychological entities (emotions) using non-linear relationships [28].

5.5. The use of icons

The educational system as a vector of knowledge and the diversity of the contributions it makes to different pupils is an example of the differentiated functioning of a complex system, which produces measurable effects, satisfactory or otherwise. How should such a system be characterised based on the observable results it provides? In particular, when a country applies one and the same generalised system to pupils belonging to different cultures (so-called "minority" groups), what can be said of the performance of the system where total assimilation on the one hand and extreme diversification on the other hand must both be considered as mistakes? The functioning of the educational system of Chile with regard to a "minority" group with a strong attachment to its land, culture and identity (the Mapuche) was studied in an initial contribution [29]. This highlights the importance of teachers possessing the two cognitive registers (that of the "minority" concerned and that of the "majority"). Considered more globally, this conclusion illustrates the arguments advanced above on the management of the intermediate system (cf. Section 3.3).

A second contribution [30] deals with the use of icons to assess how a system (school system in this case) functions with regard to the different demands represented by different groups of pupils. The term icon was chosen to stand for homogenous configurations of information which appear at the "surface" of the system and which indicate how it functions with regard to the diverse needs of users. Let us suppose, for example, that one of these icons includes several items of information signalling a lack of mastery of the written language, the decision maker, after analysis, can then proceed to choosing the action most suitable for the sub-groups concerned.

The fact that these icons are products of the systems and not just observations or perceptions differentiates them from the normal function of icons, which is pictorial in kind. Systemic icons, it is true, also "represent" but, as they are produced functionally, they do much more than this and can justifiably be described as cognitive icons as they enable knowledge. In short, while physicists referred to the energy of systems in order to differentiate them, the Human Sciences refer to cognition as a global act making it possible to assign significance to sub-sets of information (icons) which therefore draw their significance from the totality of the system while at the same time participating in it.

6. Conclusion

Changes in society today are leading psychologists to deal with the management of complex situations which are very different from those that traditionally formed part of their area of activity. Two major developments characterise contemporary psychology: (1) new fields of activity (perception of risks, management of disasters or traumatic events, climate change, etc. (2) The importance of a global reference both in the definition of the phenomena studied and at the level of the people who find themselves involved (often large groups of the population). These changes must logically lead to an adaptation of the research and intervention strategies because the experimental method, so useful in the study of certain problems, is no longer applicable while the reliability it provided with regard to its conclusions still remains an imperative.

This chapter has attempted to present a difficult but promising approach: that of the use of dynamic complex systems to construct adaptable, appropriate, and evolutive decisions. It emphasises the necessity, once certain situations have presented themselves, of a change of paradigm so that complexity is recognised as a component in research as it already is in the forms of conduct being studied, rather than being somewhat ineptly eliminated from the start. Epistemological and methodological advances are necessary in order to develop the paradigm of complex systems in psychology, a paradigm which is already a reference in other branches of the human sciences.

Author details

Bernard Cadet[1,2]*

*Address all correspondence to: bernard.cadet50@gmail.com

1 Cognitive Psychology, University of Caen Normandy, France

2 GRIE, University of Estremadura, Badajoz, Spain

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Chapter 4

Utilizing Surrogate Numbers for Probability Elicitation

Mats Danielson, Love Ekenberg and
Andreas Paulsson

Additional information is available at the end of the chapter

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Abstract

Comparatively few of the vast number of suggested decision-analytical methods have been widely spread in actual practice. The majority of those methods call for exact and accurate numbers as input, which could be one of several reasons for this lack of actual use; people frequently seem to be unfamiliar with, or reluctant to express those, in a sense, "true" values required. Many alternative methods to resolve this complication have been suggested over the years, including procedures for dealing with incomplete information. One way, which has proliferated for a while, is to introduce so-called surrogate numbers in the form of ordinal ranking methods for multi-criteria weights. In this chapter, we show how those can be adapted for use in probability elicitation. Furthermore, when decision-makers possess more information regarding the relative strengths of probabilities, that is, some form of cardinality, the input information to ordinal methods is sometimes too restricted. Therefore, we suggest a testing methodology and analyze the relevance of a set of cardinal ordering methods in addition to the ordinal ones.

Keywords: decision analysis, probability elicitation, cardinal ranking, rank order, imprecise probability

1. Introduction

Elicitation of subjective beliefs has been applied in numerous areas, such as game and decision theory [1, 2], agriculture [3], statistics [4], and various disciplines of economics [5–7], and many methods have been designed for elicitation purposes [8–10]. It is in these contexts often assumed that at least experts in the various areas are capable of acting rationally and can provide reliable information so long as they are eliciting probabilities sensitively. Those assumptions are contrary to the fact that even expert estimates may differ significantly from the true probabilities and that there are still no universally accepted methods of probability elicitation available. The process of eliciting adequate quantitative information is one of the substantial challenges within decision analysis [11, 12].

