Session 2225

Teaching Engineering Decision Making Using a Multidisciplinary Design Paradigm

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Abstract

The important role of “open-ended” problem solving in engineering systems design is well recognized. Open-ended problems are those posed by situations in which the “knowns” and “unknowns” are not obvious and there are a multitude of solutions and various means to achieve solutions. Introducing engineering students to the concept of open-ended problems is an ongoing challenge. Students are often presented with situations that pose open-ended problems and then not provided with a framework in which a solution can be posed or even a manner in which these problems can be discussed. This paper provides taxonomy for this class of engineering problems that is based upon terms and concepts used in Multidisciplinary Design Optimization (MDO). Since MDO is intended to provide a rational basis for design, its terminology is well suited for this application. The paper is intended for both faculty and engineering students as it attempts to describe the concept of an engineering trade study as means to deal with open-ended design problems.

I. Introduction

A fundamental activity in engineering systems design is decision-making. In order to make decisions, engineers are continuously faced with the task of "predicting the future" and doing so under conditions of significant uncertainty. The claim can be made that engineering is composed of two main activities. The first is gathering information; the second is making decisions based upon that information. The central focus of both activities is design, a process by which engineers attempt to address societal needs or exploit economic opportunities.

It is not possible to describe all of the activities associated with this process called design since there is not a well defined path to achieve a "design" just as there is no single "design" for a for a given need. The following briefly defines certain aspects of the open-ended problems often associated with model-based design and presents the concept of the engineering trade study. The following focuses on the design of physical artifacts, but there are relatively few important differences between the design of physical artifacts such as car, a road or an aircraft and the design of less tangible products such as software. Many of the ideas that follow are general in their application to all engineering systems. It should be noted that the following discussion does not attempt to address issues related to generating requirements, but instead focuses on aspects of the problem of defining the product details once the requirements have been established. It is recognized that often there is tight coupling and iteration between the processing of defining requirements and developing a design but those issues are not included in this paper.

The purpose of the following is to present issues associated with the formulation of open-ended engineering design problems using concepts and terminology that are becoming more prevalent in the field of Multidisciplinary Design Optimization (MDO)[1]. The purpose of this paper is to provide terminology and concepts that will assist faculty as they introduce engineering students to the idea of model-based design. Students can use this paper as they begin to apply these ideas to problems of specific interest to them.

II. Model-Based Design

Design, as a verb, is the name given to the human activity of planning, describing or is some other way formalizing the description of an artifact, activity or process. The design, as a noun, is the resulting artifact. Engineers have traditionally viewed the process of design as being objective and quantitative and involving the application of science and technology. The term design is also often associated with another perspective that involves a strong subjective, qualtitative or artistic content. The automobile is a good example. The engineer might see the new automobile design in terms of performance capabilities such as speed, fuel consumption, weight, etc., all objective measures of the product, where the style designer sees shape, color and visual appeal, all typically subjective measures. In most cases a truly effective "design" is one in which both perspectives are considered.

These radically different ideas associated with the term design can create confusion. The following discussion is directly related to the objective measures of the product and the manner in which the engineer is able to arrive at the description of the artifact in a way that it will achieve all of its desired outcomes. The following discussion addresses issues related to how engineers: CONCEPTUALIZE, MODEL, QUANTIFY and DECIDE. These are important steps in this open-ended process called design.

Conceptualize

Early in the design process, after the requirements have been established, (a topic for many other papers) the engineer or engineering team is faced with the challenge of defining concepts. These are the ideas that will germinate and when implemented, hopefully solve the problem at hand. Concepts are often expressed as ideas in an extremely abstract fashion. For physical artifacts they can take the form of very crude sketches. In some cases they are based upon an attempt to use a specific technology. Regardless of what prompts the engineer to generate the idea, at the concept level, the idea is in its "infant state" and there are often many ideas or concepts that can be proposed.

One must note that this activity takes place at many different points within the system design process. One must establish concepts for the entire system, for components that make-up the system, and for individual elements that make-up components. To some degree the issues presented herein apply to the complete automobile as well as to the bracket that will eventually support the exhaust pipe on the automobile. The existence alternative solutions to the same problem applies throughout the design process and is one of the reasons why design is often viewed as an “open-ended” process.

