Model for Design Concept Evaluation Using Decision-Matrix Logic

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***Abstract*– The selection of an optimal concept from two or more alternative concepts on the basis of alternative attributes in Conceptual Engineering Design (CED) is an iterative task, which is always tedious and may be misleading in nature. Decision-matrix based method is perhaps the most popular concept-selection approach used in engineering design. Although potentially effective and simple to use, it is not without inherent drawbacks. A typical decision matrix implementation requires the designer to specify several weighting and ranking factors in order to evaluate the total scores. However, the weighting factors sometimes prove confusing to specify. This paper describes a computer-based model, employing decision-matrix logic for concepts selection. The model presents a logical procedure for concepts evaluation considering the specified attributes and their relative importance. An example, on the design of a simple gearbox, is included to illustrate the adequacy and implementation of the model. The model can produce results that are reproducible, accurate, more informative, and more reliable to the designers. It was an integrated model for decision-making and is intended to enhance the capability of novice designers.**

***Keywords*– Computer-Model, Decision-Matrix, Concept Selection, Conceptual Design and Gearbox**

I. INTRODUCTION

The concept of engineering design is the formulation of a solution for the satisfaction of a human need. The process can be viewed as comprising two major phases: conceptual and detailed design. Conceptual Engineering Design (CED) requires processing information from diverse sources in order to define the functional requirements, operating constraints, and evaluation criteria pertinent to accomplishing a prescribed goal, as shown in Fig. 1. The ultimate goal of CED is to select the most desirable concept. The selected concept is then further developed in the detailed design phase. Figure 1 shows the two phases of design with the conceptual phase broken down into four steps involving concept clarification, generation, selection and development. Concept selection is one of the most critical decision-making exercises in a product development process. To make decisions effectively, one must (i) minimize the possibility of misrepresenting a solution that may be effective; and (ii) fully consider the different implications of a decision.

In industrial practice, numerous methods are used to perform concept selection. According to Ullman [1] and Otto [2], these methods include; decision matrices, feasibility judgment, intuition, multivoting, numeric and non-numeric selection charts, pairwise comparisons, and prototype testing, Other approaches to concept selection that are optimization-based include the use of s-Pareto frontiers, genetic algorithm, combinatorial optimization, topology optimization, knowledge based approaches, and fuzzy outranking preference models as investigated by Wang [3].

Mullur, et al. [4] stated that, the decision matrix method is perhaps the most commonly used approach to concept selection in engineering design practice,. It is an iterative evaluation that tests the completeness and understanding of requirements, which quickly identifies the strongest concept. The typical versions are Pugh method, Johnson techniques and L-shaped Matrix. Several improved versions have been proposed in the literature for different applications. For instance Rao [5] described an improved decision-matrix ranking method which helps in the selection of a suitable material from among a large number of available alternative materials for a given engineering application. The method evaluates and ranks the materials and hence selects the most suitable material. Also, Halog, [6] presented a theoretical framework on the integration of simplified Life Cycle Assessment (LCA), Life Cycle Costing (LCC), and Quality Function Deployment (QFD) methodologies for the purpose of strategic selection of product improvement alternatives with consideration to data uncertainty. The research focus was on how manufacturing companies can be assisted in the design of products where quality, environmental and cost (QEC) requirements of stakeholders in the life cycle stages of the product system are addressed at an early stage where data imprecision is common. The consideration of these three design requirements leads to a multi-attribute decision situation with regard to the selection of an optimal product system improvement concept. The rating of alternative sustainable options with respect to environment, cost, and quality was also reported.

Sanayei, et al., [7] further proposed an integrated approach of multi-attribute utility theory and linear programming (LP) for rating and choosing the best suppliers and defining the Optimum Order Quantities (OOQ) among selected ones in order to maximize total additive utility. Supplier selection is a complex multi-criteria decision problem that includes both