In a classical framework (cf., e.g., [13]), numerical probabilities are assigned to the different events in tree representations of decision problems. The assignments are made after the set of parameters, whose values need to be elicited and whom to choose for providing those estimates, have been identified. Domain experts could, for example, be asked to express their beliefs about the likelihood of a particular event in probabilistic form. Such beliefs cannot be measured objectively, and neither should they be judged in such a manner. Besides, the success of an elicitation process depends on how well a representation of the present subjective opinions can be constructed rather than on some set of objectively true values [14–16].

Methods for eliciting utilities and probabilities have been thoroughly investigated, resulting in a large number of recommendations and handbooks on the subject. Procedures range from using direct elicitation, gamble, and lottery techniques, as well as more elaborate methods to reduce biases, aversions, and a multitude of other causes of errors while producing as reliable estimates as possible (c.f., e.g., [17–22]). Here, it is generally assumed that procedures for elicitation should give rise to adequate preference orders, but this assumption is nevertheless often violated in empirical studies (c.f., e.g., [23–25]). A multitude of methods for ordinal rankings or interval approaches have been suggested to provide more realistic models. The goal is to be able to utilize the information the decision-makers can supply without forcing them to express unrealistic, misleading, or meaningless statements.

To elicit probabilities, methods based on ordinal rankings already constructed for obtaining weights for multi-criteria decision analysis (MCDA) (see [26–28]) can be adopted. The fundamental idea is that ordinal information that stems from importance can be converted to a set of normalized surrogate numbers, the values of which are consistent with the elicited ordinal rankings. The actual conversion can be done using a variety of methods, such as rank sum (RS) and rank reciprocal (RR) [29], and centroid-based methods (ROC) [30]; originally used for handling criteria weights in MCDA. However, even in MCDA, the use of only ordinal information is sometimes perceived as being too vague or imprecise, resulting in a lack of confidence in the alternatives' final values or a too large class of non-dominated alternatives.

In this chapter, a set of methods that allow for more expressive information as input when eliciting probabilities, while maintaining the relative correctness and simplicity of ordinal ranking procedures, is proposed. In the following section, we compare and discuss a set of significant features, including correctness and relevance, of various extensions to some existing ranking methods. Following a brief recapitulation and adaptation of some ordinal ranking methods in the following section, we continue with cardinal ranking methods and discuss a set of appealing candidates for probability elicitation. Using simulations, we investigate some properties of the treated methods and conclude with pointing out, according to the results, a particularly attractive method for eliciting probabilities.

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2. Ordinal ranking methods in MCDA

Different elicitation formalisms by which a decision-maker can express preferences in MCDA decision situations have been proposed. Such formalisms are sometimes based on scoring points, as in point allocation (PA) or direct rating (DR) methods. In PA, the decision-maker is given some number of points, for example, 100, to distribute over a set of criteria or consequences, depending on the type of decision [31]. Hence, for N criteria or consequences, there are $(N-1)$ degrees of freedom (DoF). Direct rating methods, on the other hand, put no limit on the number of points to be allocated.[1] The decision-maker allocates as many points as desired and the points are subsequently normalized. Thus, in DR, there are N degrees of freedom for N criteria. Regardless of elicitation method, the assumption is that all elicitations are made relative to a distribution held by the decision-maker.[2]

Surrogate methods are utilized in [26–28] and many others for handling such problems. Regardless of method, however, a key property must be to retain as much information as possible in the surrogate numbers, yet accommodating for the various constraints required by certain types of values.

Stillwell et al. [29] compare a set of different methods for eliciting surrogate numbers from ordinal rankings alone, based on the idea of maximizing the power to discriminate between values. Among those are rank sum and rank reciprocal, for which surrogate weights are derived solely from the rank order of the attributes. Take a simplex S_w generated by $w_1 > w_2 > \cdots > w_N$, $\sum w_i = 1$ and $0 \le w_i$.[3] Assign an ordinal number to each item ranked, starting with the highest ranked item as number 1. Denote the ranking number i among N items to rank. Then the rank sum (RS) surrogates for all $i = 1, \ldots, N$ are defined by

$$w_i^{\mathrm{RS}} = \frac{N + 1 - i}{\sum_{j=1}^{N} (N + 1 - j)}. \quad (1)$$

The surrogate numbers produced by the rank reciprocal (RR) method are, as the name implies, based on the reciprocal of the rank of each item. Let the number 1 corresponds to the highest ranked item, the number 2 to the second highest ranked item, and so on. Then for the i:th ranked item, the RR surrogate, given a total of N items, are obtained by

$$w_i^{\mathrm{RR}} = \frac{1/i}{\sum_{j=1}^{N} 1/j}. \quad (2)$$

[1] It could be that the sum is limited in direct rating methods as well but then as a consequence of a uniform limit to the individual numbers.