At the concept level the engineer's ability to differentiate between the relative merit of different concepts can be quite limited. This is often due to the fact that there is little quantitative information available to make an unbiased comparison between concepts. If an engineer is faced with selecting between a number of concepts, she must rely upon her experience or the experience of those with whom she works in order to identify concepts that are feasible. A feasible concept is one that, given the abstract level at which it is proposed, appears as if it could meet all of the expected requirements that are imposed upon the product. Until more detailed information can be developed for the concept, assessing the feasibility can be a highly qualitative process that is often subject to significant uncertainty.

Engineering Models

In order to reduce the level of risk in assessing proposed concepts, additional information is required. There are many sources for this information. Sometimes previous products can provide empirical information in the form of a database and information in the database can be used to quantify certain characteristics for a proposed concept.

Much of the effort in engineering and scientific research in the past 50 years has been directed toward developing the capability to predict behavior of complex systems without having to resort to costly prototyping or "cut-and-try" approaches. This has resulted in the ability to use predictive models to provide information for design-decision making. The ability to describe physical process and phenomena make up the core of the acquired knowledge in all branches of engineering. Appropriate application of this knowledge to develop the models and to facilitate the interpretation of the information that the models provide is the key to model-based design.

Selecting the appropriate model represents another key decision in the design process. In the context presented here the term model is used to represent an abstraction used to explore certain characteristics of a physical artifact or process. One of the issues involved in defining the model is associated with the concepts of inner and outer environments relative to the concept being studied[2]. A model cannot include every potential factor that will influence the behavior of the system or component being modeled. The inner environment can be defined as those factors that can be controlled and those issues that will influence the design decisions. The outer environment is made up of those factors that may be external to the system and, though they may have significant effects on the system or component, cannot be accurately or economically included in the model. Accurately drawing the line between the inner environment and the outer environment is a critical step in establishing a useful model particularly in problems that are open-ended in character.

The models may be as simple as two-dimensional free-body-diagrams or as complex as a highly detailed finite element representation. The common elements in all models are they are based upon a set of assumptions regarding the inner and outer environments and they provide quantitative information about characteristics of the system or component being considered.

In many engineering courses the goal is to develop models for various physical phenomena or processes and to provide analytic or numerical methods for developing information to describe them. The engineer is tasked with selecting the appropriate models and then interpreting the information they provide in order to justify design decisions.

Quantify

Once the appropriate model to represent the concept of interest has been selected then a somewhat traditional analysis-problem formulation process must take place. The purpose of the model discussed in the previous section is to provide quantitative information that will be used to characterize the concept. Many engineering problems encountered in academic settings are "closed" in nature. These problems focus on the inner environment and make assumptions about or ignore the outer environment. The problem is stated in a fashion in which there are a specified number of "known" pieces of information, clearly specified "unknowns" and readily identifiable relationships between the knowns and unknowns. Solution of this class of problems usually involves some form of manipulation of the relationships in order to express the unknowns in terms of the knowns. This process often results in a single solution. This solution does provide valuable information about the system, component or process but a single solution to an analysis problem does not provide the designer with adequate information to assist in making design decisions.

In the design process, the problems are not usually as well posed as those mentioned above. Early in the process there are very few knowns and very many unknowns. Deciding which variables fall into each group is a challenge and often the engineer is required to make engineering estimates in order to make progress in formulating a problem that can be solved. Considerable skill is necessary to formulate effective analysis models. Validating the information these models provide requires a sound understanding of the physical phenomena and the mathematics used in their solution. Even after an engineer has been able to solve the analysis problem there is still considerable work to be done in order to develop information that will be useful in the design decision process.

III. A Framework for Engineering Decisions – The Engineering Trade Study

As mentioned earlier, just as there is no single solution to most engineering design problems, there is no single approach to the design decision process. The following outlines aspects of a process that will be referred to as an engineering trade study. As indicated in its name, it provides the engineer with options and allows them to "trade" desirable performance in one area with that in another area until feasible and sometimes optimal designs can be achieved. It should be emphasized that not all engineering decisions are based on formalized trade studies. Some decisions are based upon requirements imposed by specifications; others on individual or corporate experience. In some cases the problem at hand does not have alternative solutions nor is the pursuit of alternatives feasible or efficient. But for those cases where engineers have the opportunity and resources to pursue alternative solutions, the trade study is a way in which design decisions can be formalized and justified with quantitative analysis.

