IDEA: an Integrated Method of Decision Making in Conceptual Design

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Abstract

The conceptual design process is one of the most important and confusing in engineering design. The Integrated Design Exploration and Analysis (IDEA) process was created to help improve conceptual design practices in the industry. An analysis of existing methods was conducted in order to identify weaknesses. The IDEA process, along with a supporting software interface, was developed to rectify these weaknesses. The interface was written in the open source program Compendium. Three multi-disciplinary case studies were conducted to validate the process. The use of IDEA led to more and higher quality design concepts.

1. Introduction

In our modern technological society the evidence of engineering is everywhere. From cars to computers, almost everything we can see has been touched by an engineer. With this heavy reliance on engineering it would seem logical that most people would have at least a cursory understanding of what it is exactly that engineers do, yet that is not the case. Many people believe that engineering is nothing more than taking advantage of a brief moment of inspiration. While these moments are important, much of the work commonly undertaken in engineering is of a far more structured and orderly nature. Most engineering work consists of finding technical solutions to problems or deficiencies that have been identified in existing products, or to fill some societal need. Regardless of the type of problem, the process for finding the solution is very similar throughout industry.

The engineering process involves several phases. The first of these is the problem exploration and conceptual design phase. In this part of the design process, engineers try to understand the underlying design problem and then generate some initial solutions. This can be one of the most enjoyable parts of the design process since there are few limits on the types of solutions which can be proposed and imagination runs at a very high level. However, conceptual design can also be a very confusing process since there is little concrete information available to designers.

Concept design is followed by detailed design – when the best concept is expanded to a complete design – and then on to production, operation, and disposal. Organisations differ in the details of their design processes. For example, Figure 1 demonstrates the engineering processes used at the ESA, NASA, and the U.S. Department of Defense.

Figure 1: Various engineering processes [1]

The next question that people typically ask is if the engineering process is divided into all of these different phases, which one of these phases is the most important to the final design? While all of the design phases are vital for a successful product, a strong case can be made for selecting conceptual design as the most critical to the final design. The main reason for this importance is the fact that the different phases of the design process are highly interconnected. The results of one phase directly affect the performance of

all of the subsequent steps. Because it is the first phase, the results of conceptual design affect all of the remaining phases. The choices made in conceptual design determine the overall direction of the design project, and poor choices there often lead to failed or substantively suboptimal products (e.g. higher cost, lower reliability, longer development times). In some cases, the problems caused by the selection of suboptimal concept are so extreme that the project itself is cancelled to minimize the losses to the company. Clearly some kind of analysis is required during the conceptual design phase in order to increase the chances of selecting the best concept.

2. Current Techniques in Conceptual Design

Concept design analysis is needed to make informed decisions. The greatest obstacle in pursuing this goal is that the conceptual design phase rarely has enough information available to conduct a rigorous analysis. However, there are a number of techniques available that are commonly used in industry to assist in design decision-making. Many of these techniques are also useful during the conceptual design phase. This section will provide a brief overview of some of these techniques, as applied to conceptual design.

The first task during conceptual design is to gain a better understanding of the problem. It is difficult to provide a reasonable answer when one does not know the question, so the first task of engineers is determining that question.

There are various techniques to do this. The first one involves interviewing users to determine their needs. Originally proposed by Ralph L. Keeney [2], this technique involves the use of personalized interviews, group interviews, and mass-distributed electronic forms to determine the needs of customers. Keeney feels that by determining the needs of average users, designers are better able to determine what features and characteristics should be present in the final design to maximize its chances of success [2].

Another popular technique for gaining a better understanding of a design problem is known as *trade space analysis*. A trade space helps designers qualitatively “trade off” different criteria for the sake of finding the best possible balance. A representation of a trade space is given in Figure 2.

Figure 2: Trade space representation

The large area in Figure 2 represents the total trade space, a construct that contains all possible solutions to all possible design problems. The best solution to a particular design problem is in this space, but is almost impossible to locate since the total trade space is infinite in size. Clearly, a more systematic approach is required; this is where trade space analysis becomes useful. Through an exploration of the design problem, engineers can determine the limitations on possible designs.

These limitations define a *sub-space*, represented in Figure 2 by the raised grey region. This sub-space becomes the trade space of the current design problem and contains all possible solutions to that problem. While this is a big improvement over the total trade space, the sub-space can still contain a vast number of alternatives, making selection of the best one difficult.

The solution is to continue analyzing the problem through brainstorming sessions, interviews with users and stakeholders, meetings with management, and analysis of the feasibility of options. The use of these techniques will allow for a greater understanding of the design problem and help to reduce the size of the trade space until it becomes a relatively simple task of identifying the “best” solution to the problem.