[2] See, for example, [32, 33] and some others from the same authors on methodological and cognitive aspects of inexactness in decision-making.

[3] Unless stated otherwise, the component vectors of decision problems will be modeled as simplexes, S_x, consisting of $x_1 > x_2 > \cdots > x_N$, where $\sum x_i = 1$ and $0 \le x_i$.

A decade later, Barron [30] suggested a method based on vertices of the simplex of the feasible space. The rank order centroid (ROC) weights are the centroid vector components of the simplex S_w. The weights then become the centroid (mass point) of S_w. The ROC weights for the ranking number i among N items to rank are given by

$$w_i^{\mathrm{ROC}} = \frac{1}{N}\sum_{j=i}^{N} 1/j. \tag{3}$$

However, RS, RR, and ROC perform well only for specific assumptions on decision-maker behavior. If we assume that the decision-maker stores its preferences in a way similar to a given point sum, considering normalization, there are $(N-1)$ degrees of freedom (DoF) for N items. On the other hand, if we assume that the decision-maker stores its preferences in a way that puts no limit to the total number of points (or mass) allocated, and the normalization is made afterward, then there are N degrees of freedom for N criteria. It remains an open question as to how a decision-maker perceives the nature of the basis of a particular preference order. Whether the linear dependence in $(N-1)$ DoF models is accounted for, or if preference values are allocated with no particular limits in accordance with N DoF models. Surrogate numbers obtained by RR and ROC models agree with a preference structure based on $(N-1)$ degrees of freedom, while the RS model conforms to a preference structure based on N degrees of freedom. Due to this apparent difference, a model, SR, in which features from both RS and RR were incorporated, was proposed by [34]. The SR method is an additive combination of the Sum and the Reciprocal functions as in

$$w_i^{\mathrm{SR}} = \frac{\frac{1}{i} + \frac{N+1-i}{N}}{\sum_{j=1}^{N} \frac{1/j(N+1-j)}{N}}. \tag{4}$$

To exemplify the above, given any probability simplexes such as (p_1, p_2, p_3) and $(p_1', \ldots, p_6')$ that satisfy the previously laid out assumptions, the various methods would assign to them numbers as in **Tables 1** and **2**.

In theory, the choice of elicitation method should preferably be based on the manner in which a decision-maker constructs a preference order; whether it is based on a $(N-1)$ DoF or N DoF model, or even a mixed model. However, since we cannot know the ratio of $(N-1)$ DoF to N DoF employed in the mind of the decision-maker, an elicitation method, to be robust, should work about equally well regardless. The SR method, assuming the principal features of both RS and RR, was found to be the method best accommodating for such a need.

Method	p_1	p_2	p_3
Rank sum (RS)	0.50	0.33	0.17
Rank reciprocal (RR)	0.55	0.27	0.18
Rank order centroid (ROC)	0.61	0.28	0.11
Sum reciprocal (SR)	0.52	0.30	0.17

Table 1. Probabilities corresponding to the ordinal ranking, $p_1 > p_2 > p_3$, rounded to two decimal places.

Method	p_1'	p_2'	p_3'	p_4'	p_5'	p_6'
Rank sum (RS)	0.29	0.24	0.19	0.14	0.10	0.05
Rank reciprocal (ROC)	0.41	0.20	0.14	0.10	0.08	0.07
Rank order centroid (ROC)	0.41	0.24	0.16	0.10	0.06	0.03
Sum reciprocal (SR)	0.34	0.22	0.17	0.13	0.09	0.06

Table 2. Probabilities corresponding to the ordinal ranking, $p_1' > p_2' > p_3' > p_4' > p_5' > p_6'$, rounded to two decimal places.

In the following, the methods for weight elicitation within MCDA presented above will be augmented with information denoting the relative difference between adjacent items and modified to meet the requirements of probability elicitation. We adhere to a standard, one-level decision-tree model, in which each of M alternatives has N consequences. Hence, there are M times N consequences in total.

3. Cardinal ranking methods

Providing ordinal rankings puts fewer demands on decision-makers; they are, in a sense, effort saving. Furthermore, there are techniques such as those mentioned earlier for handling ordinal rankings with some success. For use in probability elicitation, the same ordering is asked of the decision-maker, but this time in reference to how probable events are as outcomes of a chosen alternative of action.[4] Nevertheless, decision-makers might, in many cases, have more knowledge of the decision situation, even if the information still is not precise. For instance, cardinal probability relation information may implicitly exist, entailing that the surrogates may not really reflect what the decision-maker actually means by a particular ranking.