The trade study is based upon information provided by the model and analysis discussed above. The results of the trade study will only be as good as the information that they provide. The following description of a trade study will be illustrated with a very simple example. Consider the design of a simple component that may be part of a larger system. The component is a simple right-angled bracket that is affixed to a vertical beam and supports a horizontal deck. The engineer is tasked with defining the geometry of the bracket and fasteners that will attach the bracket to the beam and deck. In this case the models (and there can be more that one model used to provide the quantitative information necessary to conduct the trade study) will be based upon bending and shear of a slender beam, stress concentrations near cut-outs and shear loading of a bolt. Fairly simple analytic models can be developed for each of these behavioral models.

The inner environment is the bracket and bolts and the outer environment are made up of the support provided by the vertical beam and the loads applied to the system by the deck. The outer environment could also include temperature, humidity, caustic materials, or other conditions that one may want to consider as part of the models. One could also consider a more complex Finite Element Model (FEA) for this bracket and bolts. This may provide more detailed results but the time and computing resources necessary to develop such a model might be considered too great to warrant the additional information provided. The choice of the model and analysis tool is just another important decision in the engineering design process.

In order to formulate a trade study, the knowns and unknowns mentioned above will be divided into three general classes and referred to as: 1) design variables, 2) behavior variables or system states, 3) parameters.

The design variables represent the independent variables in the problem. They often represent things over which the designer has "control." For the example considered herein there are a number of variables that could be used to describe the geometry of the bracket and bolts. They could include the width, thickness, and radius of curvature for the bracket. For the bolts the designer can control the number of bolts, the size of the bolt, thread type, the material the bolt is made from, the spacing between bolts, etc.. Design variables usually represent those quantities or items about which the designer must make decisions. How many bolts should I use? How big should the bolts be? From what material should the bolts be made? How far apart should I place the bolts? <u>Assigning specific values to (i.e. quantifying) the design variables is the purpose of the trade study.</u> When the study is completed the designer should be able to answer the questions listed above and have quantitative validation for those answers.

In considering this simple example one can see that design variables fall into three classes. They can be continuous, such as the spacing between the bolts. Though this may be limited by manufacturing processes or tolerances, it might be any number in a range of real numbers. Design variables can be discrete and sequential, such as the number of bolts. One can't use half a bolt, so this design variable will belong to a set of integers and selection of this design variable corresponds to the selection of one of the integers in the set. Finally the design variables can be batch variables, as in the selection of the material for the bracket. There is no obvious relationship between steel, brass, aluminum, etc. and selecting this design variable involves selection from a finite set of choices. In the early stages of the design process, different design concepts might actually be considered as different batch variables but one must be careful in that different concepts might require different models and analysis methods and that can make the decision-making process described below more complicated.

Before the analysis can be accomplished, most models require additional information that will be referred to as parameters. These are often prescribed by the outer environment or are information necessary in the model and analysis that would remain fixed or constant through the design process. Though the designer must often define system parameters, these parameters are not directly used in the design-decision process. For our bracket, the system parameters might be the loads applied by the deck to the bracket or the range of operating temperatures. System parameters are often necessary to complete the model and perform the analysis. Prudent assumptions of these parameters are often needed in order to begin to “close” the open-ended problems.

Once the model has been establish, the analysis method defined, and design variables and parameters (i.e. the knowns) selected, the engineer should be able to solve the analysis problem for the unknowns. The unknowns are referred to as behavioral variables or system states. As implied by their name, the states approximate in a quantitative manner the behavior or performance of the engineering system or component being designed. For the single realization of the system as defined by a single set of design variables (and fixed system parameters), there is a corresponding set of system states. The values of the states depend upon the selection of the particular set of design variables used in the analysis. In the case of our bracket once the engineer has selected a complete set of design variables, the states are computed using the model and associated analysis. The system states could be weight of the bracket and bolts, stress at a select few or at many points and the deformation under a variety of load conditions, the number of steps in a machining process, fatigue life, etc. Often analysis provides a large amount of information about a particular design. It is this state information that will be used in the design-decision process.

If the engineer were then to change the values of one or some of the design variables (change the material from aluminum to steel, double the width and eliminate one bolt hole) and repeat the analysis, a second set of corresponding system states could be determined. This process of altering design variables and determining states could be repeated over and over again, and each time the engineer would be provided with even more information about the system's design space. The purpose of the trade study is to provide a rational means of selecting between the competing designs.

