AN INTELLIGENT, KNOWLEDGE-BASED MULTI-CRITERIA DECISION MAKING ADVISOR FOR AEROSPACE SYSTEMS DESIGN

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Abstract

It is of paramount importance to determine the appropriate decision making method for the problem under consideration since the use of an inappropriate method may result in an undesired solution. This paper proposes an intelligent, knowledge-based Multi-Criteria Decision Making Advisor (MCDMA) system that can supply guidance to Decision Makers (DM) in selecting the most appropriate method for a specific problem, validate the correctness of a decision made, and provide advice for generating new decision making method if there are no suitable methods in the MCDM library. This high ability system can not only help the DM find the most suitable method but can also guide him/her to reach the final decision by following the rigorous procedure of the selected method.

1 Introduction

In modern aircraft design, a significant amount of attention is paid to the conceptual and preliminary design stages in order to increase the likelihood of choosing a successful design. The decisions made during these design phases in early engineering design are mainly based on the designer's intuitions, that is, his or her experiences, values, and emotions. Aerospace systems are very complex, with interacting disciplines and technologies; thus, most of the decision activities in the design process are almost impossible tasks for the individual Decision Maker (DM) to manage. This complexity results in a requirement for advanced decision making methods that are able to handle multiple, potentially conflicting criteria.

Currently, over 70 Multi-Criteria Decision Making (MCDM) methods have been proposed to facilitate decision making processes [1], and new methods are constantly emerging to help satisfy the demand for increased capability. It is necessary to select an appropriate decision making method before the process proceeds because there is no general, universal method for all types of problems. However, the selection of the most appropriate decision making method has always been a source of frustration to DMs since the selection itself is often a complicated MCDM problem.

Over the past decades, many efforts have been made to facilitate the selection of the most appropriate decision making method for a given problem. Various approaches have been developed and can be classified into three main types including the tree diagram [2,3], criteria approach [4,5,6,7], and expert or intelligent systems [8,9,10]. The tree diagram is the traditional approach proposed by the researchers when the importance of the method selection was first recognized. This approach is embodied by a taxonomy of MCDM methods in the form of a tree diagram which consists of nodes and branches connected by choice rules. Users can use these tree diagrams to reach one or more methods for a given problem by going through the corresponding branches of the diagram.

Possible criteria for evaluating MCDM methods were proposed as an alternative solution for this method selection problem. By utilizing this approach the most appropriate MCDM method is identified by evaluating the methods with respect to a set of criteria for the given problem. In the 1990's, the researchers developed different expert and intelligent systems to aid the DMs to choose the appropriate MCDM method. Those systems work by asking the user a series of questions and then eliminating options to the most appropriate method based on the user's answers.

The approaches described above have difficulties in handling the new decision problems in aerospace systems design. Some of them require that the user has knowledge about the different methods (e.g. criteria approach) and some are too simplistic to suggest the most suitable method (e.g. tree diagram). In addition, none of the approaches have a comprehensive sample of the existing MCDM methods.

This paper presents a Multiple Criteria Decision Making Advisor (MCDMA) system as a new approach to facilitate the MCDM method selection. This system is extensible and has more capabilities in selecting the most appropriate decision making method.

2 Adapted Decision Making Process

Before the detailed explanation on the MCDMA is presented, the adapted decision making process, shown in Fig. 1, will be briefly described here. The process consists of

