

USING A MULTIDISCIPLINARY DESIGN FRAMEWORK TO TEACH DECISION-BASED DESIGN

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ABSTRACT

The important role of “open-ended” problem solving in engineering education is well recognized. Open-ended problems are those posed by situations in which the “knowns”, “unknowns” and even the “tools” are not obvious and there are a multitude of solutions and various paths to achieve solutions. Introducing engineering students to the concept of open-ended problems is an ongoing challenge. Students are often presented with 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 such a framework 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 undergraduate engineering students as it attempts to describe the concept of an engineering trade study as means to deal with the class of problems often encountered in engineering design.

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 sometimes 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 purpose of both activities is design, a process by which engineers attempt to adapt the natural world 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 significant differences between the design of a physical artifact 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 a wide class of engineering systems. It should be noted that the following discussion does not attempt to address issues related to generating requirements for these products, but instead focuses on aspects of the problem of developing a quantitative description of the product once the requirements have been established. It is recognized that often there is tight coupling and iteration between the process of defining requirements and developing a design but those issues are not included in this paper.

The following is an attempt 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.

Throughout this paper the terms “engineer” and “student” are used interchangeably. As indicated the purpose of the paper is to provide a framework whereby students, and engineers, can be assisted in addressing projects, problems or issues that are inherently open-ended. Similarly the terms “open-ended” and “design” are interchanged as the assumption is made that the

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source of most, if not all, of these problems in this category are brought about by engineers contributing to the system design process in some way.

ISSUES IN MODEL-BASED DESIGN

Design, as a verb, is the human activity of planning, describing or in some other way formalizing the description of an artifact, activity or process. The design, as a noun, is the artifact that results from the process. Engineers have traditionally viewed the process of design as being objective and quantitative and involving the application of science, technology and economics. The term design is also often associated with another perspective that involves a strong subjective, qualitative 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.

The open-ended character of the engineering design process is a manifestation of the complexity of the systems and associated natural phenomena. In most cases there are a large number of candidate designs many of which satisfy some if not all of the desired characteristics. Determining how one can develop the information to describe each of these potential designs and the subsequent selection process involves a chain of decisions where each influences all the subsequent decisions - either by opening or eliminating new alternatives. Unlike a recipe where a well defined sequences of steps results in the final product, most design processes are not well defined as a result of new technologies, changes in requirements or the desire to achieve improved performance. In all cases both economic and time constraints also influence the process and though it may be open-ended and thus allow many alternatives to be considered, it is also bounded by these practical concerns and other market factors.

These different ideas associated with the term design can create confusion when one attempts to formalize or teach these ideas. The following discussion is directly related to issues associated with 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 be realized in a form that will provide the desired results. Concepts are often expressed as ideas in an extremely abstract fashion. For physical artifacts they can take the form of 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 and at many different times within the system design process. One must establish concepts for an 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 and to the bolt that is part of the bracket. The existence of alternative solutions, and often not obvious solutions, to the same problem applies throughout the design process and as is cited above, it is one of the reasons why design is as an "open-ended" process.

At the concept definition 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 others 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 Modeling

In order to reduce the level of risk in assessing proposed concepts (and reducing risk in order to provide a higher level of confidence in a given decision is what engineering analysis is all about), additional information is required. There are many sources for this information. Sometimes previous products can provide

empirical information that is archived in a database and information in the database can be used to approximate certain characteristics for a proposed concept. Interpolation using information in a database can be useful but great care must be exercised before one attempts to extrapolate from this type of information.

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 theoretically based, predictive models to provide information for design-decision making. The ability to use models to describe physical process and phenomena make up the core of the acquired knowledge in many branches of engineering. Appropriate application of this knowledge, in order to develop useful information and to facilitate the interpretation of the information that these models provide, is the key to model-based design.

One should emphasize that the information developed using modeling and simulation techniques is in most cases not "exact." The increased emphasis on the use of these techniques has also focused attention on their limitations². This is particularly true for complex systems whose cost or potential for significant adverse societal impact is great such as nuclear power plants or space stations. Understanding the limitations imposed upon the information developed using engineering models is key in effectively using this information in the decision making process.

