Chapter 2
Multi Criteria Decision Making

Abstract 'Decision Making is the act of choosing between two or more courses of action'. However, it must always be remembered that there may not always be a 'correct' decision among the available choices. There may have been a better choice that had not been considered, or the right information may not have been available at the time. Multiple-criteria evaluation problems consist of a finite number of alternatives, explicitly known in the beginning of the solution process. In Multiple-criteria design problems (multiple objective mathematical programming problems) the alternatives are not explicitly known. An alternative (solution) can be found by solving a mathematical model. The number of alternatives is either infinite or not countable (when some variables are continuous) or typically very large if countable (when all variables are discrete). But both kind of problems are considered as a subclasses of Multi Criteria Decision Making problems. The MCDM problems can also be divided into two major classes with respect to the way the weights of the alternatives are determined: Compensatory and Outranking Decision Making. The example of the former is Analytical hierarchy Process (AHP) and the latter is ELimination and Choice Expressing Reality (ELECTRE). The basic working principle of any MCDM method is same: Selection of Criteria, Selection of Alternatives, Selection of Aggregation Methods and ultimately Selection of Alternatives based on weights or outranking.

Keywords Fuzzy decision making · Analytical hierarchy process · Outranking methods · Decision making in water resources

2.1 Definition

MCDM or MCDA are well-known acronyms for multiple-criteria decision-making and multiple-criteria decision analysis. MCDM is concerned with structuring and solving decision and planning problems involving multiple criteria. The purpose is to support decision makers facing such problems. Typically, there does not exist a

M. Majumder, *Impact of Urbanization on Water Shortage in Face of Climatic Aberrations*, SpringerBriefs in Water Science and Technology,
DOI 10.1007/978-981-4560-73-3_2

unique optimal solution for such problems and it is necessary to use decision maker's preferences to differentiate between solutions.

2.2 Steps of Decision Making

A decision making process involves the following steps to be followed:

1. Identifying the objective/goal of the decision making process
2. Selection of the Criteria/Parameters/Factors/Decider
3. Selection of the Alternatives
4. Selection of the weighing methods to represent importance
5. Method of Aggregation
6. Decision making based on the Aggregation results

2.3 Working Principle

The MCDM process follows a common working principle as described below:

1. **Selection of Criteria**
   Selected criteria must be:

   Coherent with the decision
   Independent of each other
   Represented in same scale
   Measurable
   Not Unrelated with the alternatives

2. **Selection of Alternatives**
   Selected alternatives must be:

   Available
   Comparable
   Real not Ideal
   Practical/Feasible

3. **Selection of the Weighing Methods to Represent Importance**
   The weight determination methods can be either compensatory or outrankable.
   Example of Compensatory Method:

   Analytical Hierarchy Process (AHP), Fuzzy Multi-Criteria Decision Making Process (FDM) etc.

   Example of Out-ranking Method:

   ELimination and Choice Expressing Reality (ELECTRE), Preference Ranking Organization Method for Enrichment of Evaluations (PROMETHUS)

4. **Method of Aggregation**

   Can be a Product
   Can be an Average
   Can be a Function
   The result of this aggregation will actually separate the best alternative from the available options

2.4 Types of MCDM

The MCDM methods can be classified into two groups as explained in the next section.

2.4.1 Compensatory Method

A rational decision-making model in which choices are systematically evaluated on various criteria. Attractive attributes of an alternative can compensate for less attractive ones—a systematic decision-making procedure has to be followed. A compensatory model because a positive score on one attribute can outweigh a negative score on another attribute.

A compensatory decision involves the consumer "trading off" good and bad attributes of a product. For example, a car may have a low price and good gas mileage but slow acceleration. If the price is sufficiently inexpensive and gas efficient, the consumer may then select it over a car with better acceleration that costs more and uses more gas. Occasionally, a decision will involve a non-compensatory strategy. For example, a parent may reject all soft drinks that contain artificial sweeteners. Here, other good features such as taste and low calories cannot overcome this one "non-negotiable" attribute.

The amount of effort a consumer puts into searching depends on a number of factors such as the market (how many competitors are there, and how great are differences between brands expected to be?), product characteristics (how important is this product? How complex is the product? How obvious are indications of quality?), consumer characteristics (how interested is a consumer, generally, in analyzing product characteristics and making the best possible deal?), and situational characteristics (as previously discussed).