To improve the conformance of an ordinal ranking to the true subjective beliefs of a decision-maker, information such as the relative differences between adjacent items need to be accounted for. Given a ranking of some number of consequences, relative differences in probability comprise such information. Furthermore, methods that allow for such details can also handle probabilities considered equal, something which purely ordinal methods cannot.

The following notations together with the suggested interpretations are used to exemplify the proposed methods. The symbols denote the relative strength of the difference in probability between consequences.[5]

[4]For each choice of action, we assume a decision node to be the root of a standard two-level decision tree with each branch representing an alternative, which, in turn, is followed by a set of exhaustive and mutually exclusive events. It is the probabilities of those events that the decision-maker is asked to rank. Such a setup can easily be generalized to decision trees with multiple levels.

[5]Although using verbal interpretations for illustrative purposes, we do not intend to discuss issues related to difference values and their respective meanings in relation to probabilities. In an actual implementation of the method, we consider cardinal input obtained from graphical sliders in a software tool.

$>_0$ "equally probable"

$>_1$ "slightly more probable"

$>_2$ "more probable"

$>_3$ "much more probable"

To derive probabilities for N consequences using cardinal methods, start by ranking the consequences in order of probability, giving the most probable consequence rank one, and the least probable consequence rank N. Let s_j be the number of difference steps between probabilities p_j and p_{j+1}, denoted by $p_j >_{s_j} p_{j+1}$. Setting $s_j = 1$ is equivalent to $p_j > p_{j+1}$ as in the ordinal case. The sum, Q, of all difference steps for N probabilities will then be $\sum_{i=1}^{N-1} s_i$, and for any probability p_i, $i \in \{2, \ldots, N\}$, the position on this scale of difference steps from 1 to Q is defined by $t(i) = s_{i-1} + t(i-1)$, and $t(1) = 1$.[6]

Modifying the above ordinal methods for probability elicitation can now be done without difficulty. The key is to normalize the values of the cardinal rank positions such that the higher positions result in the lower probabilities. In the cardinal version of RS (CRS), the probabilities should mirror the differences in cardinal rank positions. Hence, the CRS probabilities are given by

$$p_i^{\text{CRS}} = \frac{Q + 1 - t(i)}{\sum_{j=1}^{N} (Q + 1 - t(j))} \tag{5}$$

where $t(i) \in \{1, \ldots, Q\}$ are the cardinal rank positions derived from the cardinal differences provided by the decision-maker such that $t(i) \leq t(j)$ if and only if $i < j$. The cardinal variation of rank reciprocal (CRR) is defined in a similar fashion, and the CRR probabilities are obtained by

$$p_i^{\text{CRR}} = \frac{1/t(i)}{\sum_{j=1}^{N} 1/t(j)}. \tag{6}$$

with the usual property that a higher probability is assigned to lower ranking numbers. ROC is generalized in the same way, and the corresponding strength rank order centroid (CRC) probabilities are obtained as

$$p_i^{\text{CRC}} = \frac{\sum_{j=t(i)}^{Q} 1/j}{\sum_{k=1}^{Q} \left(\sum_{j=t(j)}^{Q} 1/j \right)}. \tag{7}$$

Finally, generalizing SR is done in the same way and using the above equation, the corresponding cardinal SR (CSR) probabilities are obtained as

[6] Here, $p_i = P(c_i)$, that is, the probability that consequence i obtains.

Cardinal method	p_1	p_2	p_3	p_4	p_5	p_6
Rank sum (CRS)	0.29	0.23	0.19	0.13	0.13	0.03
Rank reciprocal (CRR)	0.49	0.16	0.12	0.08	0.08	0.05
Rank order centroid (CRC)	0.45	0.21	0.16	0.09	0.09	0.02
Sum reciprocal (CSR)	0.37	0.20	0.17	0.11	0.11	0.04

Table 3. Probabilities corresponding to the ranking, $p_1 >_2 p_2 >_1 p_3 >_2 p_4 >_0 p_5 >_3 p_6$, rounded to two decimal places.

$$p_i^{\text{CSR}} = \frac{\frac{1}{t(i)} + \frac{Q+1-t(i)}{Q}}{\sum_{j=1}^{N} \left(\frac{1}{t(j)} + \frac{Q+1-t(j)}{Q} \right)}, \tag{8}$$

which is a generalization similar to the others. Thus, using the idea of cardinal steps, ordinal methods are easily transformed to their respective cardinal counterparts. See **Table 3** for an example of probabilities correlated with a certain cardinal ranking.

3.1. Application to a decision problem

To show the merits of cardinal methods for elicitation of both probabilities and values, we present a decision on the choice of programming language, adapted from [35]. Due to resource constraints in a current Prolog implementation, the staff considered two options:

A: Rewriting the whole system in C.