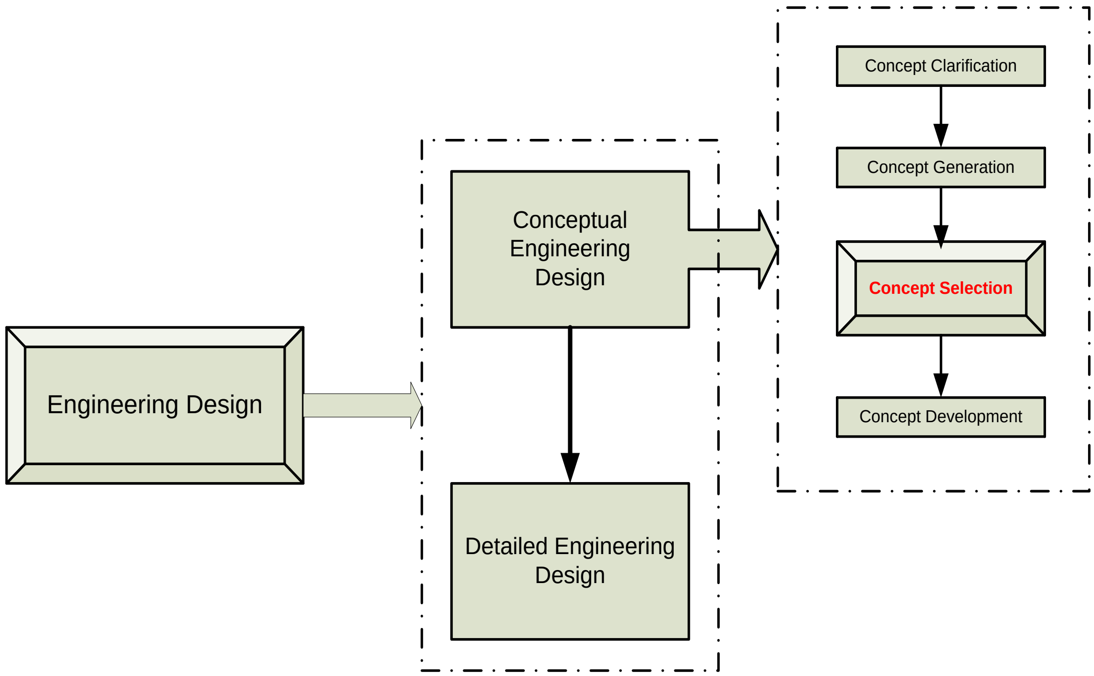


Fig. 1: Phases of Conceptual Engineering Design

qualitative and quantitative factors, which are often assessed with imprecise data and human judgment. Tavares, et al., [8] applied a mathematical multi-criteria decision-making model for selecting the 'Fire Origin Room' (FOR). In reality, the first aim of fire safety is to provide for the occupant's safety in enclosed environments: avoiding or reducing the number of fatalities. There are some criteria that influence directly or indirectly the likelihood that a specific room might be the FOR, for example, the lay-out, the size, the ventilation, the type of fuel packages, the location of the fuel packages, the surface-covering material of the walls and the ceiling properties. All of these criteria must be analyzed by design engineers for occupant's safety, in designing against inferno or fire outbreaks when they are elaborating the fire design.

Gulfem and Gulcin, [9] also proposed a Multi Criteria Decision Making, (MCDM) approach to evaluate the mobile phones options in respect to the user's preferences order where the most desirable features influencing the choice of a mobile phone were identified through a survey conducted among the target group. Their article then used the Quantitative Strategic Planning Matrix, (QSPM), which is an analytical tool to formulate the strategies used. Meredith, et al., [10] presented a QSPM framework for a retail computer store which also highlighted the benefits and limitations of this important strategic planning analytical tool. Also, Green and Mamtami, [11] stated the importance of Decision evaluation process as it plays an important role in the current scenario, as variation enterprises are keen on introducing new products within a short span of time. This paper hereby examines the drawbacks of implementing the aforementioned strategic planning techniques in manual form and explore in typical decision matrix approach which is potentially effective and simple to use by presenting a computer – based model for its usage in Conceptual Engineering Design (CED), applying the technique in the design of simple gearbox as a case study.

II. MATHEMATICAL FORMULATION OF THE CONCEPTS EVALUATION PROCEDURE

A decision-matrix allows designer to structure and solve problems by:

i). Identifying alternatives: depending upon the team's needs, these can be product features, processing steps, projects, or potential solutions. List these across the top of the matrix.

ii). Identifying selection criteria: these key criteria may come from a previously prepared affinity diagram or from a brainstorming activity, with the assurance that everyone has a clear and common understanding of what the criteria designate. The criteria are written so that a high score for each criterion represents a favorable result and a low score represents an unfavorable result. List the criteria down the left side of the matrix.

iii). Assigning weights: if some decision criteria are more important than others, review and agree on appropriate weights to assign.

iv). Designing scoring system: before rating the alternatives, the team must agree on a scoring system. Determine the scoring range (e.g., 1 to 7) and ensure that all team members have a common understanding of the rating.

v). Rating the alternatives: for each alternative, assign a consensus rating for each decision criterion. The team may average the scores from individual team members or may develop scores through a consensus-building activity.

vi). Summing the score: multiply the score for each decision criterion by its weighting factor. Then sum up the scores for each alternative being considered and analyze the results.