2.4.2 Outranking Methods

A rather different approach from any of those discussed so far has been developed in France and has achieved a fair degree of application in some continental

European countries. It depends upon the concept of outranking. The methods that have evolved all use outranking to seek to eliminate alternatives that are, in a particular sense, dominated'. However, unlike the straightforward dominance idea outlined in Sect. 4.5, dominance within the outranking frame of reference uses weights to give more influence to some criteria than others. One option is said to outrank another if it outperforms the other on enough criteria of sufficient importance (as reflected by the sum of the criteria weights) and is not outperformed by the other option in the sense of recording a significantly inferior performance on any one criterion. All options are then assessed in terms of the extent to which they exhibit sufficient outranking with respect to the full set of options being considered as measured against a pair of threshold parameters.

An interesting feature of outranking methods is that it possible, under certain conditions, for two options to be classified as 'incomparable' ('difficult to compare' is probably a better way to express the idea). Incomparability of two options is not the same as indifference between two options and might, for example, be associated with missing information at the time the assessment is made. This is not an unlikely occurrence in many decision making exercises. Building this possibility into the mathematical structure of outranking allows formal analysis of the problem to continue while neither imposing a judgement of indifference which cannot be supported nor dropping the option entirely, simply because information is not to hand. The main concern voiced about the outranking approach is that it is dependent on some rather arbitrary definitions of what precisely constitutes outranking and how the threshold parameters are set and later manipulated by the decision maker.

The outranking concept does, however, indirectly capture some of the political realities of decision making. In particular it downgrades options that perform badly on any one criterion (which might in turn activate strong lobbying from concerned parties and difficulty in implementing the option in question). It can also be an effective tool for exploring how preferences between options come to be formed.

2.5 Examples

AHP and FLDM are two most popular example of Compensatory MCDM which are widely used to solve decision making problems and in various decision support systems worldwide.

2.5.1 Analytical Hierarchal Process (AHP)

AHP has particular application in group decision making, and is used around the world in a wide variety of decision situations, in fields such as government, business, industry, healthcare, and education.

Rather than prescribing a "correct" decision, the AHP helps decision makers find one that best suits their goal and their understanding of the problem. It provides a comprehensive and rational framework for structuring a decision problem, for representing and quantifying its elements, for relating those elements to overall goals, and for evaluating alternative solutions.

Users of the AHP first decompose their decision problem into a hierarchy of more easily comprehended sub-problems, each of which can be analyzed independently. The elements of the hierarchy can relate to any aspect of the decision problem—tangible or intangible, carefully measured or roughly estimated, well or poorly understood—anything at all that applies to the decision at hand.

Once the hierarchy is built, the decision makers systematically evaluate its various elements by comparing them to one another two at a time, with respect to their impact on an element above them in the hierarchy. In making the comparisons, the decision makers can use concrete data about the elements, but they typically use their judgments about the elements' relative meaning and importance. It is the essence of the AHP that human judgments, and not just the underlying information, can be used in performing the evaluations.

The AHP converts these evaluations to numerical values that can be processed and compared over the entire range of the problem. A numerical weight or priority is derived for each element of the hierarchy, allowing diverse and often incommensurable elements to be compared to one another in a rational and consistent way. This capability distinguishes the AHP from other decision making techniques.

In the final step of the process, numerical priorities are calculated for each of the decision alternatives. These numbers represent the alternatives' relative ability to achieve the decision goal, so they allow a straightforward consideration of the various courses of action.

2.5.1.1 Inventor

The analytic hierarchy process (AHP) is a structured technique for organizing and analyzing complex decisions, based on mathematics and psychology. It was developed by Thomas L. Saaty in the 1970s and has been extensively studied and refined since then.

2.5.1.2 Working Principle

The first step in the analytic hierarchy process is to model the problem as a hierarchy. In doing this, participants explore the aspects of the problem at levels from general to detailed, then express it in the multileveled way that the AHP requires. As they work to build the hierarchy, they increase their understanding of the problem, of its context, and of each other's thoughts and feelings about both.