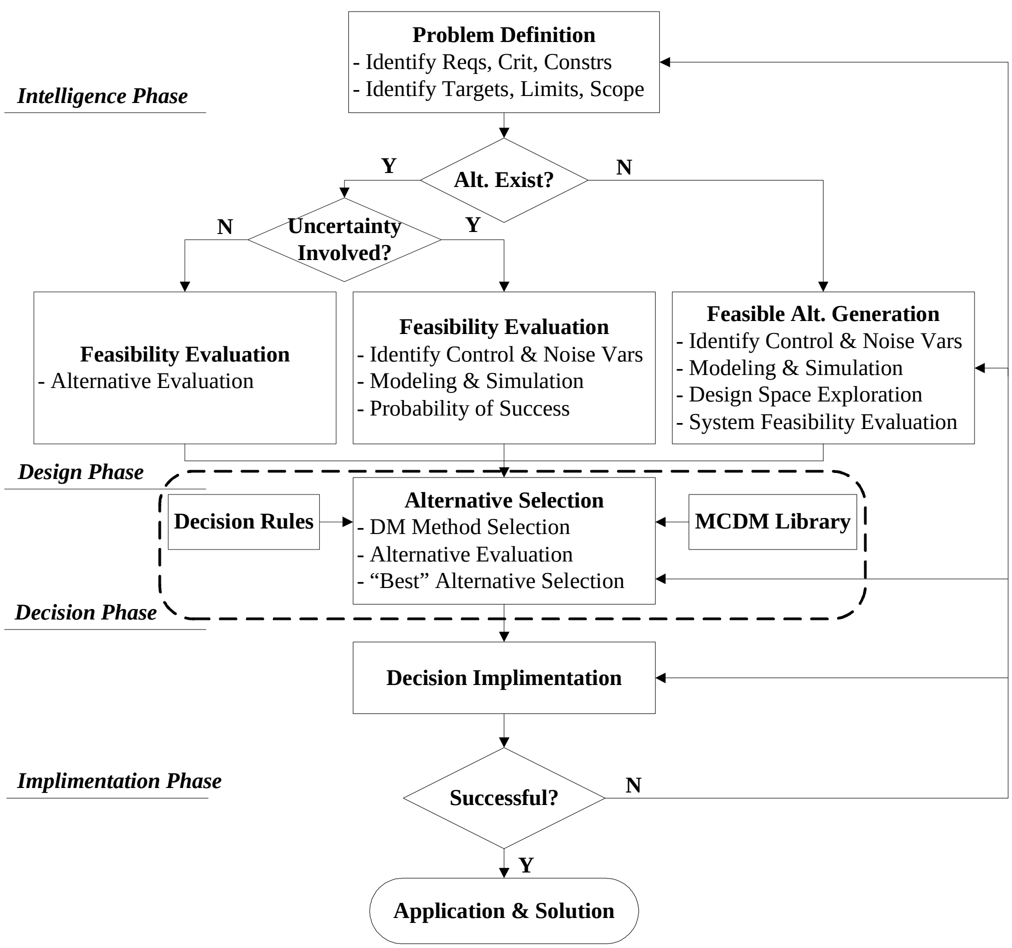

Fig. 1. Adapted Decision Making Process

four phases: intelligence, design, decision making and implementation. It begins with defining the design problem in the intelligence phase, where the customer requirements, design constraints and targets are identified and the Customer Requirements (CRs) are translated into Engineering Characteristics (ECs) by using the Quality Function Deployment (QFD) [11] technique. Then if the alternatives exist, a feasibility evaluation will be performed to determine whether the requirements and constraints defined in step 1 are satisfied. If the alternatives do not exist, they need to be generated, which results in a design problem. A generic design methodology referred to as the Technology Identification, Evaluation and Selection (TIES) [12,13] is employed for the design problems. This method encompasses a feasibility and viability examination process, explained in numerous technical publications. After the feasible alternatives are available for selection, the MCDMA takes over all the tasks in the decision making phase. Finally, the most appropriate decision making method will be selected, resulting in optimal decisions down the road.

3. Multiple Criteria Decision Making Advisor

As stated in section 1, various methods with the intentions of facilitating the decision making process have been developed. However, contrary to their intentions, these numerous methods complicate the decision making process by overwhelming the DM with choices. A method that is not suited for a given problem results in an undesired solution. Therefore, it is critical to choose an appropriate decision making method in order to obtain the "best" solution for the problem under consideration.

In this section, a MCDMA system is proposed as a possible solution to facilitate the selection of the most appropriate decision making method and provide insight to the user for fulfilling different preferences. This system is designed to alleviate the DMs' burden in the decision making process, resulting in high quality decisions in the context of the engineering problem.