The matrix is basically an array presenting on one axis a list of alternatives that are evaluated regarding, on the other axis, a list of criteria, which are weighted depending on their respective importance in the final decision to be taken, Oladejo, [12]. Table 1 shows a typically constructed decision matrix for a machine shaft design problem. It shows shaft concepts C_1, C_2, and C_3 rated against two design criteria: minimal volume and minimal deflection. A higher numerical rating indicates better concept performance. Each criterion is assigned its relative importance with respect to the other criteria. For every concept, the weight of each criterion is multiplied by its rating. The summation of all such products is the total score for each concept. The concept that receives the highest score is typically preferred over other concepts.

Table 1: Typical Construction of a Decision Matrix

Criterion	***Weight***	**Concepts**		
		C_1	**C_2**	**C_3**
Minimal Volume	0.6	2	5	3
Minimal Deflection	0.4	1	3	5
Total Score	-	1.6	4.2	3.8
Concept Rank	**-**	**3rd**	**1st**	**2nd**

The following equation shows the simple mathematical formulation of the evaluation procedure, Mullur, et al., [4].

$$J^i = \sum_{j=1}^{n} w_j u_j^i \qquad (1)$$

Where,

J^i is the total score for concept i,
n is the number of design criteria,
w_j is the weight of the j^{th} criterion, and
u_j^i is the rating of concept i for the j^{th} criterion.

III. DEVELOPMENT OF THE APPLICATION PACKAGE

Computer modeling of dynamic systems is a valuable tool for engineering analysis and design. It allows for active experimentation, design modification, and subsequent analysis with ease and flexibility. The model was developed on the Visual BASIC platform that runs in the Microsoft Windows environment with graphical user interface (GUI). The GUIs define how the various elements look and functions. Major activities involved in the development of the model detailed in the framework are shown in Fig. 2. It comprises of the design of the programmable algorithm, development of flowchart (Fig. 3), selection of appropriate programming language, project development, project debugging, validation and implementation of the model. Fig. 4 illustrates the architecture of the model. It consists of six major GUIs.

Interface 1: **Introductory Section**

This gives brief introduction of the model, author and usefulness.

Interface 2: **Definition of Concepts**

This allows the proper definition, by title, of all concepts to be given consideration by the model.

Interface 3: **Selection of Criteria**

The designer is allowed to select concerned criteria from a pool of attributes that will be made available by the model.

Interface 4: **Computation of weighting factor**

The model computes weighting factor for each attributes. Each criterion is assigned a weight that is intended to capture its relative importance with respect to other criteria. To do so, a *pair-wise comparison matrix* was constructed using a scale of relative importance designated as:

0: No difference in importance
1: Minor difference in importance
2: Major difference in importance
3: Critical difference in importance

The weighting factor (WF) is obtained by adding the number of times the particular criterion was chosen in preference to its paired criteria.

Interface 5: **Rating of Criteria per concept**

The influence of each performance criterion on each concept individually, is determined by rating each criterion of each concept according to the following rating priority:

1: Marginal satisfaction
2: Minimal satisfaction (objective satisfied to a small extent)
3: Minor satisfaction (objective satisfied not less than ½ of the aspect)
4: Moderate satisfaction (about ½ aspects satisfied)
5: Considerable satisfaction (majority of aspect satisfied)
6: Extensive satisfaction (all important aspects satisfied)
7: Complete satisfaction (Objectives satisfied in every respect)

Interface 6: **Computation of Total Score per concept**

The rating factor (RF), for each criterion and for each concept is multiplied with the weighting factor (WF) to obtain a final weight value for each concept. Each GUI was created using the three-step process for planning the project and process is repeated for creating the interfaces. The three-step process involves setting of the GUI, defining the properties, and then creating the codes. Setting the user interface involves the creation of the forms and controls. Defining the properties involves the setting of attributes of all objects on the forms e.g. name, contents of a label, size, words on command button etc. The last step involves writing the procedures that will execute on run time. This is the use of BASIC programming language statements to define the actions of the program.