Hierarchies Defined

A hierarchy is a stratified system of ranking and organizing people, things, ideas, etc., where each element of the system, except for the top one, is subordinate to one or more other elements. Though the concept of hierarchy is easily grasped intuitively, it can also be described mathematically. Diagrams of hierarchies are often shaped roughly like pyramids, but other than having a single element at the top, there is nothing necessarily pyramid-shaped about a hierarchy.

Human organizations are often structured as hierarchies, where the hierarchical system is used for assigning responsibilities, exercising leadership, and facilitating communication. Familiar hierarchies of "things" include a desktop computer's tower unit at the "top", with its subordinate monitor, keyboard, and mouse "below."

In the world of ideas, we use hierarchies to help us acquire detailed knowledge of complex reality: we structure the reality into its constituent parts, and these in turn into their own constituent parts, proceeding down the hierarchy as many levels as we care to. At each step, we focus on understanding a single component of the whole, temporarily disregarding the other components at this and all other levels. As we go through this process, we increase our global understanding of whatever complex reality we are studying.

Think of the hierarchy that medical students use while learning anatomy—they separately consider the musculoskeletal system (including parts and subparts like the hand and its constituent muscles and bones), the circulatory system (and its many levels and branches), the nervous system (and its numerous components and subsystems), etc., until they've covered all the systems and the important subdivisions of each. Advanced students continue the subdivision all the way to the level of the cell or molecule. In the end, the students understand the "big picture" and a considerable number of its details. Not only that, but they understand the relation of the individual parts to the whole. By working hierarchically, they've gained a comprehensive understanding of anatomy.

Similarly, when we approach a complex decision problem, we can use a hierarchy to integrate large amounts of information into our understanding of the situation. As we build this information structure, we form a better and better picture of the problem as a whole.

2.5.1.3 Application

The AHP method of decision making has been applied in water resources planning and management (Hajkowicz and Collins 2007), wetland management (Gamini 2004), selection of desalination plants (Hajeeh and Al-Othman 2005), agriculture management (Giri and Nejadhashemi 2014) etc. Among them the application of AHP in evaluation of rural water supply system, desalination plants and building resilience to water scarcity is discussed in more detail to show the way AHP method can be applied to solve decision making problems in water resources.

1. Resilience in water scarcity
2. Evaluation of desalination plants
3. Evaluation of Rural Water Supply

Resilience in Water Scarcity

Agricultural water management needs to evolve in view of increased water scarcity, especially when farming and natural protected areas are closely linked. In the study site of Doñana (southern Spain), water is shared by rice producers and a world heritage biodiversity ecosystem. Our aim is to contribute to defining adaptation strategies that may build resilience to increasing water scarcity and minimize water conflicts among agricultural and natural systems. The analytical framework links a participatory process with quantitative methods to prioritize the adaptation options. Bottom-up proposed adaptation measures are evaluated by a multi-criteria analysis (MCA) that includes both socioeconomic criteria and criteria of the ecosystem services affected by the adaptation options.

Criteria weights are estimated by three different methods—analytic hierarchy process, Likert scale and equal weights—that are then compared. Finally, scores from an MCA are input into an optimization model used to determine the optimal land-use distribution in order to maximize utility and land-use diversification according to different scenarios of funds and water availability. While our results show a spectrum of perceptions of priorities among stakeholders, there is one overriding theme that is to define a way to restore part of the rice fields to natural wetlands. These results hold true under the current climate scenario and even more so under an increased water scarcity scenario (de Jalón et al. 2014).

Evaluation of Desalination Plants

Seawater desalination plants have been utilized to supply fresh water to the Gulf Cooperation Council countries since the early 1950s. In spite of the fact that there are several types of desalination technology that can be used more efficiently and economically, one type of desalination technology, namely multi-stage flash, has been used extensively in the region. This work is an attempt to identify the most suitable technology for the specific use by soliciting expert opinions. Based on several relevant factors, the analytical hierarchy process (AHP) was utilized to select the most appropriate technology for seawater desalination. The selection process in this study was limited to seawater feed and seven factors and four commercially available desalination technologies, i.e., multi-stage flash, multi-effect desalination, vapor compression and reverse osmosis (Hajeeh and Al-Othman 2005).

