

Multi-Criteria Decision-Making Selection Model with Application to Chemical Engineering Management Decisions

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Abstract—Chemical industry project management involves complex decision making situations that require discerning abilities and methods to make sound decisions. Project managers are faced with decision environments and problems in projects that are complex. In this work, case study is Research and Development (R&D) project selection. R&D is an ongoing process for forward thinking technology-based chemical industries. R&D project selection is an important task for organizations with R&D project management. It is a multi-criteria problem which includes both tangible and intangible factors. The ability to make sound decisions is very important to success of R&D projects. Multiple-criteria decision making (MCDM) approaches are major parts of decision theory and analysis. This paper presents all of MCDM approaches for use in R&D project selection. It is hoped that this work will provide a ready reference on MCDM and this will encourage the application of the MCDM by chemical engineering management.

Keywords—Chemical Engineering, R&D Project, MCDM, Selection.

I. INTRODUCTION

CHEMICAL engineering is an extended branch of engineering and the role of management in its decision making is irrefragable. One of the most important parts of each chemical industry is Research and Development (R&D).

In other word, R&D is an ongoing process for forward thinking technology-based companies. Development of

existing products is advisable to keep ahead of advances that competitors may be making. Further, when a potential customer approaches a firm outlining its requirements for a product, R&D may be required to fulfill the request [1]. R&D management has several common features with strategic management. It actively aims at utilizing possibilities supplied by new technologies and innovations in business operations. Similarly to strategic management, R&D management also has to define objectives for the R&D operations [2]. R&D project selection is an organizational decision-making task commonly found in organizations like government funding agencies, universities, research institutes, and technology-intensive companies. It is a complicated and challenging task to organizations with the following reasons: (1) it is very difficult to predict the future success and impacts of the candidate projects; (2) it is a multi-stage multi-person decision making process involving a group of decision makers (e.g. external reviewers and panel experts). Thus, it can be very hard to manage the decision making process, especially when the decision makers have heterogeneous decision-making strategies [3]. Meade and Presley (2002) revealed four major themes for R&D project selection: (1) the need to relate selection criteria to corporate strategies. (2) The need to consider qualitative benefits and risks of proposed projects. (3) The need to reconcile and integrate the needs and desires of different stakeholders. And (4) the need to consider the multi-stage and group decision processes. Limitations of existing R&D project selection models are: (1) Inadequate treatment of multiple, often interrelated, evaluation criteria. (2) An inability to handle non-monetary aspects and inadequate treatment of interrelationships among projects. (3) No explicit recognition and incorporation of the experience and knowledge of R&D managers. And (4) perceptions by R&D managers that these models are difficult to understand and use. Most research on R&D project selection concentrates on the private sector while little research has been done on government-sponsored R&D projects [4]. Totally, Projects today seek much wider business benefits than just the reaching of immediate project goals [5]. Performance of a project has always been an important issue in the construction industry. There have been many past studies on project success and factors affecting project success [6] much of the work conducted in organizations occurs as projects [7]. Various strategy-related decision criteria are being used, to

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ensure the right focus for projects, and to increase probability for business benefits. Traditional product development decision-making literature largely focuses on phase (gate) related decision making and neglects decision making on changes between the gates. Continuous, nongate-specific change decision schemes are important, as they suggest flexibility in projects as a response to dynamic business environment. Large numbers of proposed R&D projects may potentially be pursued when considering this R&D philosophy. The ability to consistently select the best projects to fund is therefore vitally important to firms. Extensive academic research has been conducted over the past 35 years or so to produce methods to improve the R&D project selection processes [1]. In the past four decades, a number of decision models and methods (e.g. Mathematical Programming and Optimization, Decision Analysis, Economic Models, and Interactive Method) have been developed to help organizations make better decisions in R&D project selection [8]. Many project selection models have been developed over the years taking into account projects' financial aspects, risk considerations, or ranking projects by using scoring models. Research has shown that the most successful approach is to select projects by considering financial, risk and project ranking, using a so-called hybrid selection model. Despite the fact that many models for R&D project selection have been developed by academics, very few seem to have been tested in companies. Similarly, relatively little research has been published on the project selection techniques that are actually used in companies. When an organization is tasked with deciding which research projects to proceed with, and which projects to reject, the selection process is often inconsistent [1]. Decision Analysis (DA) broadly refers to methods that involve quantified evaluations of possible alternative courses of action. The evaluations often include an assessment of probabilities and preference elicitation using direct or indirect utility functions. There is some debate about whether specific techniques belong in the decision analysis domain [9]. Multiple criteria decision making is an analytic method to evaluate the advantages and disadvantages of alternatives based on multiple criteria. MCDM problems can be broadly classified into two categories: multiple objective programming and multiple criteria evaluation. MCDM approaches are major parts of decision theory and analysis. They seek to take explicit account of more than one criterion in supporting the decision process [10]. MCDM methods have shown to be popular and widely used by researchers. Essentially, each one reflects a different approach to solving a given discrete MCDM problem of choosing the best among several preselected alternatives [11]. The aim of MCDM methods is to help decision-makers learn about the problems they face, to learn about their own and other parties' personal value systems, to learn about organizational values and objectives, and through exploring these in the context of the problem to guide them in identifying a preferred course of action. In other words, MCDM is useful in circumstances which necessitate the consideration of different courses of action, which can not be evaluated by the measurement of a simple, single dimension. Hwang and Yoon published a comprehensive survey of multiple attribute decision making methods and