B: Trying to find an implementation of Prolog that could handle the system.

After thoroughly discussing the pros and cons of the two options, they arrived at the following possible scenarios. For option A, the staff concluded that either (c_1) a prototype in C would be ready on time or (c_2) a prototype in C would be slightly delayed due to external circumstances. For option B, (c_3) a prototype in Prolog would be ready on time, (c_4) a prototype in Prolog would be slightly delayed due to external circumstances, or (c_5) only fractions of a prototype in Prolog would be ready on time.

Having considered the probabilities and the values of the consequences, the staff arrived at the following assumptions, where p_i represents the probability of c_i, and v_i represents the value of c_i. For option A, p_1 was thought to be at least 0.67, and consequently, p_2 would be at most 0.33. For option B, p_5 would lie somewhere between 0.40 and 0.90, hence the sum of p_3 and p_4 could range from 0.10 to 0.60.

With regard to value, c_3 was the most desirable with c_4 being slightly less so. Both c_3 and c_4 would be clearly better than c_1, which in turn was slightly better than c_2. By far, c_5 would be the worst consequence.

Applying a cardinal ranking to the above probabilities and values, the staff agreed on the following:

$$p_1 >_3 p_2$$

$$p_5 >_3 p_3 >_0 p_4$$

$$v_3 >_1 v_4 >_2 v_1 >_1 v_2 >_3 v_5$$

Using a purely ordinal ranking, one would end up with the following, less precise ordering:

$$p_1 > p_2$$

$$p_5 > p_3 > p_4 \text{ or } p_5 > p_4 > p_3$$

$$v_3 > v_4 > v_1 > v_2 > v_5$$

Computing the values of the rankings about using SR and CSR yielded the results presented in **Tables 4** and **5**. Let E_o^m be the expected value of option o given elicitation method m, we then have $E_A^{SR} = 0.16$ and $E_B^{SR} = 0.19$, resulting in option B being the preferred alternative, while $E_A^{CSR} = 0.16$ and $E_B^{CSR} = 0.14$ resulting in the contrary.

Possible alternatives in the case of ordinal rankings, such as strict uses of either of the rankings $p_5 > p_3 > p_4$ or $p_5 > p_4 > p_3$, do not affect the preference order of the options. However, a change from $p_5 >_3 p_3 >_0 p_4$ to $p_5 >_2 p_3 >_1 p_4$ when applying the cardinal method would alter the outcome, indicating the decision problem's sensitivity to uncertainty, something which is not reflected when using a purely ordinal ranking of the consequences.

When treating the decision problem in the professional software program DecideIT [36], the probability values from the original assumptions can be used, resulting in the constraints:

1. $p_1 \geq 2/3$ and $p_1 + p_2 = 1$
2. $0.4 \leq p_5 \leq 0.9$ and $p_3 + p_4 + p_5 = 1$

which in turn can be entered directly into the program. The values are specified as in the cardinal case. Eventually, we end up with the decision tree in **Figure 1**.

Method	p_1	p_2	p_3	p_4	p_5
SR	0.67	0.33	0.24	0.24	0.52
CSR	0.80	0.20	0.17	0.17	0.66

Table 4. The probabilities of the consequences of the options of the decision on a computer programming language.

Method	v_1	v_2	v_3	v_4	v_5
SR	0.18	0.12	0.38	0.25	0.07
CSR	0.17	0.13	0.38	0.26	0.05

Table 5. The values of the consequences of the options of the decision on computer programming language.

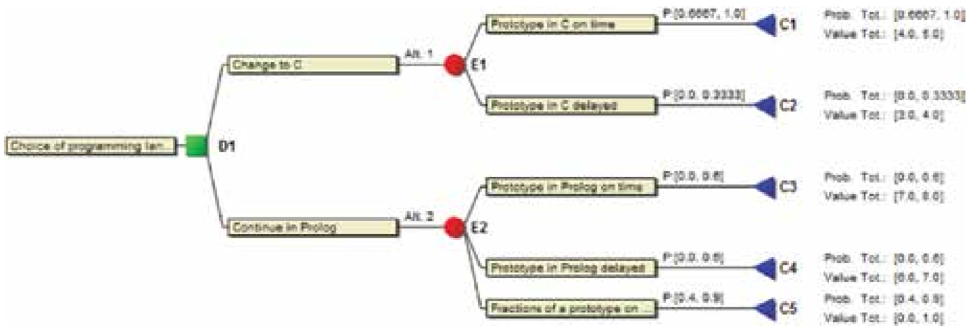

Figure 1. Modeling the decision problem of choosing a programming language in DecideIT.