Evaluation of Rural Water Supply

Some rural water supply (RWS) schemes were constructed in 2002 in the Dhule district of Maharashtra State in India as part of pilot projects launched in 68 districts throughout the country with financial assistance from the Government of India. The present research is derived from an investigation conducted on 11 such RWS schemes constructed during the period of 2002–2005 and aims to establish a composite sustainable management index for assessing long-term sustainability in the context of the level of service and evaluating the current performance level of piped-water supply schemes. The identification of factors influencing sustainable management is a prerequisite for developing a composite index. Various investigators have worked on the sustainability of RWS systems worldwide considering different sets of factors and subfactors. In this research, a set of five factors and 25 subfactors is considered. Two factors, though being a part of functional sustainability, are excluded in building the index; however, they are used to validate the results. The analytical hierarchy process is used for the development of metrics in decision making, i.e., for establishing the weight of factors and subfactors. The proposed model enables RWS utilities to identify the key sustainable management factors and provides a framework for aggregating various factors and subfactors into a composite sustainable management index. The outcome may also be used to identify the factors/subfactors that have potential for improvement and thus be helpful in finalizing the strategies for enhancing the functional sustainability of the system. The results demonstrate that nine subfactors out of the 25 dominate in all 11 RWS utilities studied. The RWS utilities are classified on the basis of their performance as high, moderate, or low in sustainability. The derived factors' sustainability index may be useful for decision makers to discover the tradeoffs between them. The derived index may be a rational and transparent basis for recommending postconstruction support for a rural water utility. The limitations of the presented research are the comprehensiveness and effectiveness of the data considered, being slightly biased to the accessibility of information, in the absence of a more rational data-recording system (Dwivedi and Bhadauria 2014).

2.5.2 Fuzzy Logic Decision Making (FLDM)

Fuzzy logic is a form of many-valued logic; it deals with reasoning that is approximate rather than fixed and exact. Compared to traditional binary sets (where variables may take on true or false values), fuzzy logic variables may have a truth value that ranges in degree between 0 and 1.

Fuzzy logic has been extended to handle the concept of partial truth, where the truth value may range between completely true and completely false. Furthermore, when linguistic variables are used, these degrees may be managed by specific functions. Irrationality can be described in terms of what is known as the fuzzjective.

2.5.2.1 Inventor

The term "fuzzy logic" was introduced with the 1965 proposal of fuzzy set theory by Lotfi A. Zadeh. Fuzzy logic has been applied to many fields, from control theory to artificial intelligence. Fuzzy logics had, however, been studied since the 1920s, as infinite-valued logics—notably by Łukasiewicz and Tarski (Pelletier 2000).

2.5.2.2 Working Principle (Calvin 2011)

The logic with which people decide can be represented by the following algorithm:

$$\begin{aligned}&\textbf{If}\ \ \textbf{P},\ \textbf{then}\ \textbf{Q}.\\&\textbf{P}.\\&\textbf{Therefore},\ \textbf{Q}.\end{aligned}$$

The reasoning is strict as Q can exist only if P exists. This type of conditions are crisp and in many cases such rigid conditions does not represent the true situation. This problem is solved by Fuzzy Logic. Where Q can mostly exist if P is mostly valid.

$$\begin{aligned}&\textbf{If}\ \textbf{P},\ \textbf{then}\ \textbf{Q}.\\&\boldsymbol{mostly}\ \textbf{P}.\\&\textbf{Therefore},\ \boldsymbol{mostly}\ \textbf{Q}.\end{aligned}$$

where P and Q are now fuzzy numbers. The reasoning above requires a set of rules to be defined. These rules are linguistic rules to relate different fuzzy sets and numbers. The general form of these rules are: "if x is A then y is B," where x and y are fuzzy numbers in the fuzzy sets A and B respectively.