applications. Two types of the problems that are common in the project management that best fit MCDM models are evaluation problems and design problems [12]. The evaluation problem is concerned with the evaluation of, and possible choice between, discretely defined alternatives. The design problem is concerned with the identification of a preferred alternative from a potentially infinite set of alternatives implicitly defined by a set of constraints [13]. Zhou et al (2006) shall classify DA methods into the three main groups as shown in Figure 1: single objective decisionmaking (SODM) methods, MCDM methods, and decision support systems (DSS). They show that MCDM methods are the most commonly used DA methods. Specifically, they show that AHP (18%) is the most popular method, followed by MAUT (17%), MODM (14%) and DT (14%).

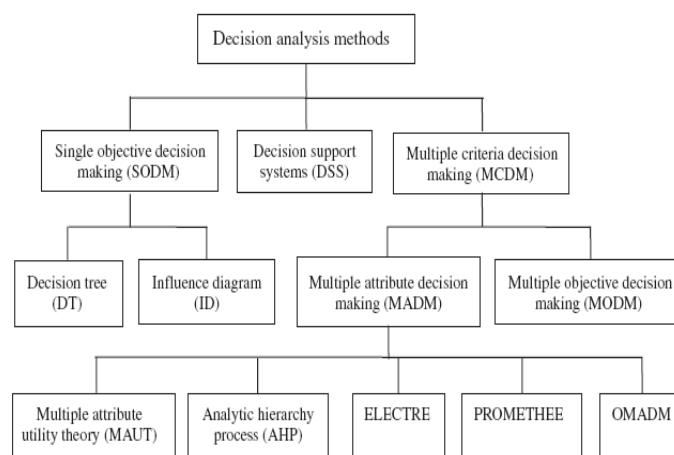


Fig. 1 Classification of decision analysis methods

MCDM allows decision makers to choose or rank alternatives on the basis of an evaluation according to several criteria. Decisions are made based on trade-offs or compromises among a number of criteria that are in conflict with each other. Multiple objective decision making (MODM) and multiple attribute decision making (MADM) are the two main branches of MCDM. MODM methods are multiple objective mathematical programming models in which a set of conflicting objectives is optimized and subjected to a set of mathematically defined constraints. The purpose is to choose the "best" among all the alternatives. A special case of MODM is the multiple objective linear programming (MOLP) where the objective functions and constraints are linear functions. MADM refers to making preference decisions by evaluating and prioritizing all the alternatives that are usually characterized by multiple conflicting attributes. Fig. 1 shows the more popular MADM methods in E&E studies. Multiple attribute utility theory (MAUT) allows decision makers to consider their preferences in the form of multiple attribute utility functions. A special case of MAUT is multiple attribute value theory (MAVT) where there is no uncertainty in the consequences of the alternatives. The analytic hierarchy process (AHP) is a methodology consisting of structuring, measurement and synthesis, which can help decision makers to cope with complex situations. The elimination and choice

translating reality methods, including ELECTRE I, II, III and IV methods, are a family of outranking methods. The preference ranking organization methods for enrichment evaluation (PROMETHEE) are also a class of outranking methods. Other multiple attribute decision making (OMADM) methods such as conjunctive and disjunctive methods, TOPSIS are also popular in practice [14]. However, they have not been as widely adopted in E&E modeling and as such are lumped together as OMADM. According to Zhou et al (2006) classified DA methods and their explanation most commonly method used, in this paper we described these different methods wildly, as follows.