3.1 Architectural Framework of MCDM Advisor

This advisor consists of a user interface allowing the interaction between users and the system, an inference engine managing the execution of the system, an MCDM library storing the widely used decision making methods and a knowledge base providing the information required in the method selection process. The architectural framework is illustrated in Fig. 2.

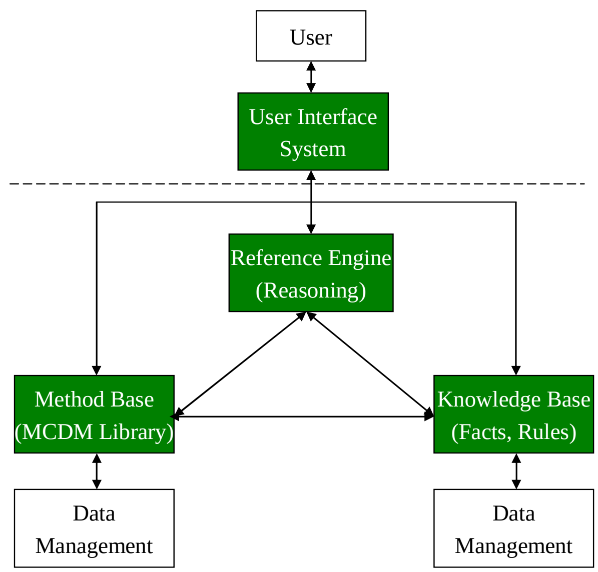

Fig. 2. Architectural Framework of MCDM Advisor

3.1.1 User Interface

The user interface subsystem of the MCDMA allows the user to interact with the system to accomplish a certain task. The advisor presents the user a questionnaire with the decision options to the individual question. To complete the process, the user is required to provide the corresponding answers, select the desired options, and input the supplemental information. Based on the information, the advisor will output the results to the user through the interface.

The user interface provides a convenient means of communication between the user and the advisor through various graphic screens. The users are allowed to control the knowledge and data which are usually necessary for the proper operation of the advisor system. The advisor responds to the users by outputting some data and graphs through the interface to complete the interaction.

3.1.2 Inference Engine

The inference engine in the MCDM advisor system is the control mechanism that manipulates the information present in the knowledge base and method base. It organizes and controls the steps taken to solve the task-specific problem and handles the execution of the system. The inference engine needs to interpret the inputs that the users entered through the user interface in order to determine which rules or facts will be applied to the current problem. Then, it applies the rules or facts to the problem to form a line of reasoning and arrives at a conclusion.

There are two typical inferences that the engine uses: forward chaining or data driven and backward chaining or goal driven. For this example both inference techniques are utilized. When selecting the most appropriate decision making method, the forward chaining is used because the selection is based on the characteristics of the given problem, which are represented by some fragmentary inputs. Based on the situation (all the inputs), the desired goal (selecting the most appropriate method) will be reached by employing the forward chaining reasoning process. On the other hand, where advice for the generation of new methods is desired, the backward chaining reference engine is utilized since the advice is obtained by evaluating the properties of the problem and the existing methods. That is, the desired goal (providing advice for generating a new method) needs to be supported by some evidences (evaluation of the problem and methods).

3.1.3 Knowledge Base

The knowledge base is the core of the advisor system. Its main purpose is to "provide the guts of this system --- the connections between ideas, concepts, and statistical probabilities that allow the inference engine to perform an accurate evaluation of a problem" [14]. The knowledge base stores the facts and rules, which include both factual and heuristic knowledge and support the judgment and reasoning of the inference engine.