The linguistic rules are used to find the relationship between input and output whose relationship is fuzzy. The actual answer is given by method of aggregation and inference as demonstrated by Mamdani, Larsen, Takagi-Sugeno-Kang, and Tsukamoto and explained with the below statement:

$$\text{If}\ \ x\ \text{ is }\ \mathbf{A}\boldsymbol{i}\quad\text{then}\quad y\ \text{ is }\ \mathbf{B}\boldsymbol{i},\ \ i = 1, 2, \ldots, n$$

Defuzz method	Result
Centroid	7.319
Bisector	7.230
Largest of max	9
Smallest of max	6
Middle of max	7.5

2.5.2.3 Application

Almost any control system can be replaced with a fuzzy logic based control system. This may be overkill in many places however it simplifies the design of many more complicated cases. So fuzzy logic is not the answer to everything, it must be used when appropriate to provide better control. If a simple closed loop or PID controller works fine then there is no need for a fuzzy controller. There are many cases when tuning a PID controller or designing a control system for a complicated system is overwhelming, this is where fuzzy logic gets its chance to shine.

One of the most famous applications of fuzzy logic is that of the Sendai Subway system in Sendai, Japan. This control of the Nanboku line, developed by Hitachi, used a fuzzy controller to run the train all day long. This made the line one of the smoothest running subway systems in the world and increased efficiency as well as stopping time. This is also an example of the earlier acceptance of fuzzy logic in the east since the subway went into operation in 1988.

The most tangible applications of fuzzy logic control have appeared commercial appliances. Specifically, but not limited to heating ventilation and air conditioning (HVAC) systems. These systems use fuzzy logic thermostats to control the heating and cooling, this saves energy by making the system more efficient. It also keeps the temperature more steady than a traditional thermostat.

Another significant area of application of fuzzy control is in industrial automation. Fuzzy logic based PLCs have been developed by companies like Moeller. These PLCs, as well as other implementations of fuzzy logic, can be used to control any number of industrial processes.

For some examples see: http://www.fuzzytech.com/e/e_a_plc.html.

Fuzzy logic also finds applications in many other systems. For example, the MASSIVE 3D animation system for generating crowds uses fuzzy logic for artificial intelligence.

This program was used extensively in the making of the Lord of the Rings trilogy as well as The Lion, The Witch and the Wardrobe films.

As a final example of fuzzy logic, it can be used in areas other than simply control. Fuzzy logic can be used in any decision making process such as signal processing or data analysis. An example of this is a fuzzy logic system that analyzes a power system and diagnoses any harmonic disturbance issues. The system analyzes the fundamental voltage, as well as third, fifth and seventh harmonics as well as the temperature to determine if there is cause for concern in the operation of the system.

Fuzzy Logic decision Making has been widely used in many areas of science and engineering. Three example application is discussed from the following fields of application:

- Water Quality
- Urban Water Management
- Reservoir Operation

Water Quality

Agharaabi et al. (2014) presents the use of two multi-criteria decision-making (MCDM) frameworks based on hierarchical fuzzy inference engines for the purpose of assessing drinking water quality in distribution networks. Incommensurable and uncertain water quality parameters (WQPs) at various sampling locations of the water distribution network (WDN) are monitored. Two classes of WQPs including microbial and physicochemical parameters are considered. Partial, incomplete and subjective information on WQPs introduce uncertainty to the water quality assessment process. Likewise, conflicting WQPs result in a partially reliable assessment of the quality associated with drinking water. The proposed methodology is based on two hierarchical inference engines tuned using historical data on WQPs in the WDN and expert knowledge. Each inference engine acts as a decision-making agent specialized in assessing one aspect of quality associated with drinking water. The MCDM frameworks were developed to assess the microbial and physicochemical aspects of water quality assessment. The MCDM frameworks are based on either fuzzy evidential or fuzzy rule-based inference. Both frameworks can interpret and communicate the relative quality associated with drinking water, while the second is superior in capturing the nonlinear relationships between the WQPs and estimated water quality. More comprehensive rules will have to be generated prior to reliable water quality assessment in real-case situations. The examples presented here serve to demonstrate the proposed frameworks. Both frameworks were tested through historical data available for a WDN, and a comparison was made based on their performance in assessing levels of water quality at various sampling locations of the network.