A. Analytical Hierarchy Process (AHP)

Analytic Hierarchy Process (AHP) is one of the most popular and powerful methods for group decision making used in project selection and AHP is a multi-criteria decision-making approach that simplifies complex, ill-structured problems by arranging the decision factors in a hierarchical structure. The AHP is a theory of measurement for dealing with quantifiable and intangible criteria that has been applied to numerous areas, such as decision theory and conflict resolution [15]. Project evaluation is usually a team effort, and the AHP is one available method for forming a systematic framework for group interaction and group decision-making [16]. Dyer and Forman [17] describe the advantages of AHP in a group setting as follows: (1) both tangibles and intangibles, individual values and shared values can be included in an AHP-based group decision process; (2) the discussion in a group can be focused on objectives rather than alternatives; (3) the discussion can be structured so that every factor relevant to the discussion is considered in turn; and (4) in a structured analysis, the discussion continues until all relevant information from each individual member in a group has been considered and a consensus choice of the decision alternative is achieved. A detailed discussion on conducting AHP-based group decision-making sessions including suggestions for assembling the group, constructing the hierarchy, getting the group to agree, inequalities of power, concealed or distorted preferences, and implementing the results can be found in [18,19]. For problems with using AHP in group decisionmaking, see [20]. AHP method require the pre-selection of a countable number of alternatives and the use of a countable number of quantifiable (conflicting and noncommensurable) performance attributes (criteria). The attributes (criteria) may indicate costs and benefits to a DM. A larger outcome always means greater preference for a benefit or less preference for a cost criterion. After inter- and intra-comparison of the alternatives with respect to a given set of performance attributes (criteria), implicit/explicit trade-offs are established and used to rank the alternatives [21]. The AHP method is selected for its specificity, which offers a certain freedom to a DM to express his preferences for particular attributes (criteria) by using the original AHP measurement scale. The AHP method does not require such explicit quantification of attributes (criteria), but it needs specific hierarchical structuring of the MCDM problem. The method itself then generates the weights of the criteria by using the AHP measurement scale according to a specified

procedure. Under such circumstances, a comparison of the results from such different methods applied to the same problem appears to be very interesting and challenging from both academic and practical perspectives. In the next subsections, the basic structures of three MCDM methods and the procedures for assigning weight to the attributes (criteria) are described [11].

Saaty [22, 23 and 24] developed the following steps for applying AHP:

1. Define the problem and determine its goal,
2. Structure the hierarchy with the decision-maker's objective at the top with the intermediate levels capturing criteria on which subsequent levels depend and the bottom level containing the alternatives, and
3. Construct a set of $n \times n$ pair-wise comparison matrices for each of the lower levels with one matrix for each element in the level immediately above. The pairwise comparisons are made using the relative measurement scale in Table I [25, 26 and 27]. The pair-wise comparisons capture a decision maker's perception of which element dominates the other.

TABLE I
PAIR-WISE COMPARISON SCALE FOR AHP PREFERENCE

Numerical rating	Verbal judgments of preferences
9	Extremely preferred
8	Very strongly to extremely
7	Very strongly preferred
6	Strongly to Very strongly
5	Strongly preferred
4	Moderately to strongly
3	Moderately preferred
2	Equally to moderately
1	Equally preferred

4. There are $n(n-1)/2$ judgments required to develop the set of matrices in step 3. Reciprocals are automatically assigned in each pair-wise comparison.
5. The hierarchy synthesis function is used to weight the eigenvectors by the weights of the criteria and the sum is taken over all weighted eigenvector entries corresponding to those in the next lower level of the hierarchy.
6. After all the pair-wise comparisons are completed, the consistency of the comparisons is assessed by using the eigenvalue, λ , to calculate a consistency index, CI:

$$CI = (\lambda - n) / (n - 1) \quad (1)$$

where n is the matrix size. Judgment consistency can be checked by taking the consistency ratio (CR) of CI with the appropriate value in Table II. Saaty [1980] suggests that the CR is acceptable if it does not exceed 0.10. If the CR is greater than 0.10, the judgment matrix should be considered inconsistent. To obtain a consistent matrix, the judgments should be reviewed and repeated.

7. Steps 3-6 are performed for all levels in the hierarchy [13].

1.2. Group AHP Method

While AHP can be used to capture the priorities of individual decision participants, it is necessary to combine these individual assessments into a consensus. To aggregate individual AHP judgments into a group decision, there are two perspectives.