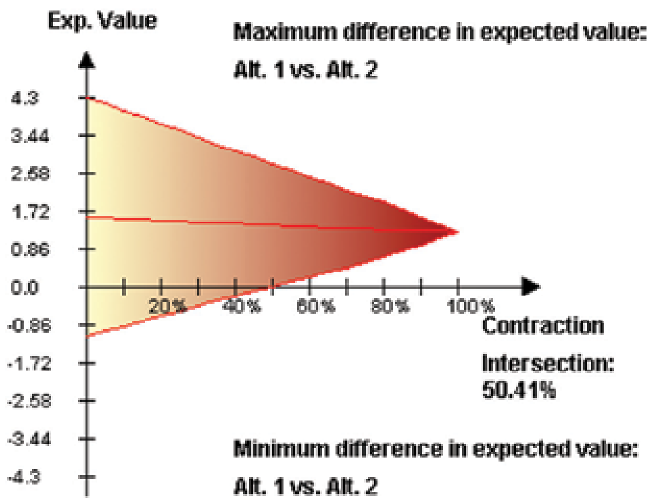

Figure 2. The expected value graph generated by DecideIT.

Looking at the expected value graph in **Figure 2**, we note that although about 50% contraction is needed, it is arguable so that either the assumptions need to be revised or option *A* should be the preferred one. Consequently, a cardinal ranking of the probabilities and the values seem to resonate better with a more detailed examination in which imprecise numbers are taken into account than a purely ordinal one.

4. Assessing models for cardinal relations

Given that we have a set of cardinal methods as in the previous section, how can they be validated? For ordinal relations in MCDA, simulation studies similar to [27, 37–39] and others have become a kind of de facto standard. The simulations herein are based on the fundamental idea that a set of genuine, or "true," probabilities, in fact, exists in the mind of the decision-maker. No elicitation method is capable of completely mirroring these probability values, but in the simulations, the potency of the probability ranking approaches is judged by comparing the "true" values to those elicited by the methods mentioned earlier.

The modeling caters to the two extremes of decision-makers' mindsets outlined earlier in the way the decision problem vectors are randomly generated. Following an N DoF model, a vector is generated, where the components are kept within [0%, 100%], and subsequently normalized, that is, a process with N degrees of freedom. Details on this kind of simulation can be found, for example, in [40]. For an $(N-1)$ DoF model, the components are generated such that they sum to 100% already from the outset; that is, using a process of $(N-1)$ degrees of freedom. This simulation is based on a homogeneous N-variate Dirichlet distribution generator. Details on this kind of simulation can be found, for example, in [41].

The "true" probabilities in the minds of decision-makers might, of course, follow a distribution different from the ones used in this study, and there might eventually be models available to elicit values following those. Nonetheless, the crucial observation is that the validity and reliability of the results of the simulations are highly dependent on how the minds of decision-makers are modeled. Although the difference in the number of degrees of freedom is only one of several parameters related to cognitive behavior, it still offers a meaningful way of distinguishing between cognitive models.

4.1. Biases of simulation studies

The results of the simulations are highly dependent on the type of generator used. A generator corresponding to an N DoF model is referred to as an N-generator. In the same manner, a generator corresponding to an $(N-1)$ DoF model is referred to as an $(N-1)$-generator. In applying the N-generator, probabilities elicited by the RS method outperforms those elicited by other methods. Not because the RS method is superior per se, but because it produces numbers at regular intervals. Likewise, ROC outperforms the other methods when an $(N-1)$-generator is used for the reason that the values elicited by the ROC method are similarly skewed toward the lower end of the interval.

In actual fact, it is impossible to determine whether decision-makers, in general (or even some), elicit values in particular accordance with $(N-1)$ or N DoF representations of their knowledge. As a group, or as individuals, it is possible that they completely adhere to either one or that they follow an arbitrary mix of the two. Due to this uncertainty pertaining the cognitive processes of decision-makers, a rank ordering mechanism, to be robust, must elicit values that conform to both types of representations reasonably well. Therefore, to find the method that yields the most robust and efficient assignments, the evaluations in this study employ both types of generators and combinations of them.

4.2. Comparing the methods

To evaluate the validity of the RS, RR, and ROC methods for multi-criteria weight elicitation, Barron and Barrett [27] simulated a large set of "true" weights, using an $(N-1)$-generator.