In the advisor system, the knowledge is acquired carefully from expert and documented sources in order to obtain an accumulation of high-quality knowledge. Once the knowledge is endowed to the system, some further operations are necessary, including the evaluation, validation and verification of the acquired knowledge, to be taken to ensure the quality of the knowledge. After the knowledge is obtained, it needs to be organized and represented in an appropriate manner. There are several ways to represent knowledge, such as a representation method, production rules, formal logic, object-attribute-value, and so on. In this study, production rules are employed since almost every piece of knowledge can be written as a rule and it is simple to use. The rules have the following form:

IF
  Conditions (assumptions)
THEN
  Actions (conclusions)

The above form implies that when the conditions are satisfied then a conclusion is arrived at or an action is triggered. Each rule describes a certain knowledge case and thus the represented knowledge is characterized by independence and a high level of transparency.

3.1.4 Method Base

The method base, also referred to as MCDM library, stores a number of MCDM methods. Each method is represented by two sets of data: one indicates the characteristics of the method, the other provides the problem solving steps of the method. The characteristics of the MCDM methods are divided into four classes: DM related, method related, problem related and solution related characteristics [15], and each category of characteristics is independent of the others.

DM related characteristics are those which reflect the DM's level of knowledge, ability and preference on selecting a MCDM method. Some of the characteristics are related to the DM's knowledge about a specific method, and some are associated with the DM's time availability. In addition, these characteristics include the DM's willingness to accept the assumptions and limitations of the method and the ones that reflect the DM's preference form.

Method related characteristics play a central role in the method selection process. The reason is that the characteristics of the method determine what information the method needs to construct the decision model, what aspects of the given problem need be taken into account, and how the decision is made. Therefore, they determine the quality of the decision made. Some of them are listed below:

- MADM, MODM or MCDM: Is the method able to handle the MADM problem or MODM problem, or both (MCDM)?
- Feasibility evaluation: Does the method evaluate the feasibility of the alternatives?
- Preference representation: How is the preference information represented? Is it represented by relative weight, utility function or another preference function (e.g. class function or loss function)?
- Input requirements: What input data are required by this method?
- Uncertainty: Is the method able to capture the uncertainty existing in the problem?
- Dynamic behavior: Can the method deal with a time dependent problem, such as changes in inputs or attributes over time?
- Decision rule: What ranking metric does the method use, relative importance, utility, probability of success (PoS) or other metrics?
- Hierarchical criteria: Can the method handle the problem with multi-level criteria?

Problem related characteristics are those depending upon the real decision making problem, such as the number of alternatives, attributes/objectives, constraints, the amount of information available, and whether it is linear or nonlinear. An MCDM method must satisfy the problem related characteristics in order to obtain a desired decision.

The choice of one MCDM method over another is related to the appropriateness of the results obtained from the use of that method [1]. These characteristics are captured in the solution related characteristics which are associated with the types of solution produced by the methods. For example, the solutions obtained from different methods have different sensitivity (how sensitive are the results to changes in weighting, or selection of a datum point?) and robustness (how robust are the results to changes in preference changes?).

With the technology evaluation, advanced methods with improved capabilities are continuously emerging, therefore, it is not possible to include all the decision making methods in the MCDM library at the time when the advisor system is developed. To keep the system from being obsolete, the new methods are allowed to be added into the MCDM library for further use, eventually increasing the capability of the advisor.

3.2 High Abilities of MCDMA

The MCDMA presented here is a high ability system that can select the most appropriate decision making technique, guide the users to solve their specific problems, validate the decision made, and help in generating a new method that is suitable to handle the problem under consideration if no existing method is recommended.

3.2.1 Decision Making Method Selection

It is well known that different problems have different properties, such as the hierarchical attributes, existing uncertainty and risk. Similarly, the methods also vary in their requirements, assumptions and limitations. Hence, if a problem with certain properties is solved using a decision making method which is designed for this type of problem, a more appropriate solution can be obtained. This is the concept that the MCDMA uses to select the most suitable decision making method.