While trade space exploration is meaningful and beneficial, the design team will have to make decisions eventually on how best to proceed with the design problem.

Again, there are a number of tools available to designers to assist with this task. One of the simplest is known as *pairwise comparison*. One of the most common types of pairwise comparison is known as the *drop and re-vote* (D&R) method. In D&R, the members of the design team each order alternative concepts in a *weak order*, an ordinal ranking with no level of preference [3]. The weak orders are then compared to some common filtering criterion (such as “choose the best of the best” or “avoid the worst of the worst” [3]), and the most poorly ranked concepts are

dropped from further consideration. The process is then repeated until only one alternative remains.

Like most engineering decision-making techniques, this method violates one or more axioms of what is known as Arrow's Impossibility Theorem, which is a set of rules (axioms) for creating a fair voting procedure [3]. In this case, a D&R pairwise comparison breaks the *Independence of Irrelevant Alternatives* (IIA) axiom [3]. As a result, the ranking of alternatives changes whenever the lowest-ranked alternative is removed. This is unacceptable since the removal of the lowest ranked item should have not affect the ranking of the other alternatives. D&R is particularly sensitive to rank reversals of this sort because of its iterative nature.

An alternative pairwise comparison method uses what is known as the *pairwise comparison chart*, which is a graphical technique of pairwise comparison, and which produces results that are identical [3] to the well-known Borda Count. Like D&R, the Borda Count also violates the IIA axiom; however, unlike D&R, the Borda Count is insensitive to the effects of breaking the axiom. This is because a Borda Count can be completed in one iteration and without discarding any information, so rank reversals are not possible. This makes the Borda Count much more robust for engineering decision making. The pairwise comparison chart method shares these strengths while also allowing the design team to calculate the level of preference between the items under comparison. These attributes make the pairwise comparison chart ideal for choosing between relatively few alternatives and single ranking criteria.

When there are multiple criteria, however, a simple pairwise comparison chart is not enough. The solution to this problem is to use a *decision matrix* [4]. It is particularly useful when choosing amongst a number of different concepts whose performance is being compared by a number of different criteria. Typically, a standardized ranking scale is used to rate how well each of the concepts achieves each of the different characteristics. An example of a completed decision matrix for a fictional garden tool is given in Figure 3.

Design Characteristic	Relative Weight	Concept					
		A		B		C	
		Modified Hoe	Ranking	Rotating Mower	Ranking	Electric Autoblade	Ranking
Mass	0.2	2	0.4	1	0.2	0	0
Speed	0.1	-2	-0.2	2	0.2	2	0.2
Operating Comfort	0.25	0	0	1	0.25	2	0.5
Ease of Operation	0.15	1	0.15	1	0.15	2	0.3
Reliability	0.15	2	0.3	1	0.15	0	0
Cost	0.15	2	0.3	1	0.15	-1	-0.15
Total Score			0.95		1.1		0.85

Figure 3: Completed decision matrix

The matrix shows the comparison of three different concepts. Each concept is judged against a

standardized set of design characteristics (derived from the requirements) that are listed on the left side of the matrix. The fact that each of the concepts is being ranked against a common set of criteria allows meaningful comparisons to be made since they are all being measured against a common baseline.

The left side of the matrix also lists the relative weights of the design characteristics. Since the characteristics are usually not equally important in a specific design problem, the capacity to make such distinctions improves the accuracy of the results.

Each of the concepts is rated using a standardized scale. This example uses a -2 to +2 scale that is commonly used in the automotive industry. A -2 means that a concept is very poor at achieving a given characteristic; a +2 means that a concept achieves it exceptionally well. Many other scales are possible. The final score for a concept is calculated using a Simple Additive Weighting (SAW) aggregation function with the following form, where w_i is the relative weight of a particular design characteristic and R_i represents the rating for that characteristic for the current concept as assigned by the design team.

$$score = \sum_{i=1}^n w_i R_i$$

The concept with the highest total score best meets the given design characteristics and is most likely the best concept. While this is a very simple additive function, it has been proven [5] to generate results that are comparable to more complex functions.

3. The IDEA Process

The techniques discussed above have several weaknesses. First, while each technique is very good at a particular task, none is generally usable. For example, while trade space analysis is an excellent tool for gaining a better understanding of the problem and possibly generating concepts, it includes no real facilities to assist designers with making design decisions. At best, it will present a limited number of suitable concepts, yet it is up on the design team to make the final selection. Conversely, while a decision matrix is good at selecting amongst a set of concepts, it does not really help with the initial generation of those concepts. Furthermore, the techniques really do nothing to guide designers during conceptual design.