Two final items that will assist the designer in making their decisions are the concepts of constraints and merit. Usually there are a number of requirements imposed on the characteristics or behavior of the system. These requirements can often be expressed as limits (i.e. upper and/or lower bounds) on either design variables or state variables. For example; the vertical leg of the bracket can be no shorter than 8 inches or no longer than 15 inches, the stress cannot exceed 50% of the room temperature yield stress, the deflection at the end of bracket cannot exceed 0.25

inches, etc.. These requirements can be viewed as limit constraints on either design variables or system states. Once the designer has quantified these constraint limits he can determine whether or not a particular design satisfies all of the constraints imposed on the system. If a design does satisfy all of the expressed constraints, the design can be classified as feasible, at least relative to that set of constraints.

Since the designer can control the values of the design variables, satisfying the constraints on the design variables is simply accomplished by considering only those designs that fall within all constraint limits. It is a different story for constraints on system states or behavioral variables. The states are determined using the model and analysis and are dependent upon the design variables. The designer cannot insure that all the states will satisfy the appropriate state constraints. Much of the design decision process revolves around the process of selecting appropriate values of the design variables to achieve feasible designs. There are a number of methods available to assist in determining those feasible designs. It is recognized that much of the intangible skill, associated with the process called engineering, is related to the ability to understand the models and analyses and then how one uses the information provided to identify feasible designs.

Once the designer has determined a single feasible design, is the process complete? Depending upon time and other resources, feasibility is not the only feature one may want to achieve in a design. Each engineering system should also have associated with it some idea of merit. What makes one design preferred to another? Establishing a quantitative measure or measures of the "goodness" of the design will assist in the decision process. For the bracket mentioned above, weight, cost, service life, could all be considered merit. Merit is usually determined using state information though design variables may also be used to compute merit (e.g. weight is a function of geometry and material). These quantitative measures of merit can then be used within the design decision process.

Once the engineer is able to determine feasibility and quantify merit she can now consider conducting an engineering trade study as a means of performing the process of design selection. This is the time at which the "what-if" questions can be asked. What if we double the number of attachment bolts? What if we use plastic? What if…? These questions will lead to a variety of designs. By posing these questions and then evaluating the impact of the results on the merit, the designer is able to "trade" benefits in one area with costs in another. This process of design refinement is the goal of the trade study. This process also provides the engineer with indications of the most important design variables, constraints and merit.

The what-if questions can even get more complex if one begins to ask, "What if you change the applied loads?" In this case you have not changed a design variable, you've changed something that you may have earlier considered a fixed parameter. This now becomes a semantic argument. Can a system parameter become a design variable, can you reformulate the analysis so that a constraint is part of the analysis or consider a design variable a state. Unfortunately, the answer is yes to these and a number of other similarly confusing questions. This is why “open-ended’ problems may be more difficult to formulate than to solve. As mentioned very early, there is no simple path to achieving successful designs. The manner in which the design problem and associated trade study is formulated is another key decision that is the responsibility of the designer.

As a final note it should be obvious at this point that no specific direction has been provided as to how one actually changes the design variables to achieve the preferred designs indicated above. This is an important question in the design process and one that has many answers. To give some idea as to the scope of this problem, consider if our bracket is defined by just 20 design variables (this is actually rather low considering all of the geometric detail needed to completely describe this geometry). Also assume that each of these design variables can be assigned only four different values (low, medium low, medium high and high) within their allowable range. If our engineer can perform an analysis of a single design in just one second, it would still take approximately 37,000 years to consider every possible design! – so an exhaustive search of all possible designs is not a realistic option.

An exhaustive search of the design space as implied in the example above would be prohibitive. The designer would most likely want to take far less time to achieve an acceptable design. How is this dilemma resolved? Usually the number of design variables must be kept rather low. Often graphical presentation of results of variations in design variable can allow the designer to identify improve designs by inspection. Finally there exists an entire domain of analytic and numerical procedures that are intended to improve this selection process. These procedures are referred to as optimization methods and should be seriously studied by all engineers.

IV. Introducing Students to Engineering Trade Studies

The concept of open-ended problems and engineering trade studies should be integrated throughout an engineering curriculum. As the student’s abilities to develop an analytic and numerical models and to use and interpret the results that these methods provide, they are more able to use them as part of the engineering decision making process associated with design. Care should be taken to achieve a balance between instruction in the development of new analysis tools and the use of those tools in engineering decision making.

By encouraging students to approach open-ended design projects using the framework of an engineering trade study presented herein, instructors will have the ability to discuss the formulation of the problem as well as its solution. If students can effectively distinguish between design and behavioral variables, identify constraints and establish merit, they will be more able to achieve feasible solutions to this type of design problems.