Table 1 shows six decision making methods that are decomposed in terms of their characteristics and requirements. In this table, for example, it can be seen that TOPSIS is a selection process, and it needs a decision matrix to help it organize the input data. The relative weight represents its preference information and is given in advance. TOPSIS is able to handle the discrete attributes, but can not be used to solve the problem with dynamic behavior. In addition, it evaluates the alternatives based on the decision rule of maximizing the closeness to the ideal solutions. Therefore, it is clear that TOPSIS is a good method for a decision making problem with a single attribute level, relative weight and discrete attributes. It is not an appropriate method for problems that need uncertainty analysis and dynamic consideration.

To select the most appropriate decision making technique, the advisor presents the DM some questions, and tries to capture the essences of the problem based on the answers. For each question, the advisor provides two or more options for the DM to choose as the answers to the corresponding questions. Each question is related to one of the characteristics described in section 3.1.4, and weights, representing DM's preference, are assigned to each question. After the system collects all the inputs about the problem, it utilizes the information in the knowledge base and method base to perform the method selection analysis. Eventually, the methods in the method base are ranked in order of goodness. The goodness is obtained by first identifying the characteristics of the method which match the characteristics of the problem, and then dividing the weighted number of these characteristics by the total number of the characteristics. The methods with goodness greater than 0.9 are considered as appropriate methods and the one with the highest goodness is selected to solve the given problem. Fig. 3 shows the method selection process.

3.2.2 Decision Validation

A DM is usually familiar with one or a few decision making methods, and tends to use these methods to handle any decision problems. It is impossible for the DM to know all the existing methods, so the decisions made using the method(s) that the DM is familiar with do not ensure their appropriateness. It has been stated that the use of inappropriate method often results in the misleading solutions, so the decision validation should be performed before the decisions are implemented.

The MCDMA is able to validate the decisions made by using a specific method. The validation process is similar to the

Table 1. Characteristics of the Decision Making Methods

	Technique Ordered Preference by Similarity to the Ideal Solution (TOPSIS)	Analytical Hierarchy Process (AHP)	Expected Utility Theory (EUT)	Joint Probability Decision Making (JPDM)	Multi-Attribure Utility Theory (MAUT)	Goal Programming (GP)
Feasibility Check?	No	No	No	Yes	No	Yes
Optimization/ Selection?	Selection	Selection	Selection	Both	Selection	Optimization
Deterministic/P	Deterministic	Deterministic	D/P	Probabilistic	Deterministic	Deterministic
Input Data Available	Decision Matrix	Comparison Matrix	N/A	N/A	N/A	N/A
Complexity	Single Level	Hierarchical	Single Level	Single Level	Single/Hierarchical	Single Level
Preference	Relative Weight	Relative Weight	Utility Function	Relative Weight	Utility Function + Relative weight	Preemptive Weights +Relative
Weight	Given	Calculated	N/A	Assigned	Assigned	Assigned
Info. Req.	N/A	N/A	Probabilities + Utility Function	Interest of Area	Utility Function	Goals
Decision Rules	Closeness to Ideal Solution	Ordinal Ranking	Maximize Utility	Maximize POS	Maximize Utility	Minimize the variation to the set of goals
Visualization	Yes	Yes	No	Yes	No	No
Dynamic/Static	Static	Static	Static	Static	Static	Static
Discrete/Cont.	D/C	D/C	C	D/C	D/C	C
Complete/Incomp	Complete	Complete	Incompete	Incomplete	Complete	Complete