Selecting the appropriate model represents another key decision in the design process. In the current context the term model is used to represent an abstract representation 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 studied³. 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 (design variables) and those issues that will influence the design decisions (state or behavioral variables). 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 that 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. Often the students are quite familiar with a certain class of models and the analytic or numerical procedures used to characterize the behavior based upon the models. A challenge often encountered is that engineering students are not sure as to when to invoke a particular model, a situation not necessarily any easier for the practicing engineer - but the students also often lack the experience needed to assist in selecting the model and solution procedure. Preparing the students to function as an engineer requires giving them the opportunity to select appropriate models and then to interpret the information the models provide. Giving the students the chance to make and justify decisions is the reason why the educational process must include experiences that are open-ended in nature.

Quantify

Once the appropriate model to represent the concept of interest has been selected then the somewhat traditional analysis-problem formulation and solution processes must take place. The ultimate 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. 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 for a fixed set of "knowns". This solution does provide useful information about the system, component or process but a single solution to an analysis problem does not provide the engineer with adequate information to assist in making design decisions.

Often in the design process, the information "gathering" tasks are not as well defined and the subsequent engineering "problems" are not 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 solution². 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.

Decide

As stressed above, decision making is central to the design process. Engineering design is a sequence of decisions, often made under levels of considerable uncertainty. Most undergraduate engineering students are not given many opportunities to make decisions based upon their analysis, modeling and simulation efforts. The class of open-ended problems mentioned above and often associated with design activities provides them these opportunities. The engineering parametric trade study discussed below has been a central means whereby practicing engineers were able to justify and validate their decisions. Though this paper does not address the actual decision making process, its premise is that introducing the engineering student to the concept of the parametric trade study will assist them in developing an understanding of the challenges that face practicing engineers.

MULTIDISCIPLINARY DESIGN AND ENGINEERING TRADE STUDIES

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 are based 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, simulation and analysis as discussed above. The results of the trade study will only be as good as the information available to the engineer. The following description of a trade study will make reference to a very simple example. Consider the design of a simple component that may be part of a larger system. The component is a simple 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 than one model used to provide the quantitative information necessary to conduct the trade study) will be based upon internal stress in a slender beam under concentrated and distributed loads, stress concentrations near cut-outs and shear loading of a bolt. Fairly simple analytic models can be developed for each of these physical phenomena that have been deemed important for this particular system.

The inner environment is composed of the bracket and bolts and the outer environment is 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 consider a wide range of system models ranging from the relatively simple beam model suggested above to a complex finite element representation for the bracket and bolts. This more complex representation 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 $\{x\}$,
- 2) behavioral variables or system states $\{y\}$,
- 3) parameters $\{p\}$.

This division into these classes and the understanding of the roles of each class is central to the formulation of the trade study. It is this distinction that is derived from notation used in multidisciplinary design optimization. In order to formalize and automate the solution of these complex optimization problems, this type of classification was necessary. Assisting students by

providing “structure” to the problem solving process, (even though the problem may be open-ended, the process can have structure) is a central thesis for the current paper.

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? Assigning specific values to (i.e. quantifying) the design variables is the purpose of the trade study. 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 ordering relationship between steel, brass, aluminum, etc. and selecting this design variable representing material type 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 system parameters or simply 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. The designer must define system parameters and selecting these is very important and can

significantly alter the subsequent decisions. Since they are often associated with the outer environment, they can carry with them a high degree of uncertainty and in those cases, students have a more difficult time setting appropriate values. These parameters are not directly used in the design-decision process but their selection can have an important influence. 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 usually 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 and specifically recognizing when to make “assumptions” is an important skill for students to develop.

Once the model has been established, the analysis method defined, and design variables and parameters (i.e. the knowns) selected, the engineer should be able to perform the analytic manipulations or develop the appropriate numerical procedures to yield the unknowns in the problem. This process of quantifying a set of behavioral variables or system states $\{y\}$, as functions of design variables $\{x\}$ and parameters $\{p\}$, is herein referred to as a system analysis, SA. 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 most cases the corresponding states are unique for a given set of design variables and parameters, though for some classes of problems involving random or chaotic processes this may not be the case, and the manner in which the state information is represented is highly problem dependent. 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 machining steps required to fabricate the bracket, 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.