Based on those, they then produced a corresponding set of surrogate weights for each of the elicitation methods. As shown earlier, the generation procedure does have significant effects with regard to such a comparison. The set of "true" weights is dependent on how we model the minds of decision-makers. Barron and Barrett [27] presented a computer simulation consisting of four main steps, which for probability elicitation is modified as follows:[7]

4.2.1. Generation procedure

1. For a decision problem with M alternatives, where each alternative can result in one of N consequences, generate M probability vectors, $\mathbf{p}_1, \ldots, \mathbf{p}_M$, in N dimensions. These vectors contain the so-called true probabilities. Then, for each elicitation method μ', produce vectors $\mathbf{p}_1^{\mu'}, \ldots, \mathbf{p}_M^{\mu'}$, according to the order of the "true" probabilities.
2. After that, generate an $M \times N$ matrix of random numbers v_{ij} corresponding to consequence j, of the ith alternative. These are the values of each consequence.
3. Let p_{ij}^{μ} be the probability obtained by method μ for consequence j of alternative i (where μ is either μ' or "true"). For each method μ and each alternative i, calculate the expected value $E_i^{\mu} = \sum_{j=1}^{N} p_{ij}^{\mu} v_{ij}$. Note the rank order of E_i^{μ} for each μ, that is, the preference order of the alternatives for each method.
4. Lastly, determine if method μ resulted in the same most preferred alternative as "true." If that is the case, then record a hit.

The abovementioned procedure (a simulation round) is repeated a large number of times, with the ratio of the number of hits to the total number of simulation rounds used as a measure of efficacy. In some MCDA studies, two additional measures of efficacy have been reported, namely the average value loss and the average proportion of the achieved maximum value range. These measures do not, however, add anything in particular in terms of value due to their strong correlation with hit ratio.

Using an (N–1)-generator MCDM simulation model over the simplex S_x, ROC outperforms the other two methods. But a study by Roberts and Goodwin [40] came up with a different result where RS performed better than ROC with RR in third place, by employing a different distribution generating function where a fixed number, say 100, is given to the most important criterion and the others are uniformly generated as U[0,100]. This N-generator is, of course, different from (N–1)-generators based on a Dirichlet distribution, and thus, their simulation study instead yields the result that RS outperforms ROC with RR in third place. As we see later, using surrogate weights for probability elicitation yields similar results.

[7]For simplicity in generation procedures but without loss of generality, assume that all alternatives have the same number of consequences, N.

4.3. Simulations of the cardinal surrogate numbers

This chapter focuses on the performance of cardinal surrogate weights in probability elicitation. The simulations included 20 different scenarios made up of 3, 6, 9, 12, and 15 alternatives, and for each of those cases, the number of consequences was set to 3, 6, 9, and 12, respectively. Each combination was simulated 10 times, and this was then repeated 10,000 times, totaling 2,000,000 decision problems. The probability vectors for the N DoF model was generated using a standard round-robin random number generator with subsequently normalized numbers, and the probability vectors for the $N-1$ DoF model was generated using an N-variate Dirichlet distribution. The value vectors were generated on a uniform interval but left unscaled, analogous to MCDA studies such as [27]. Compared to alternative value distributions, there was no significant difference in the results.

A subset of the results, using a 50% combination of N DoF and $N-1$ DoF models, is presented in the tables mentioned later. As described earlier, the numbers denote the ratio of the number of times the most preferred alternative according to method μ' coincides with the most preferred alternative obtained from the "true" probabilities to the total number of simulation runs.[8]

The marginal utility of various levels of cardinal expressibility was evaluated by varying the levels of maximum cardinal differences in the simulations. The numbers, say j, in the "Symbols" column denotes the maximum $>$-index, $\max(i)$, of the set of $>_i$ symbols, such that $\max(i) = j$, for $j > 0$. The results are obtained from the ordinal counterparts when $j = 0$. Hence, $j = 1$ implies $\{>_0, >_1\}$, $j = 2$ means $\{>_0, >_1, >_2\}$, and so on. The actual results of the methods, the hit ratios, are given in percentages.[9]

Albeit there is a clear advantage of introducing the possibility of equivalence ($>_0$) between probabilities, the results, in general, indicate diminishing returns with an increase of the maximum $>$-index, in particular, when the number of possible consequences for each alternative is high. For example, at nine or more consequences, cardinal probability elicitation with only $>_0$ and $>_1$ is to prefer for CRC. Also, the cognitive burden on decision-makers tends to increase with the granularity of the scale. Hence, a maximum $>$-index of 2 seems to provide enough expressional power for probability elicitation (**Tables 6–12**).

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Three consequences and three alternatives	0	86.9	86.8	86.7	87.0
	1	88.8	87.7	87.9	88.0
	2	89.3	90.1	89.4	90.3
	3	89.5	91.2	90.2	91.3

Table 6. Comparing the methods using three consequences to each alternative and three alternatives.

[8] Two alternative sets of measurements, not shown in this chapter due to the strong correlation with the hit ratio, exist. One is the number of times to three most preferred alternatives obtained using μ' as elicitation method agrees with the three most preferred alternatives according to the "true" probabilities (i.e., the "podium"). A second is the number of times the overall rank of the alternative-using method μ' agrees with the overall rank based on the "true" probabilities.