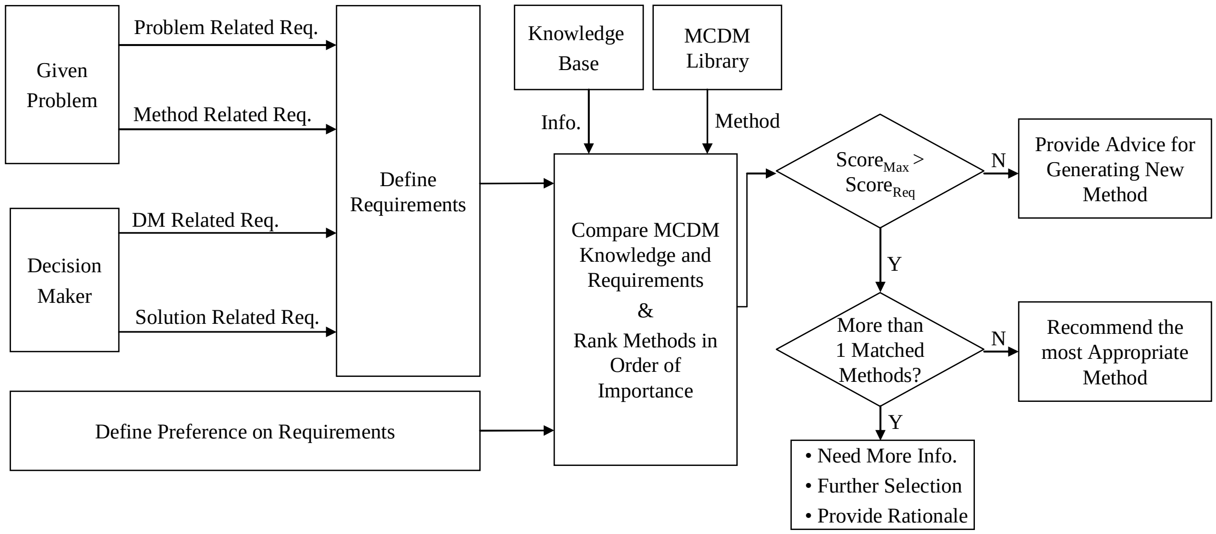

Fig. 3. Method Selection Process

method selection process. For the given problem, the advisor determines the most appropriate method existing in the MCDM library based on the characteristics of the problem provided by the DM. If the method suggested by the advisor is the same as the one the DM used, it implies that the decisions made may be appropriate. Otherwise, it indicates the decisions made may not be good enough and need to be refined using the selected method. The MCDMA can also provide guidance to the DM in the problem solving procedure. This will be briefly explained in the next section.

3.2.3 Decision Making Using a Specific Method

After a decision making method is selected as the most appropriate method to deal with the decision problem, the DM will follow the step by step problem solving procedure to get the final decision solution. However, the selected method may be one that the DM is not familiar with so he/she does not know how to get the problem solved using the method. This situation requires that the DM is allowed to use the method without knowing too much about the method.

The MCDMA is capable of providing such guidance to the DM. For each method in the MCDM library, the advisor has an explicit procedure for the DM to follow. The DM is only required to input some basic information of the problem, such as the number of the alternatives, the number of the attributes, the values of the attributes, and the preference information. This type of problem solving procedure exists for each method in the MCDM library, and the new interfaces can be developed for the new methods which are added to the library to increase the MCDMA's decision making capability.

3.2.4 New Method Generation

In some cases, the decision advisor may not be able to find an appropriate method for the given problem in the MCDM library. This issue may occur when the problem is more complicated than the types of the problems typically considered by the advisor, or just because of the limited number of the methods in the library.

The MCDMA is able to handle this issue. When the advisor can not find an appropriate method for the decision problem, it will analyze the information associated with the problem. Based on the analysis, the advisor will find out what capabilities are required for a method to be fulfilled to deal with the problem. Then it will give the DM some advice for solving the problem. The advice can be to suggest the DM to find an existing decision making method, which is not in the MCDM library, with some certain capabilities or characteristics. If there is not such an existing technique or the expected method can not be found by the DM, the advisor will suggest the DM to create a new method capable of handling the current problem. In this case, the advice provided by the advisor will act as the hints for developing the new technique. These hints include the generation of a brand new decision making method or the suggestion of combining two or more existing techniques to create an advanced hybrid technique with higher abilities.

4. Implementation

To demonstrate the capabilities of the MCDMA system, an aircraft selection problem was performed as a proof of implementation. As shown in Table 2, an airline considers purchasing one aircraft among three competing designs based on the six attributes of interest. They need to make their decision with the help of a decision making method.