Figure 1, shown below, represents this concept in which the central “box” is the process referred to as the system analysis.

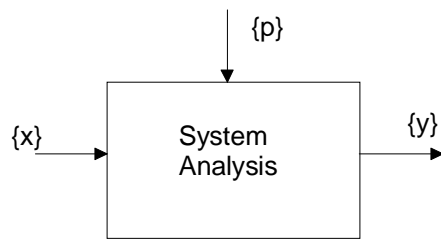


Figure 1. Schematic of a System Analysis

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.

All but the simplest of system analyses require the use of multiple models, numerous calculations and often iterative solutions. Describing these issues is also expedited by the use of the NxN or N² diagram. The representation in Figure 2 below assumes that a number of different analytic or numerical models or multiple disciplines are used to represent the system being studied.

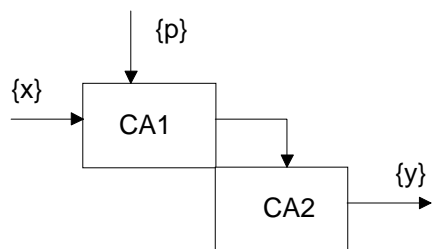


Figure 2. Hierarchic System Analysis

The individual processes that make up the SA are referred to as Contributing Analyses, CAs. In the example represented in Figure 2, there are two CAs in the complete SA and information is fed-forward from CA1 to CA2 in order to compute the complete set of system states. In this case the system analysis is hierarchic in that information is only fed-forward, as illustrated by the arrow above the boxes passing from CA1 to CA2. The order in which the CAs are

performed and the manner in which the information is exchanged are important issues in the execution of the process. Having the students explicitly define the models, solution procedures and information exchange as part of the engineering trade study enhances the learning process and provides them with valuable experience in process planning.

A final variation on the concept of the system analysis is presented in Figure 3 which represents a non-hierarchical SA.

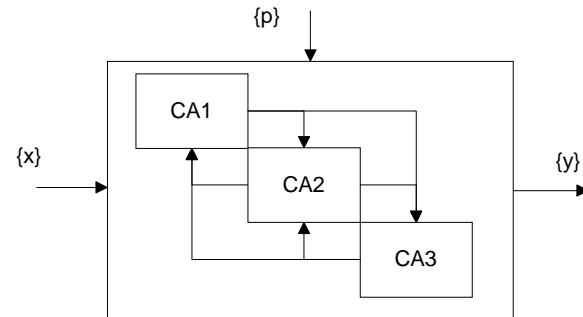


Figure 3. Non-Hierarchical System Analysis, SA

In this case of a completely coupled system shown above, each of the CAs are the sources of information that are needed in another one of the CAs, as indicated by the arrows. The arrows illustrate that information is both fed-forward and fed-back during the execution of the SA of a complex, multidisciplinary system. This requires that this process is iterative in nature. The concept of a coupled system analysis is central to many issues in MDO and introducing it to students who are faced with open-ended problems can help them focus on establishing a systematic process whereby a solution can be achieved. It also assists them in “sorting out” the complexity associated with multiple models and analyses. The realization that information exchange, event sequencing and process dependency are particularly important can be stressed. This is especially important in problems or projects that require teams of students to work together and by formalizing the SA as shown above the students can begin to appreciate its importance.

Two final ideas that will assist the engineering student in making 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 engineer has quantified these constraint limits she 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 engineer 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 system analysis (SA) and are dependent upon the design variables and parameters. The engineer 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 to how one uses the information provided to identify feasible designs.

Once the engineer 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. Often there are numerous characteristics that are considered as merit, thus leading to the concept multi-objective optimization. These quantitative measures-of-merit are used by the engineer to assist in 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. In aerospace engineering the trade studies often lead to "carpet" or "thumbprint" plots. These are developed by systematically varying selected independent variables and performing a system analysis. The manner in which this systematic variation takes place is very problem dependent, but if provided this framework, engineering students can more easily understand how this can be accomplished. The 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.