[9] The results of the sets of 10 runs yielded a standard deviation of around 0.2–0.3%.

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Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Three consequences and 15 alternatives	0	70.9	69.2	69.1	69.5
	1	73.9	71.2	70.7	71.0
	2	74.6	76.1	74.4	76.2
	3	74.6	77.7	76.5	78.6

Table 7. Three consequences to each alternative and 15 alternatives.

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Six consequences and six alternatives	0	79.4	79.8	78.0	80.8
	1	83.5	80.8	81.0	82.4
	2	84.0	83.9	80.5	85.4
	3	83.8	85.3	79.3	86.4

Table 8. Six consequences to each alternative and six alternatives.

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Six consequences and 12 alternatives	0	75.0	73.8	72.3	75.1
	1	78.6	75.6	75.3	77.2
	2	78.3	78.3	74.1	78.4
	3	77.6	79.6	72.9	80.9

Table 9. Six consequences to each alternative and 12 alternatives.

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Nine consequences and nine alternatives	0	76.7	76.5	72.2	78.3
	1	81.0	77.2	76.8	79.8
	2	80.1	78.7	73.3	81.3
	3	78.5	79.7	70.2	81.6

Table 10. Nine consequences to each alternative and nine alternatives.

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Twelve consequences and six alternatives	0	80.1	80.5	73.2	82.2
	1	83.6	79.9	78.3	82.5
	2	81.9	81.1	73.3	83.5
	3	80.2	81.7	70.0	83.3

Table 11. Twelve consequences to each alternative and six alternatives.

Combined DoF	Symbols	ROC/CRC	RS/CRS	RR/CRR	SR/CSR
Twelve consequences and 12 alternatives	0	74.8	74.4	67.9	76.3
	1	78.5	73.8	72.3	76.8
	2	77.0	75.7	67.3	78.2
	3	74.8	77.2	62.0	78.7

Table 12. Twelve consequences to each alternative and 12 alternatives.

The results show that cardinal methods markedly outperform the ordinal methods. Among the cardinal methods, it is CRC and CSR that provide the best outcomes, but the difference between these lies within this investigation's margin of error.

5. Summary and conclusion

Elicitation methods available today are often either too cognitively demanding and require too much time and effort or unable to use the available information. The aim of this study was to offer decision-makers a set of methods for probability elicitation with a reasonable balance between simplicity and usability on the one hand and correctness and accuracy on the other hand. In particular, we strived to reduce the issues of applicability by loosening the requirements of precise information, while allowing for more details than what ordinal methods can handle. Also, the methods should be relatively robust and applicable to a wide range of decision problems.

By augmenting a set of ordinal elicitation methods, originally developed for weight elicitation within MCDA, with a notion of a difference between adjacent probabilities, we arrived at a collection of cardinal probability elicitation methods. The robustness of the methods was evaluated using a large number of simulated decision problems, where we also accommodated for two different cognitive models, based on the degree of freedom used during the ranking, including a mix of them. The results of the simulations point toward a significant improvement of cardinal methods over purely ordinal ones. In particular, due to the introduction of equality between probabilities. Among the cardinal methods, in particular, CSR and CRC seem to provide the most robust results. CSR generalizes SR from [42] by also taking the cardinal differences of the probabilities into account in a more straightforward way than, for example, [34].

More fine-grained expressions seem to produce diminishing returns when the number of consequences of each alternative becomes high. For alternatives with 12 consequences or less, a cardinal method with the set $\{>_0, >_1, >_2\}$ seems to supply the decision-maker with adequate options for producing quite reliable probability elicitations. For alternatives with more than 12 consequences, the reduced set $\{>_0, >_1\}$ seems to provide a sufficient granularity.

In conclusion, cardinal methods rather than ordinal ones should be preferred for eliciting probabilities when applicable. More specifically, CSR and CRC have been shown to produce surrogates, which outperform those of their competitors. They keep decision-makers from having to provide too much detail, something which has turned out to be difficult for decision-makers in general, while at the same time reducing the risk of neglecting available information.

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Conflict of interest

All authors report no conflicts of interest relevant to this chapter.

Author details

Mats Danielson[1,2], Love Ekenberg[1,2] and Andreas Paulsson[1]*

*Address all correspondence to: apaulsson@dsv.su.se

1 Department of Computer and Systems Sciences, Stockholm University, Kista, Sweden

2 International Institute for Applied Systems Analysis (IIASA), Laxenburg, Austria

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Decision Making is a book where each chapter has been contributed to by a different author(s). The book synthesizes the analytical principles with business practice of Decision Making. Specifically, the book provides an interface between the main disciplines of engineering/technology and the organizational, administrative, and planning abilities of decision making. It is complementary to other sub-disciplines such as economics, finance, marketing, decision and risk analysis, etc.

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