Table 2. Aircraft Selection Example

Attribute	Airplane A	Airplane B	Airplane C
Range	1500	2000	3000
Speed	550	450	600
Payload	30000	25000	50000
Cost	15M	20M	10M
Reliability	0.97	0.98	0.999
Safety	0.99999	0.99999	0

4.1 Decision Validation and Method Selection

To solve this concept selection problem, some DMs may prefer to employ AHP which they are familiar or feel comfortable with. A study shows that, with the same preference information (all attributes have the same weight), aircraft C is recommended as the "best" design by the AHP method [16]. One can see that aircraft C is unsafe and few passengers would want to fly on it, hence, it is not a design that any airline will spend money on. This implies that AHP, which recommend an undesired solution, is not an appropriate method for the problem.

The inappropriateness of the AHP method can also be proved from the utilization of MCDMA system by performing the method validation. In the method validation process, the system asks the user to answer the questions related to the problem characteristics. The answers can be obtained by selecting the appropriate one from the answer options that the system provides. In some cases, necessary information needs to be inputted to reach the answer to a question. This process is accomplished through the user interface.

The advisor then analyzes the inputted information using the data in the knowledge base through the help of the inference engine and then calculates the goodness for each method in the method base. In this example, the questions are assigned the same weight when the goodness is calculated. The final result of the method selection is illustrated in Fig. 4. It can be seen that TOPSIS is evaluated as the best method, and AHP has much lower goodness. This result is consistent with the fact that AHP is not an appropriate method to solve the problem shown in Table 2.

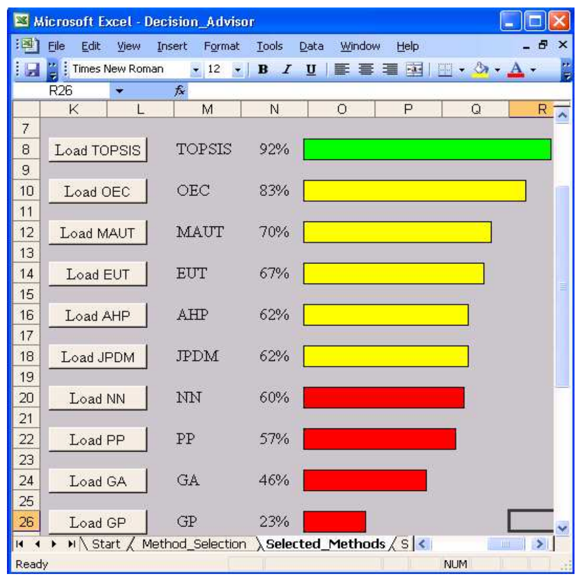

Fig. 4. Method Selection Result

The obtained result can be explained by comparing the TOPSIS and AHP on the given problem. It is known that AHP works well for problems with the hierarchal attributes and the weights of the attributes require a pairwise comparison. While the given problem has non-multiple level attributes and the weights of the attributes are given. In addition, the available data is in the form of a decision matrix that is the exact data form the TOPSIS requires.

Therefore, the characteristics of the given problem match the characteristics of TOPSIS very well, which makes TOPSIS the most appropriate method for the given problem.

The method selection process is similar to the decision validation process. That is, for the problem shown in Table 2, if no decision is made and one wants to select the most appropriate decision making method for the problem, the same process above will be performed and TOPSIS will be selected as the method.

4.2 Decision Making Using Selected Method

Once TOPSIS is selected as the most appropriate method, the decision problem can be solved by using this method. By clicking the 'Load TOPSIS' button in Fig 4, the decision making process of TOPSIS technique, shown in Fig. 5, will be loaded. In the process, the only information needs to be inputted by the DM is the data highlighted in blue. Once the necessary data are obtained in step 1, the following five steps are accomplished by simply clicking the corresponding command button till the result is obtained. This simple operation allows the DM to make his/her decisions using TOPSIS without knowing how the technique works.