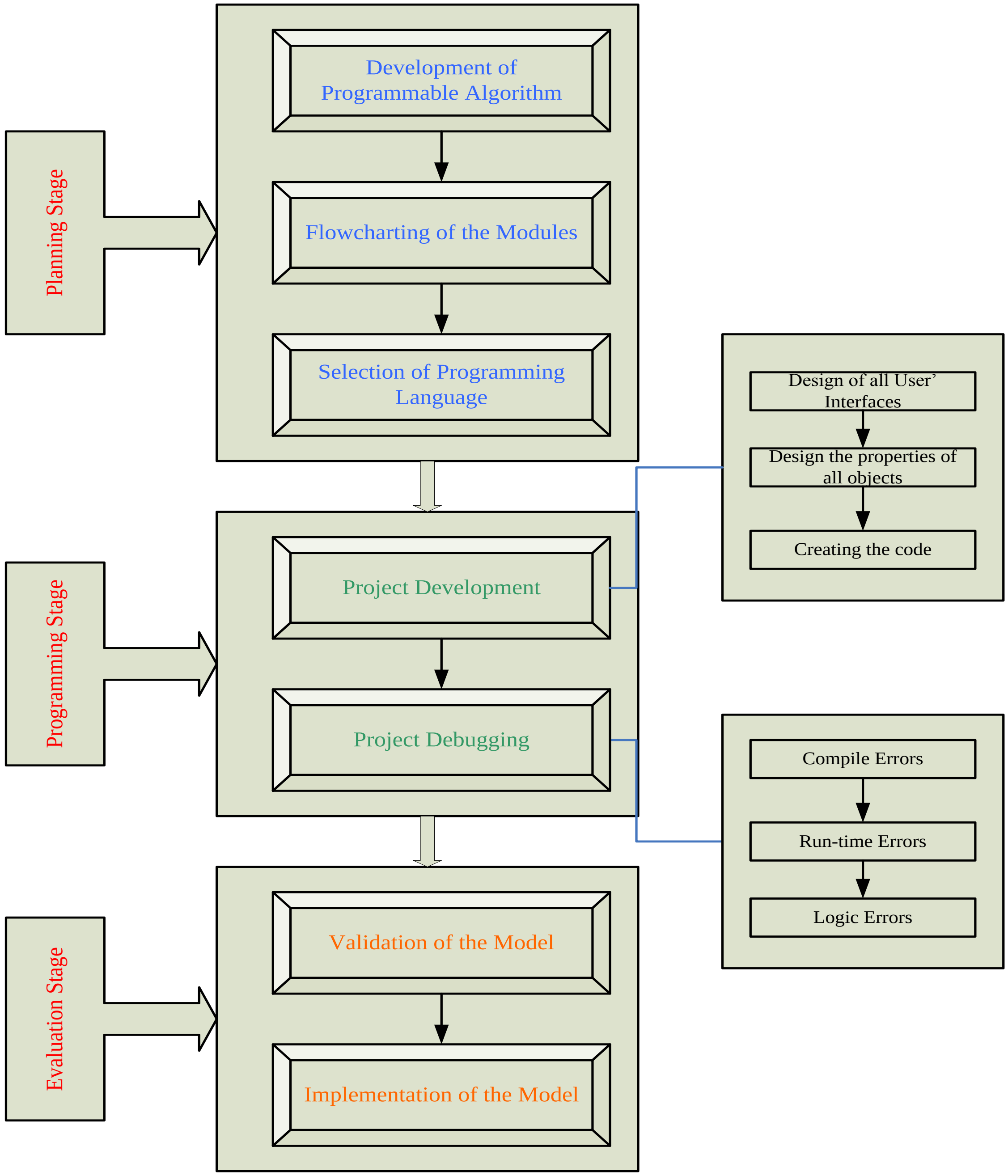


Fig. 2: Framework of major activities involved in the Package Development

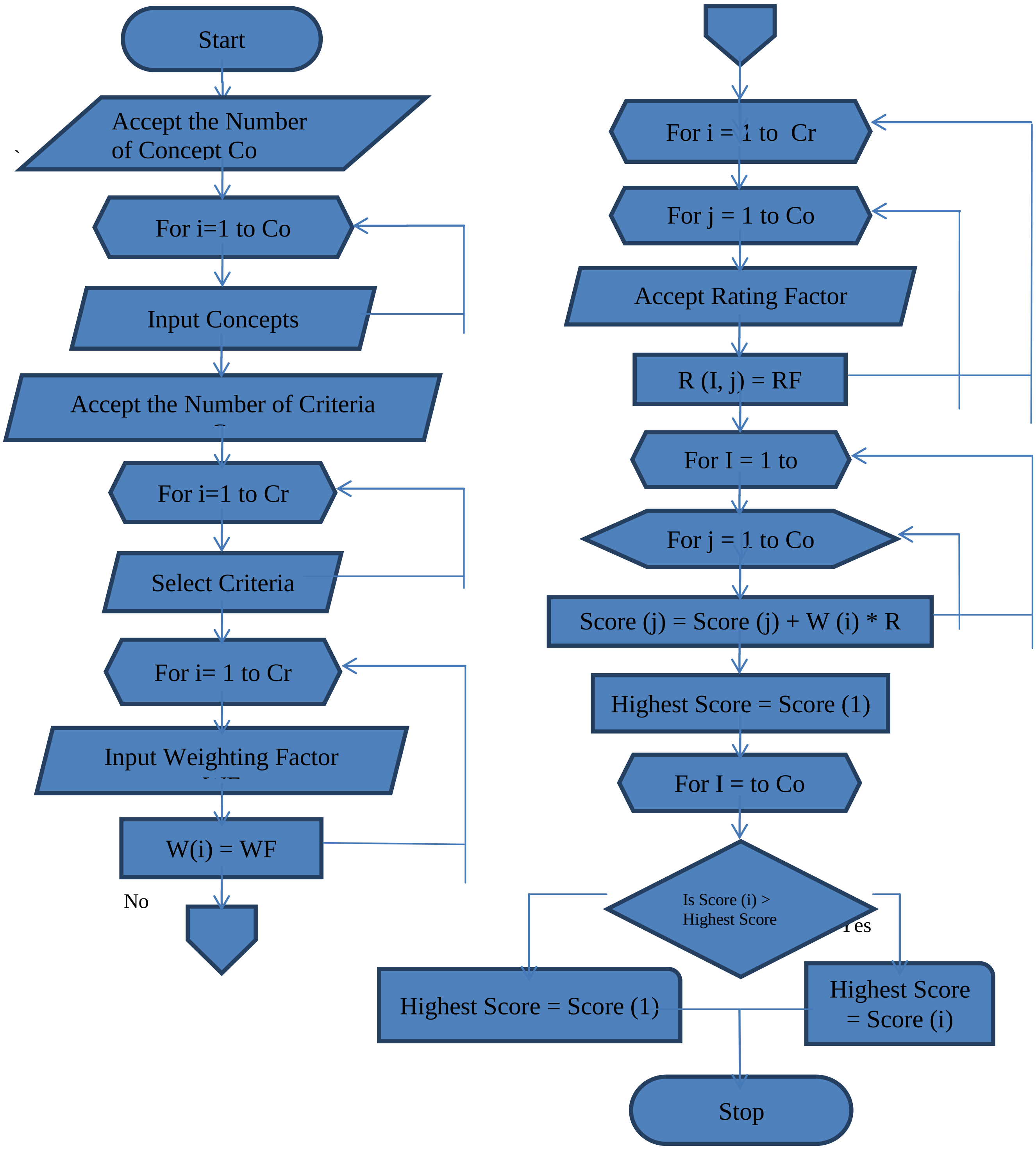


Fig. 3: Flowchart of the package computation

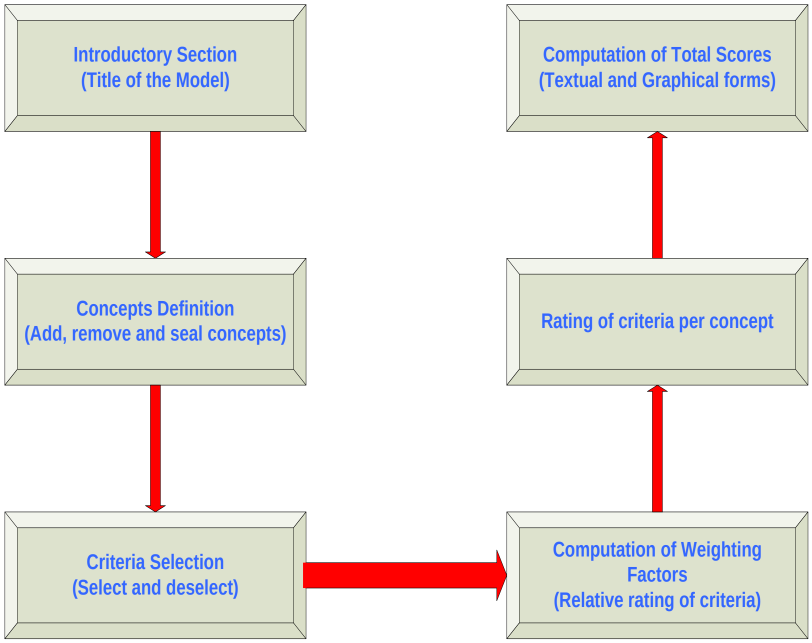


Fig. 4: Major Structure of the Package

IV. TESTING OF THE PACKAGE

The first stage of a design plan is to find out the true nature of the problem, and a major factor influencing this is the way the problem is defined. A considerable amount of valuable time may be lost, in evolving the design, by not defining the problem accurately and hence allowing the project to start off from the wrong base, as indicated by Brooks and Oldham [13]. Once the problem has been satisfactorily defined, all factors which influence the design can then be examined. These factors are the requirements of the design – just what is the design expected to achieve? From these requirements a specification can be written. The specifications will include the precise details of the demands of the design and will state the limits, if any, in physical size and mass of the product and the force applied to it or resulting from its action. The type of material and protective finish will be included if they need to be of a specific nature. The next stage