The goal of the *Integrated Design Exploration and Analysis* (IDEA) process is to address these problems. IDEA is a collection of tools and methods intended to not only reduce confusion during conceptual design, but also to stimulate creativity in order to obtain better

designs. IDEA provides a flexible structure for executing conceptual design. It brings together methods that have been demonstrated to be useful, and tools that provide an integrated system for following the method. It lets designers focus on cognitive tasks rather than on the "administrative" side of managing the process of conceptual design. The IDEA process follows a standardized procedure for all problems as can be seen in Figure 4.

Figure 4: IDEA overall outline

As can be seen in Figure 4, the IDEA process consists of four main modules, each responsible for one aspect of conceptual design. The first module is used to *identify* the primary and secondary objectives of the design problem. These objectives are used to determine product requirements. Primary objectives are requirements that the product *must* accomplish in order to be considered a success; secondary objectives are things that are desirable but are not necessary to the product. These objectives are typically identified through brainstorming and meetings with the various stakeholders for the problem.

The second module is used to *determine* the design characteristics for the product and their relative importance, as well the functional requirements for the design. The determination of the design characteristics is once again carried out through brainstorming sessions between design team members as well as meetings with other stakeholders and with a list of commonly pertinent design characteristics. The relative importance of the design characteristics is determined using a pairwise comparison chart. In many design problems, the list of characteristics can be quite large. Using a pairwise comparison chart not only helps to make this task more manageable, but also encourages discussion amongst team members, ensuring that all opinions are represented in the final

rankings. The functional requirements are derived from the primary and secondary objectives and are determined using brainstorming techniques.

While the first two modules are about gaining a better understanding of the design problem, the third module lets designers *explore* possible solutions. With the information gathered in the Identify and Determine modules, the design team now has a better understanding of what the boundaries of the trade space are. The Explore module lets the team use that knowledge to invent solutions. This is accomplished in one of two ways: using trade space analysis techniques, or using a technique called *ideation*.

The trade space analysis portion of the *explore* module is quite straightforward. The design team first generates different options for each of the functional requirements or subsystems in the final design. These different options are then plotted on a trade space diagram as shown in Figure 5. The design team then tries different combinations of options until they generate 5 to 10 plausible concepts that will go on to the final module for more detailed analysis.

Figure 5: IDEA Trade Space diagram

The *ideation* option is a different way of exploring the trade space. In this case, each member of the design team is assigned a different design characteristic. It is then the job of each team member to generate concepts which optimize for their assigned characteristic at the expense of all others. The team members then combine the various concepts together into a smaller set of superior combined concepts.

The final module of the IDEA process is to *analyze* the resulting concepts in more detail to determine which is the most suitable for the design project and should move onto detailed design. This is done using a decision matrix as described in the previous section. A decision matrix is a perfect tool for this task since selecting amongst concepts is an example of a multiple criteria decision-making problem. Using a decision matrix also allows for the participation of the entire design team when the various concepts are being rated. This allows multiple points of view to be represented in the final selection and improves the odds that the best concept is identified. In addition,

the decision matrix also utilizes the relative weights generated in the *Determine* module. If other stakeholders were included in the discussions to determine those weights, then their views will also be expressed in the final concept selection.

4. The IDEA Software Interface

As defined in Section 3, the IDEA process brings together established methods to support conceptual design in engineering. However, the process still has a significant amount of “bookkeeping.” This data recording and simple calculation can be easily and reliably computerised, which will increase the efficiency of the process because it frees the designers’ time to focus on the real cognitive tasks. Furthermore, computerisation of IDEA can provide an “information trail” to improve traceability of the decision-making process.

The IDEA software was created using an open source program called Compendium (<http://www.compendiuminstitute.org>) that implements *issue-based information systems* (IBIS). The authors have extended Compendium by connecting it with other software (discussed below). During the early stages of planning the software, the authors decided to use a graphical interface because graphical representations are far better representations of richly interconnected information of the kind one finds in engineering situations.

The main question was whether to use an existing graphics engine to power the interface, or whether to write specifically for the needs of the IDEA interface. While a purpose built engine would have several advantages, the main disadvantage is that writing a graphics engine from scratch is very time consuming. Thus, it was decided to find an existing engine that would meet the needs of the interface.