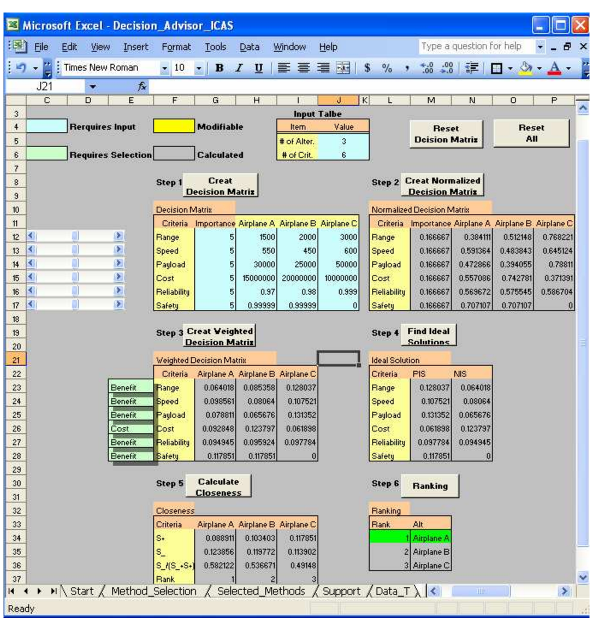

Fig. 5. TOPSIS Problem Solving Procedure

From Fig. 5, one can see that airplane A is suggested by TOPSIS as the best concept to buy based on the evaluation of the given attributes. Aircraft C, selected by AHP as the best solution, is considered as an undesired concept by the TOPSIS technique.

4.3 New Method Generation

Consider the example described in Table 2 with two changes: 1) the airline requires that the safety must be greater than 0.8; 2) instead of totally unsafe, aircraft C has a safety of 0.2. Studies show that with these two modifications TOPSIS selects aircraft C as the "best" design. However, obviously aircraft C is not a feasible design because it violates the safety requirement and no airline will buy it for risking their business. The reason that TOPSIS selected an infeasible solution as the best solution is that TOPSIS is a method which ranks the alternatives based on the concept that the "best" alternative has the closest distance from positive ideal solution and furthest distance from negative ideal solution. The distances from the ideal solutions are in the form of Euclidean distance, which is an equivalent to the average goodness. Therefore, TOPSIS may select an alternative with the highest average goodness as the "best" solution which is dominative at other attributes but violates one or more constraints. This inconsistency shows that TOPSIS may suggest an infeasible design, which makes TOPSIS alone not an appropriate method to solve this specific problem.

In this case, the MCDMA cannot find an appropriate method in the method base (the goodness of TOPSIS is below 0.9). This causes the MCDMA to further analyze the information that the DM provided about the problem and try to find out the capabilities required to handle the problem. For this example, the advisor suggested that a feasibility evaluation must be performed before the decision making process proceeds. And TOPSIS still has the highest goodness (though it is less than 0.9) among the methods. Thus, the MCDMA suggested that performing a feasibility evaluation before employing TOPSIS may smoothly solve this problem and result in a desired solution. This suggestion does work for this problem. The MCDMA can also deal with more complicated problem and provide hints for the generation of hybrid methods with high abilities.

5. Concluding Remarks

The selection of the most appropriate decision technique is critical in the aerospace systems design since an inappropriate technique often produces misleading decisions. Though its importance is obvious, few studies have been done on this issue.

The study presented in this paper proposed a high ability, intelligent, and knowledge-based MCDMA which can supply guidance to DMs in selecting the most appropriate method for a decision problem, validate the correctness of a decision made, and provide advice for generating a new decision making method if there are no suitable methods in the MCDM library. The advisor system provides the guidance for the above tasks by utilizing an intelligent inference engine supported by a knowledge base and a method base through a user interface subsystem. An aircraft selection problem was performed as a proof of implementation and the high abilities of the MCDMA were demonstrated.

It is obvious that it is not possible to include all the decision making methods in the MCDM library at the time when the advisor system is developed. To keep the system from being obsolete, the new methods are allowed to be added into the MCDM library and eventually the advisor is capable of handling the increasing complicated aerospace systems design.

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