is to compare a number of possible solutions, evaluate each one, and select the most suitable. The final solution may be a compromise between requirements which are of common relative importance in criterion with each other; and for this reason it is often better for an individual to select the most suitable after a team of designers has presented its observations. When the final decision has been made, the design sketch has to be translated into working drawings to facilitate the manufacture of the component. This model was tested for the design of a low-cost simple gearbox for a special purpose machine with the following specification:

- (i) the speed ratio is rated 5:1;
- (ii) overall size of the gearbox shall not exceed (300 x 200 x 200) mm;
- (iii) the total mass of the gearbox shall not exceed 10 kg;
- (iv) gear selector is not required; and
- (v) the gearbox will operate on a machine in a workshop and its working temperature range will be 15–50˚C.

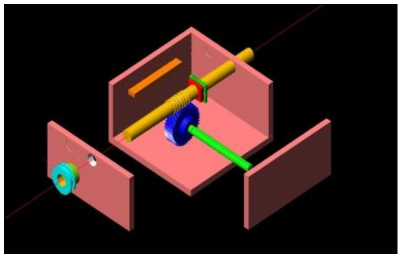
The product specifications define the functional requirements that the equipment must satisfy.

The following four solutions were conceptualized, as detailed in Fig. 5.

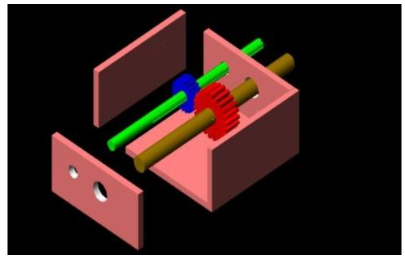
- (i) Worm gearing system;
- (ii) Spur gear system;