1. 2.1. Aggregation of Individual Judgment

In this view, a group decision matrix is constructed from the unique matrix of each decision participant. An element of this

TABLE II
AVERAGE RANDOM CONSISTENCY

Size of Matrix	1	2	3	4	5	6	7	8	9	10
Random Consistency	0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49

matrix (a_{ij}^G) is calculated using a geometric average of the elements from each unique matrix,

$$a_{ij}^G = \left\{ \prod_{K=1}^n (a_{ijk})^{\beta_k} \right\}^{\frac{1}{\sum \beta_k}} = \left\{ \prod_{K=1}^n (a_{ijk})^{\beta_k} \right\}$$

$$, i, j = 1, \dots, m, K = 1, \dots, n \quad (2)$$

Where β_k and a_{ijk} are the importance and efficiency of the K decision and are elements of the K matrix, respectively [28].

1. 2.2. Aggregation of Individual Priorities (AIP):

In this approach, the order of the decision weights for each decision alternative for the K decision (W_i^k), $K=1 \dots n$, where, n is the number of decision makers, is calculated and a group decision weight (W_i^G) for the alternative is constructed:

$$W_i^G = (W_i^G) ; W_i^G = \prod_{K=1}^n (W_i^K)^{\beta_k} \quad i = 1, \dots, m \quad (3)$$

Where β_k indicates amount and importance of effectiveness of K decision and W_i^G matrix indicate aggregation weight of a single judgment in respect to each alternative. In both approaches, each individual judgment affects the final judgment β_k . So that:

$$\sum_{K=1}^n \beta_k = 1 \quad (4)$$

After aggregating the individual judgments, matrices with the same dimensions as the unique individual matrices are constructed in which the local and final weights as well as the inconsistency of each matrix and total inconsistency are calculated with the same basic AHP method [28].

B. Multiple Attribute Utility (value) Theory(MAU(V)T)

MAUT, developed by Keeney and Raiffa, attempts to maximize a decision maker's utility or value (preference) which is represented by a function that maps an object measured on an absolute scale into the decision maker's utility or value relation. It is based on the following fundamental axiom: any decision maker attempts unconsciously to maximize a real valued function $U=U(g_1, g_2, \dots, g_n)$,

aggregating the criteria g_1, g_2, \dots, g_n , that is, all the different points of view which are taken into account. The role of the researcher is to try to estimate that function by asking the decision maker some well-chosen questions. Utility independence is one of central concepts in MAUT and various utility-independence conditions imply specific forms of utility functions. However, only the additive and multiplicative forms are generally used in practice. The additive utility function can be represented as:

$$u(x_1, \dots, x_m) = k_1 u_1(x_1) + \dots + k_m u_m(x_m) \quad (5)$$

where $u(x_1, \dots, x_m)$ is on a scale from 0 to 1, the component utility function $u_i(x_i)$ are on a scale from 0 to 1 and the scaling constants k_i are positive and sum to one. The multiplicative Form is given as:

$$1+k u(x_1, \dots, x_m) = \prod_{i=1}^m [1+k k_i u_i(x_i)] \quad (6)$$

where $u(x_1, \dots, x_m)$ is on a scale from 0 to 1, the component utility function $u_i(x_i)$ are on a scale from 0 to 1. However, the scaling constant k_i may be greater or less than one and the constant k is chosen to satisfy the following equation:

$$1+k = \prod_{i=1}^m [1+k k_i] \quad (7)$$

Procedure in this method as follows;

- step1. Identify relevant characteristic (attributes)
- Step2. Assign quantifiable variables to each of the attributes and specify their restrictions.
- Step3. Select and construct utility functions for the individual attributes.
- Step4. Synthesize the individual utility functions into a single additive or multiplicative utility function.
- Step 5. Evaluate the alternatives using the function obtained in the fourth step.

The primary advantage of MAUT is that the problem becomes a single objective problem once the utility function has been assessed correctly, thus ensuring achievement of the best-compromise solution [29].