After a search of several available options, the authors chose Compendium for several reasons. The first is that Compendium is already graphically oriented, and the IDEA interface could be created with it without writing any code. Instead, Compendium uses a WYSIWYG interface to create databases and templates. This eased greatly the creation of the interface and reduced our development time. The second reason for choosing Compendium was that it is an open source program, so it is both ubiquitous and economical. Thus, using Compendium will help make IDEA available to a broad audience. Finally, Compendium is already being used in a wide variety of different settings. One of the most interesting uses has been at the Jet Propulsion Laboratory (JPL) in California where they use a custom interface built in Compendium to operate the Mars Exploration Rovers

currently on Mars [6]. That such a respected group would use Compendium for such an important mission speaks well of its power and reliability.

The software implements the structure IDEA as in Figure 4. Special attention was given to make the overall outline diagram clear and concise. Each of the four IDEA modules is assigned a separate region and colour on the home screen. Each of these regions contains icons that represent the tasks that the design team must execute to complete that module. Double-clicking on any of the icons opens a window that outlines the tasks to be executed and provides access to task-specific tools. The home screen and sample task windows are shown in Figures 6 and 7.

Figure 6: IDEA home screen

Figure 7: IDEA task window

In these figures, arrows connect the various icons and guide the user on what they should do next. In the case of the task window, the arrows are labelled with

suggested ways to complete specific tasks. For example, reading the icon and arrow text in Figure 7 from left to right, the current task becomes clear. In this case, it states that the design team must “**Brainstorm to identify goals for success** and add these to the list of **primary objectives**.” This graphical structure is repeated in all of the task windows to provide immediate guidance and a familiar pattern to the user.

The brainstorming and primary objectives lists are each represented by their own icons, which can be selected by a double-click. In the case of the brainstorming icon, a blank template is opened for the design team to use during a brainstorming session; double-clicking on the primary objectives icon opens a template to record primary objectives. While the team is still required to manually record the actual results of a design session, the use of standardized templates does save some time and helps keep things organised.

Two additional items of note in the IDEA interface are the *Concept Evaluation Workbook* and the *Trade Space Analysis Tool*. Recall that the overriding goal of the IDEA software is to save time and increase efficiency. While the pairwise comparison and trade space analysis techniques are very useful, they are also time consuming to implement.

In the case of the pairwise comparison chart, the design team must set up a matrix that can become very large, and then calculate the weights of the design characteristics based on the contents of that matrix. Both of these tasks can be quite difficult and prone to error. The *Concept Evaluation Workbook* is used to automatically generate the empty pairwise comparison chart, and as the design team conducts the pairwise comparisons, the workbook automatically calculates the relative importance of the design characteristics and displays them in real time both numerically and graphically. This not only saves time, but also improves accuracy since the computer is performing the necessary calculations.

Furthermore, the workbook uses the information from the pairwise comparison chart to generate an empty decision matrix automatically. The design team only has to fill in the appropriate ratings for each of the concepts and the workbook automatically calculates the aggregate scores, while simultaneously generating a graphical representation of the strengths and weaknesses of each concept.

The *Trade Space Analysis Tool* is used to generate trade space diagrams. In a complex design problem, the generation of these diagrams can become quite tedious. Designers simply enter the various options available for the functional requirements and the tool then automatically generates a trade space diagram. In both of these cases these tools have helped the

software to achieve its primary goal of allowing designers to spend more time actually designing, rather than performing the more mundane tasks that are commonly associated with it.

5. Case Studies

In order to validate the effectiveness of the IDEA process three case studies were conducted. The three case studies were on a broad range of topics to not only establish the validity of the IDEA process, but also to demonstrate its versatility in a wide range of different applications.

The first case study was based on work done during Masur’s undergraduate thesis. It dealt with the design of a sample-processing unit (SPU) for the Mars Science Laboratory mission. The purpose of the SPU was to accept either loose or solid samples from the Martian surface and process them down into a fine powder suitable for use in NASA-supplied scientific instruments. This problem was selected because it is a good mechanical engineering problem, and because both authors are familiar with the original work. While the act of performing the SPU design is of some interest, the most important conclusions are derived from the results of the design.

The conceptual design in the original study was not done using any kind of standardized method. Because of this, only three different concepts were generated.

The more recent design was done using the IDEA process and software. The IDEA trade space analysis module generated 756,000 different concepts. After an initial screening step this number was reduced to six, which is still double the number of concepts in the original study. The sheer increase in the number of concepts generated demonstrates that the use of the IDEA process has resulted in a much more thorough exploration of the design space, which in turn has increased the probability of finding the “best” concept.