- (iii) Straight-helical gearing system, and
- (iv) Straight-bevel gearing system.

In line with the specifications for the design, the following attributes were spelt out to be relevant:

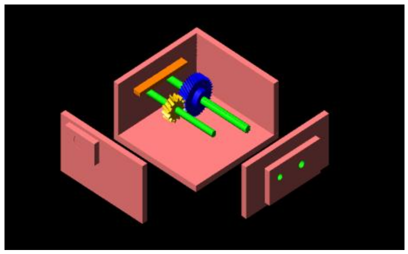
- (i) Technical Performance;
- (ii) Processing Techniques;
- (iii) Size;
- (iv) cost; and
- (v) Development risk.



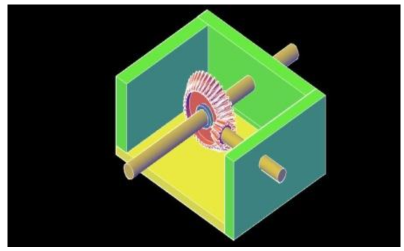
A: Worm



B: Spur



C: Straight-helical



D: Straight-bevel

Fig. 5: Conceptualized Solutions

The implementation of the model for the above case is shown in the screenshots of Fig. 6 through Fig. 9. The first GUI allows the user to supply the title of the exercise which will be automatically repeated in the other GUIs (e.g., Design of a simple gearbox). Fig. 6 shows the interface for the designer to define the alternative concepts to be considered. These alternatives should be those that proceed from the concept generation. It is important that all the concepts to be compared be at the same level of abstraction. This involves worm, spur, straight-helical, and straight-bevel gearing systems. Fig. 7 illustrates the GUI for attributes selection. Pool of criteria is made available on the interface for the user to select. The list of criteria is developed from the engineering specifications.