Figure 4 shown below graphically illustrates some of these concepts as well as allows for the introduction of the concept of the design space and "searching" the design space, two central issues in MDO. In this simple example there are only two elements of the design variable vector $\{x\}$ and no system parameters. There are three elements of the state vector $\{y\}$ that are represented on the plot. Two of the elements of the state vector represent performance constraints and they are the dashed lines. The third state represents the measure-of-merit for the design. Lines of iso-merit are plotted and what appears to be the best or the "optimum" design based upon this merit occurs near the upper-right-hand corner of the figure. These lines would represent the design requirements and objectives as provided by the SA. Assuming that in order to satisfy the design constraints, the values of the design variables must be "below" the two constraint lines. Visual inspection of this two-dimensional design space indicates that the "optimum" design occurs with a design vector $\{7,6\}$ and is labeled with an "o" on Figure 4.

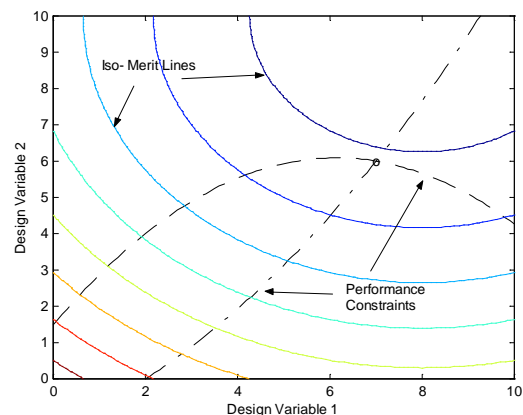


Figure 4. A simple two-dimensional design space

Introducing engineering students to the concept of the design space and the ideas associated with searching the

space to satisfy constraint, determine merit, quantify design sensitivities, all important topics in MDO, help them focus on the important aspects of the open-ended problems. Many of these ideas may also assist faculty in formulating more reasonable open-ended problems for their students.

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 engineer.

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 a complete system 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 engineer 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 variables can allow the engineer to identify improve designs by inspection. But this then provides the instructor the opportunity to introduce the ideas of optimization central to MDO. Bridging this gap between engineering practice and research is an

important side benefit to using these concepts in teaching.

USING 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. 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 two different capstone design classes at the University of Notre Dame^{4,5}, one in aerospace engineering and another in mechanical engineering, for a number of years. The purpose of this requirement was to allow the students to focus on one aspect of a team-based project, become an expert on a particular aspect of a system and develop the information needed to contribute to design decisions associated with the overall system. When the author first introduced this requirement and attempted to describe the expectations for the students - simply in terms of the desired results- it was obvious that due to the difference between this type of activity and the conventional problem solving the students were familiar with that they were often unable to proceed on their own. After about 10 years of this limited success, the author realized around six years ago it was necessary to provide the students with an improved understanding of the process associated with formulating the engineering trade study. By adapting the nomenclature and framework from ongoing research in MDO, the process of introducing the students to the process became very straightforward. They were given the opportunity to define for themselves the inner and outer environments for the issue at hand and then began to understand how to establish justification for making design decisions. 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 results they achieve. Feedback from the students indicates they have a much better idea as to how to formulate the trade study and interpret the subsequent results as result of their improved understanding of the process. The introduction of these concepts 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.

CLOSING COMMENTS

The purpose of this paper was to propose a framework in which engineering students can be exposed to the concept of open-ended problems often encountered in the engineering design and presented in the form of engineering trade studies. It should be obvious to most practicing engineers that the issues raised and concepts introduced are simply those associated with good engineering practice. Formalizing the concepts and providing the faculty and students a means to discuss the process of solving this class of problems has been particularly useful.

The primary concepts adapted from the MDO taxonomy and introduced in the paper are:

- design variable
- system state or behavioral variable
- system parameter
- system analysis
- contributing analyses
- N² diagram
- non-hierarchic and hierarchic systems
- design space
- constraints
- measures of merit
- sensitivity
- feasible conditions
- optimum conditions
- optimization

By introducing the students to a these terms and concepts that have evolved from the developments in the field of multidisciplinary design optimization, it has been found that the faculty can more effectively communicate, evaluate and assess their student's efforts in this important class of engineering problems.

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