To achieve this end, engineering trade studies have been included as part of a capstone design class for many years. This requirement, outlined in Appendix A, has allowed the students to focus on one aspect of the project, define for themselves the inner and outer environments for the topic at hand and then establish justification for making design decisions. A scoring rubric for evaluating this type of project is provided in Appendix B. With such a assessment tool, the students are provide some means of determining how they have approached an open-ended problem. Since the solution of this class of problems is not unique and students will arrive at many solutions, it is the process they follow that is important as well as the result. This also assists the faculty in their role of providing useful feedback to the students since they have established a common set of terms and concepts. The author has used this, or similar, evaluation forms or scoring rubrics for the past few years. The evaluation forms are provided to the students while they are developing the trade study and this has, from this instructor's perspective, improved their performance and understanding on this class of "open-ended" projects. It appears to help them properly define the problem at hand and that is a critical step in the entire problem solving process.

V. Closing Comments

The purpose of this paper was to provide a framework in which engineering students can be exposed to the concept of open-ended problems often encountered in the engineering design. By introducing the students to a variety of terms and concepts that have evolved from the developments in the field of multidisciplinary design optimization, faculty can more effectively communicate, evaluate and assess their student's efforts in this important class of engineering problems.

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Appendix A. ENGINEERING TRADE STUDY REPORTING REQUIREMENTS

The trade study will be one of the major individual deliverable items during the engineering phase of a product development project. The trade study will be documented as part of a formal report that will contain the following readily identifiable items.

1. Statement of the purpose/goals of the study.
2. Detailed list of design variables - those parameters that you can control.
3. List any constraints on the design or behavioral variables or other system characteristics.
4. Measures of merit - those parameters that will be used to evaluate the design.
5. Detailed description of the analysis or simulation tools used with particular emphasis on the assumptions associated with them and their limitations.
6. Results of the study - graphical are preferred but tables or charts are acceptable if they adequately represent the results.
7. Discussion of the results of the study.
8. Brief discussion of the impact of the study on the design.

The basic format for the presentation of the trade study is up to each engineer. A technical memo format might be ideal. The report should not exceed 10 pages that include all background, discussion and results.

Appendix B: Trade Study Grading Rubric

1. Brief summary of purpose [3 pts] _____
   - 0 - no mention of purpose
   - 1 - purpose implied but not explicit
   - 2 - purpose stated but not specific or useful to assess role of study
   - 3 - clear statement of purpose and anticipated influence of study on design

2. List of design variables if appropriate and any appropriate constraints [6 pts] _____
   - 0 - no explicit mention of design variables (DV)
   - 2 - general list of potential design variables (no constraints or limits)
   - 3 - general list of potential design variables and appropriate limits
   - 4 - explicit statement of potential DVs and associated constraints but misused or not used
   - 6 - explicit statement of DVs and constraints and then appropriate use of each

3. Measures of merit or some means to evaluate the impact of decisions [3 pts] _____
   - 0 - no mention of merit or means of differentiation between competing designs
   - 1 - some statement of merit but no effective use in trade study
   - 2 - multiple measures of merit and no indication of how to use them
   - 3 - effective statement of a useful means to differentiate between competing designs

4. Description of tools or methods used in the study [9 pts] _____
   - 0 - no mention of analysis tools or models upon which they were based
   - 3 - vague description without details that would allow process to be duplicated
   - 6 - effective description of method of analysis without validation or benchmarking
   - 9 - effective description of models and methods and validation of methods

5. Presentation of the results [6] _____
   - 0 - no explicit presentation of results from analysis using model and method proposed
   - 2 - presented only "raw data" or data without appropriate supporting information
   - 4 - excessive data (but correctly presented) that is not used to support discussion
   - 6 - concise tabular or graphical presentation with labels and legend that support results

6. Discussion of the results [9] _____
   - 0 - no discussion
   - 3 - general review of results but no attempt to identify key DV's, constraints or states
   - 6 - some use of merit to differentiate designs but identification of key issues left to reader
   - 9 - concise discussion that stresses key issues and references quantitative results

7. Presentation of the influence of the results [3] _____
   - 0 - no mention of impact of study on current design
   - 1 - some attempt but unable to identify how the design was influenced
   - 2 - indication of impact but no justification based upon information in the study
   - 3 - concise statement of influence study (positive or negative) and quantitative validation