For the case considered, selected criteria are technical performance, processing technique, size, cost and development risk. Fig. 8 shows the interface for computing the weighting factor of each criterion. It involves the use of a pair-wise comparison matrix in which all the selected criteria are paired and then evaluated against each other according to the order of relative importance listed earlier. For instance, if the difference in importance of processing technique B over size C is major, then the rating will be B2. The weighting factor in the interface is computed by adding the number of times the particular criterion was chosen in preference to its paired criterion. The values obtained for the attributes are 4, 7, 3, 6 and 5 respectively, as shown in Fig. 8. These values were automatically transferred to the next slide (Fig. 9), where the ranking factors were selected for the computation of the total score for each concept.

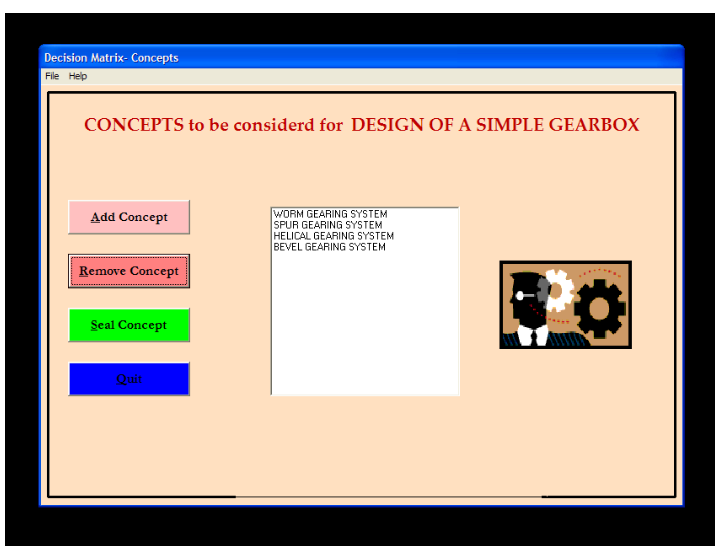


Fig. 6: Interface to input the alternative concepts

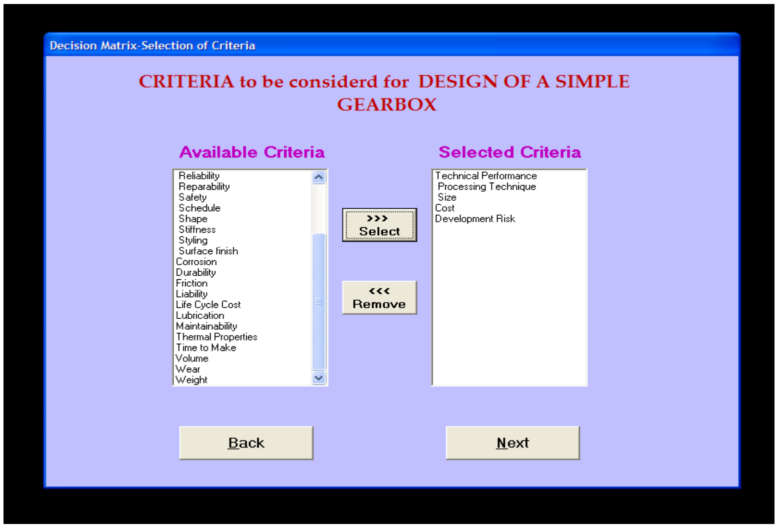


Fig. 7: Interface to select attributes for consideration

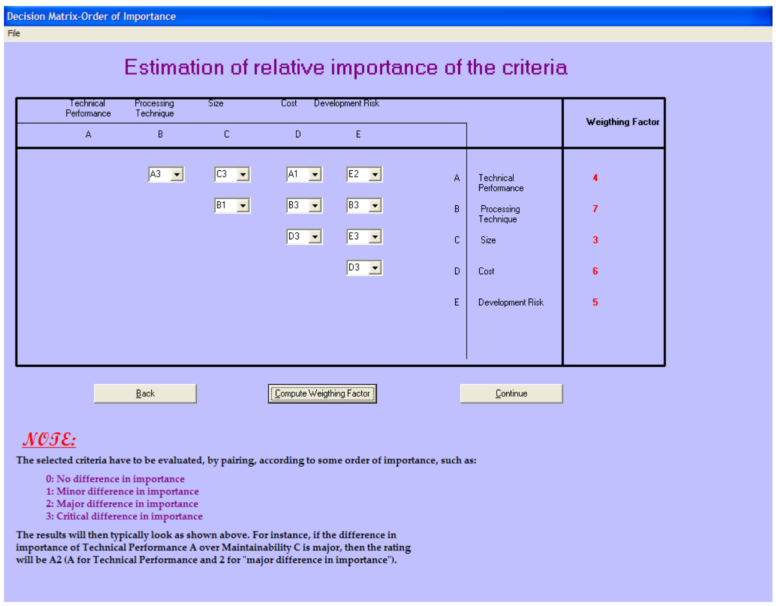


Fig. 8: Interface to evaluate the weighting factors for each attributes

This case study demonstrates the efficacy of the developed model in assessing the qualitative attributes and in incorporating the designer's preference regarding the relative importance of the attributes. The model can be used for any type of decision-making situations and has an edge over the manual method. The computation is very simple and other characteristics of the model involve the followings:

(i) It allows the designer to systematically assign the values of relative importance to the attributes based on his preferences;
(ii) It gives room for systematically assigning of ranking factor;
(iii) The GUIs were designed in a proper format to be understood conveniently; and
(iv) It is error-free and fault tolerant.

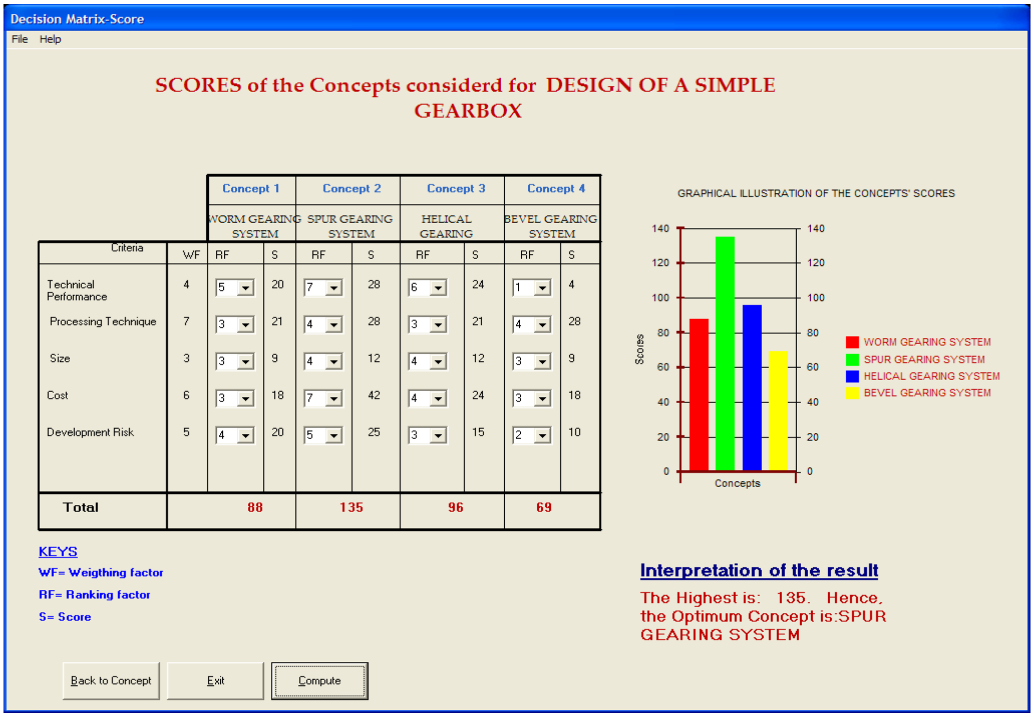


Fig. 9: Interface to compute the total scores for each concept

V. CONCLUSION

This study presents a computer package developed for the selection of an optimum concept from among a large number of available alternative concepts, for a given engineering application, during conceptual engineering design. The model was developed using decision-matrix logic on the platform of *Visual BASIC*. It accepts possible concepts from the user, evaluates, ranks the concepts, and presents the results in both textual and graphical forms for easy interpretation. The implementation of the package for concepts evaluation in the design of simple gearbox revealed its potential as a useful tool in CED. The model can be used for any type of selection problem involving limited number of selection attributes; and can also serve as teaching aid in engineering design courses.

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