C. The Elimination and Choice Translating reality (ELECTRE)

This method is capable of handling discrete criteria of both quantitative and qualitative in nature and provides complete ordering of the alternatives. The problem is to be so formulated that it chooses alternatives that are preferred over most of the criteria and that do not cause an unacceptable level of discontent for any of the criteria. The concordance, discordance indices and threshold values are used in this technique. Based on these indices, graphs for strong and weak relationships are developed. These graphs are used in an iterative procedure to obtain the ranking of alternatives. This

index is defined in the range (0–1), provides a judgment on degree of credibility of each outranking relation and represents a test to verify the performance of each alternative. The index of global concordance C_{ik} represents the amount of evidence to support the concordance among all criteria, under the hypothesis that A_i outranks A_k . It is defined as follows.

$$C_{ik} = \frac{\sum_{j=1}^m W_j C_j(A_i A_k)}{\sum_{j=1}^m W_j} \quad (8)$$

where W_j is the weight associated with j^{th} criteria. Finally, the ELECTRE method yields a whole system of binary outranking relations between the alternatives. Because the system is not necessarily complete, the ELECTRE method is sometimes unable to identify the preferred alternative. It only produces a core of leading alternatives. This method has a clearer view of alternatives by eliminating less favorable ones, especially convenient while encountering a few criteria with a large number of alternatives in a decision making problem [10].

D. Preference Ranking organization Method for Enrichment Evaluation (POMETHEE)

This method uses the outranking principle to rank the alternatives, combined with the ease of use and decreased complexity. It performs a pair-wise comparison of alternatives in order to rank them with respect to a number of criteria. Brans et al.(1986) have offered six generalized criteria functions for reference namely, usual criterion, quasi criterion, criterion with linear preference, level criterion, criterion with linear preference and indifference area, and Gaussian criterion. The method uses preference function $p_j(a, b)$ which is a function of the difference d_j between two alternatives for any criterion j , i. e. $d_j = f(a, j) - f(b, j)$ where $f(a, j)$ and $f(b, j)$ are values of two alternatives a and b for criterion j . The indifference and preference thresholds q' and p' are also defined depending upon the type of criterion function. Two alternatives are indifferent for criterion j as long as d_j does not exceed the indifference threshold q' . If d_j becomes greater than p' , there is a strict preference. Multi-criteria preference index, $\pi(a, b)$ weighted average of the preference functions $p_j(a, b)$ for all the criteria is defined as :

$$\pi(a, b) = \frac{\sum_{j=1}^J w_j p_j(a, b)}{\sum_{j=1}^J w_j} \quad (9)$$

$$\phi^+(a) = \sum_A \pi(a, b) \quad (10)$$

$$\phi^-(a) = \sum_A \pi(b, a) \quad (11)$$

$$\phi(a) = \phi^+(a) - \phi^-(a) \quad (12)$$

where W_j is the weight assigned to the criterion j ; $\phi^+(a)$ is the outranking index of a in the alternative set A ; $\phi^-(a)$ is the outranked index of a in the alternative set A ; $\phi(a)$ is the net ranking of a in the alternative set A . The value having maximum $\phi(a)$ is considered as the best.

a outranks b if $\phi(a) > \phi(b)$, a is indifferent to b if $\phi(a) = \phi(b)$ [10].

E. The Technique for Order Preference by Similarity to Ideal Solutions (TOPSIS)

This method is developed by Huang and Yoon (1995) as an alternative to ELECTRE. The basic concept of this method is that the selected alternative should have the shortest distance from the negative ideal solution in geometrical sense. The method assumes that each attribute has a monotonically increasing or decreasing utility. This makes it easy to locate the ideal and negative ideal solutions. Thus, the preference order of alternatives is yielded through comparing the Euclidean distances. A decision matrix of M alternatives and N criteria is formulated firstly. The normalized decision matrix and construction of the weighted decision matrix is carried out. This is followed by the ideal and negative-ideal solutions. For benefit criteria the decision maker wants to have maximum value among the alternatives and for cost criteria he wants minimum values amongst alternatives. This is followed by separation measure and calculating relative closeness to the ideal solution. The best alternative is one which has the shortest distance to the ideal solution and longest distance to negative ideal solution [10].

II. CONCLUSION

Chemical engineers require discerning abilities and methods to make sound decisions. R&D is a driving force of a chemical industry and one of the important strategies for a chemical industry is to make clear the way to execute R&D, the rule to select R&D projects and set priority levels to projects, etc. It depends on the knowledge of an administrator and the thinking of the executive in most cases. Despite the fact that many models for R&D project selection have been developed by academics, very few seem to have been tested in companies. Similarly, relatively little research has been published on the project selection techniques that are actually used in companies. MCDM approaches seem major parts of decision theory and analysis. In this paper we have described several different methods of MCDM as a most commonly method that used for solving multi criteria decision problems in R&D project selection in chemical industry. It is hoped that this work will provide a ready reference on MCDM and this

will encourage the application of the MCDM by chemical engineering project management.

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