While a greater number of concepts were generated, the analysis conducted with the decision matrix still resulted in the selection of the same concept as in the original study. Since the original study was considered quite innovative and received high marks, this result seems to validate the effectiveness of IDEA.

The second case study was based upon a problem called the Speluncean Explorers that is used by law schools to illustrate philosophies of law. It is a fictional problem set in the state of Newgarth in the year 4300 [7]. In it, four men are trapped in a cave a forced to kill and consume one of their numbers to survive until rescue. They are subsequently rescued, and when they have sufficiently recovered, they are charged with murder and eventually found guilty and sentenced to death. The verdict has been appealed and

it is the job of the reader to act as the head of Newgarth's legal system and decide whether to uphold the verdict.

The case is structured in such a way that there is no real answer; it is merely an exercise in problem solving techniques. This problem was selected as the second case study because it would provide a good contrast to the engineering problem of the first case study while also demonstrating the versatility of IDEA.

One of the things that immediately became apparent was that not all of the tools and modules were applicable to the case. A problem such as this is more of a subjective moral and ethical dilemma than an objective engineering problem. Because of this, it was deemed improper to use tools such as trade space analysis and pairwise comparison to decide the outcome of the case. Most of the work was done in the Identify and Determine modules, which were used to gain a better understanding of the problem and to more clearly outline all of the facts.

While at first glance there may seem to be relatively few stakeholders in the outcome of the case, the analysis conducted using IDEA revealed that there are far more people with a vested interest in the outcome of the case than initially realized. The needs of these people have a drastic effect on the final verdict and to ignore them would lead to incomplete information and a less than optimal solution. Using the IDEA process it was determined that the men should be found guilty to uphold the laws of the state, but that their sentence should be commuted to account for the fact that they were forced into the situation and did not act willfully. This is one of the options presented in the original source, which once again confirms that the IDEA process can generate meaningful results. This, coupled with the fact that the use of IDEA leads to a better exploration of the possible options, demonstrates that the process can be of use in problems other than just engineering.

The final case study dealt with the design of the PowerPC 603 processor. This problem was selected for a number of reasons. Firstly, while it is an engineering problem, it is in a different discipline than the first case study. This would once again demonstrate the versatility of the IDEA process in that it could be used in the many different engineering disciplines. Secondly, a vast amount of information is available on the design itself. There are several papers [8,9] available that describe the conceptual design of the actual designers in detail.

Much of the original work was done using a program called BRAT that was able to simulate the performance of the processor as it was being designed. Many of the results of this were available which

showed how the performance of the processor changed and the designers altered its characteristics. The use of this information allowed for not only a large number of different concepts to be generated, but also allowed each of these different concepts to be assigned rough performance values based on the analytic results.

The application of the IDEA process allowed for the generation of eight different concepts for the final design of the PowerPC 603. Each of these concepts struck a different balance with respect to the design characteristics. Some sacrificed speed for lower power use and less heat generation, while other concepts were the exact opposite and were designed for maximum performance at the expense of all other characteristics. In the end, the authors identified a concept that struck the best balance between all the characteristics. While not identical to the actual 603 design, the concept that was selected by the authors was very similar to the actual one. This result yet again proved that the IDEA process was generating meaningful results, while the large number of generated concepts once again demonstrated that forcing designers to analyze all aspects of the problem lead to a greater exploration of the design space and the generation of "better" designs.

6. Conclusions

It can be argued that conceptual design is the most important phase of the engineering design process. Many of the decisions made during this phase can have far ranging impacts on the rest of the development process. The selection of an unsuitable concept can lead to delays, budget overruns, and possibly project cancellation. It is thus critical to conduct conceptual design in as thorough and logical a manner as possible.

Of great concern, however, is the fact that the conceptual design phase of a project is also one of the most confusing because the early stages of design have very little hard information available and the vast array of different tools that designers have at their disposal can be very confusing. The purpose of the IDEA process is to provide a standardized method for conceptual design that not only helps to remove confusion by presenting designers with the same set of tools regardless of the problem, but also helps to ensure a thorough exploration of the design space by forcing designers to look at many different aspects of a design problem.

The use of the software system enhances the usability and efficiency of the IDEA process since it leverages all of its strengths while also offsetting its usability problems. The results of the various case

studies demonstrate that these goals have been achieved. Not only has the use of IDEA led to a greater exploration of the design space in all three of the case studies, but the use of the interface has also created permanent documentation which outlines not only what decisions were made, but why designers made them. The achievement of these goals has led to an increase in the effectiveness of conceptual design which leads to the betterment of the engineering design process in the general.

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