Urban Water Management

Engineering is currently expanding its conceptual boundaries by accepting the challenge of interdisciplinarity, while often adopting social and biological concepts in developing tools (e.g. evolutionary optimization or interactive autonomous agents) or even world views (e.g. co-evolution, resilience, adaptation). The emerging socio-technical knowledge domain is still very much restricted by partial knowledge associated with the lack of long-term transdisciplinary research effort and the unavailability of robust, integrated tools able to cover both the technical and the socio-economic domains and to act as ‘thinking platforms’ for long-term scenario planning and strategic decision making under (high-order) uncertainties. Here we present an example of a toolkit that attempts to bridge this gap focusing on urban water (UW) systems and their management. The toolkit consists of three tools: the UW Optioneering Tool (UWOT); the UW Agent Based Modelling Platform (UWABM); and the UW System Dynamic Environment (UWSDE). The tools are briefly presented and discussed, focusing on interactions and data flows between them and their typical results are illustrated through a case study example. A further tool (a Cellular Automata Based Urban Growth Model) is currently under development and an early coupling with the other tools is also discussed. It is argued that this type of extended model fusion, beyond what has traditionally been thought of as 'integrated modelling' in the engineering domain is a new frontier in the understanding of environmental systems and presents a promising, emerging field in modelling interactions between our societies and cities, and our environment (Christos 2014).

Reservoir Operation

Imprecision is often involved in reservoir-systems operation, as these systems are too complex to be defined in precise terms. Fuzzy programming has an essential role in fuzzy modeling, which can formulate uncertainty in the actual environment. In this study, a multipurpose, single-reservoir operation model is developed by assuming triangular fuzzy-number distribution of the parameters. The applicability of the model is demonstrated through the case study of the Jayakwadi reservoir stage II, Maharashtra State, India. The reservoir-operation model considers two objectives: maximization of the releases for irrigation and maximization of the releases for hydropower generation. The model is solved for a vector of a triangular fuzzy-number by giving a priority to each objective. By individual optimization, the fuzzy optimal solution is obtained for each objective in the form of a triangular fuzzy-number distribution. This solution is defuzzified to obtain the crisp values, which are further used to develop a fuzzy-compromised model. The compromised model is solved for the maximization of the degree of satisfaction (λ) by simultaneously optimizing both of the objectives. The degree of satisfaction (λ) achieved is 0.67, and the corresponding values for irrigation releases and hydropower releases are equal to the 388.54 and 195.19 Mm^3, respectively (Kamodkar and Regulwar 2014).

2.6 Limitations

The major limitation of the AHP and FLDM is each of the method accept either qualitative or quantitative ratings while comparing the parameters with each other.

References

Aghaarabi E et al (2014) Comparative study of fuzzy evidential reasoning and fuzzy rule-based approaches: an illustration for water quality assessment in distribution networks. Stoch Env Res Risk Assess 28(3):655–679

Calvin (2011) Fuzzy logic decision making. https://www.calvin.edu/~pribeiro/othrlnks/Fuzzy/fuzzydecisions.htm

Christos M (2014) Thinking platforms for smarter urban water systems: fusing technical and socio-economic models and tools. Geol Soc London Spec Publ 408:SP408-4

de Jalón SG et al (2014) Building resilience to water scarcity in southern Spain: a case study of rice farming in Doñana protected wetlands. Reg Environ Change 14(3):1229–1242
Dwivedi A, Bhadauria S (2014) Composite sustainable management index for rural water supply systems using the analytical hierarchy process. J Perform Constr Facil 28(3):608–617
Gamini H (2004) Incorporating community objectives in improved wetland management: the use of the analytic hierarchy process. J Environ Manage 70(3):263–273
Giri S, Nejadhashemi AP (2014) Application of analytical hierarchy process for effective selection of agricultural best management practices. J Environ Manage 132:165–177
Hajeeh M, Al-Othman A (2005) Application of the analytical hierarchy process in the selection of desalination plants. Desalination 174(1):97–108
Hajkowicz S, Collins K (2007) A review of multiple criteria analysis for water resource planning and management. Water Resour Manage 21(9):1553–1566
Herath G (2004) Incorporating community objectives in improved wetland management: the use of the analytic hierarchy process. J Environ Manage 70(3):263–273
Kamodkar RU, Regulwar DG (2014) Optimal multiobjective reservoir operation with fuzzy decision variables and resources: a compromise approach. J Hydro Environ Res 8:428–440
Pelletier FJ (2000) Review of metamathematics of fuzzy logics in the bulletin of symbolic logic. JSTOR 421060 6(3):342–346