Decision Based Design

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Preface

This book aims to be the first formal presentation of the central ideas that constitute decision based design (DBD). Engineering education aims to prepare us to solve challenging problems that confront our everyday lives. The connection between curriculum and practice, however, is not always obvious. There are concerted efforts all around the world to bridge this gap and enable the resulting integrated thinking in students, researchers, and practitioners. Through the work of many researchers and educators, DBD has evolved into a discipline in its own right that promises to accomplish this. It views the engineering design process as a set of decisions made by various stakeholders and attempts to model and predict the overall impact of these decisions.

Decision based design in many ways mirrors product design and development. Many fields have developed concurrently to aid product design as well as manufacturing, distribution, and commercialization. Engineering analysis methods have become more and more sophisticated. This sophistication has come at the cost of fuzzy boundaries between different disciplines. A design decision propagates through many levels of engineering and management, and its overall impact is rarely understood well. The field of decision based design aims to train engineers in understanding this interdisciplinary and coupled nature of modern engineering systems.

This book teaches most fundamental concepts encountered in engineering design, such as concept generation, multiattribute decision analysis, reliability engineering, design optimization, simulation, and demand modeling. It can be used in its entirety to teach a course in decision based design, while selected chapters can also be used to cover courses in subdisciplines that make up DBD.

Note to Students

Undergraduate and graduate students can gain immensely from this book. It presents many relevant concepts that you will encounter in the future, whether you choose to stay in academia or move to industry. You will be better equipped to understand an engineering system in its entirety and view yourself as a decision maker. Prerequisites for this book include basic courses in calculus and engineering design. Some knowledge of programming can be helpful in solving exercise problems or finishing projects assigned by the course instructor using this book. Most topics covered in the book are self-sufficient unless you intend to get deeper into a topic, for example, reliability engineering or optimization. At the conclusion of a course utilizing this book, you can be expected to be well versed in core concepts of decision analysis, optimization, product development, simulation, and reliability engineering. If the book is used to teach a course in any of the subdisciplines covered in the book, you are encouraged to browse through the chapters not covered to familiarize yourself with closely related topics.

Note to Instructors

This is a self-sufficient course in decision based design. The course can be supplemented with research papers and relevant books for in-depth analysis of certain areas. The course should include homework that enables students to not only practice concepts, but also think critically about the topic. An involved project can be a very good assistive tool. Students can be asked to apply DBD concepts to the design and development of a product for daily use. In cases where the book is being used for teaching DBD subdisciplines, the following guidelines can be used: Chapters 1, 2, 5, and 6 can be used for courses in optimal design or engineering optimization. Chapters 1, 2, 3, 7, 8, and 9 can be used in a product development course. Chapters 1, 2, 3, 6, and 9 can be used in a stand-alone course in multiattribute decision analysis. Chapters 4 and 6 can supplement a course in reliability engineering.

Any suggestions or comments that may improve the book are always welcome.

Vijitashwa Pandey, PhD

Acknowledgments

This book would not have been possible without the help of many friends and colleagues. I thank Prof. Efstratios Nikolaidis, Prof. Zissimos Mourelatos, and Prof. Deborah Thurston for the direct and indirect guidance provided. I thank friends Cheryl Eash, Akhil Indurti, Ananya Indurti, David Schenk, Danielle Dougherty, Bailey Kretz, Bill Larowe, Monica Majcher, and Dean Mollenkopf, among others, for support and encouragement. The book is also a result of tireless work by Cindy Carelli, Amber Donley, Tara Nieuwesteeg, and Amy Blalock of Taylor & Francis, who were always ready to help when needed. Their patience during the many inordinate delays in manuscript submission is also deeply acknowledged. Finally, I thank my family for their constant support and guidance.

About the Author

Dr. Vijitashwa Pandey received his PhD from the University of Illinois at Urbana–Champaign in 2008. He is an active researcher in mechanical engineering, particularly in the areas of design optimization, decision based design, reliability engineering, and sustainability. His work has appeared in many peer-reviewed journals and conference publications, in addition to a textbook. Dr. Pandey is a strong proponent of interdisciplinary and sustainable efforts in engineering design.

1

Decision Based Design: Introduction

1.1 Is Design a Decision?

Look at the nearest synthetic product around you. Who built it and why? What needs does it satisfy? Why was a particular material chosen? Why is the shape of the product the way it is? What could be done to improve the product? As you ask yourself these questions repeatedly you will realize that at least two (decision-making) entities were involved at some point in time that caused the product to exist: the manufacturer who made the product and the end user who purchased the product (which could be you). The end user had a desire for the functionalities of the product and believed that the resources required to acquire the product were justified. In most cases the resource required is money. The manufacturer fulfilled this need by providing the product at a reasonable price and made some profit in the process.

The interplay between customer needs and their fulfillment by a manufacturer is not always obvious. If we want to design a product, or effect an improvement in one, we would ideally like to be able to answer the question: Which way does the arrow of causality flow in product design—from the customer to the manufacturer (customer demands what the manufacturer makes) or the manufacturer to the customer (manufacturer makes a product and the customer buys it)? A historical perspective on product design is helpful in answering this question. Humanity has been producing tools for millennia. It is, however, only a recent phenomenon that we depend so much on man-made products without necessarily realizing where they come from—most of us were born into a society already dependent on man-made products. Most products that we see are a result of evolution in something simpler. Consider this, nowadays, the need for personal transportation is met by a gasoline-powered automobile. A few centuries ago, this need was met by simpler systems where animals provided the power. Then steam engines and internal combustion engines were built that could increase speed and reliability. Finally, the evolution of the transportation systems culminated into the automobiles we see today. At each step in the evolution of the personal transportation system, either customers demanded something better or the manufacturer provided something extra to stave off competition or

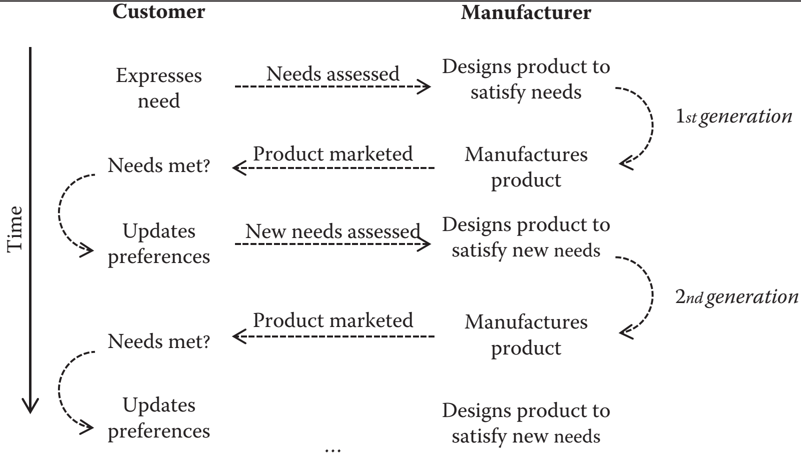

FIGURE 1.1
Evolution of products as a result of evolution of customer preferences.

invite new customers. Something better in personal transportation can mean higher speed, higher acceleration, increased safety, amenities such as car radio, heated seats, and more recently, Bluetooth and navigation systems—or combinations of these. So the causal arrow flowed from the customers to the manufacturer in the sense that they demanded what a car should be like. It also flowed from the manufacturer to the customers in the sense that customers had to choose from whatever the manufacturers offered. However, the causality is not circular; it is separated in time, as Figure 1.1 shows. Customer needs evolve, and so does the manufacturer's design in response to them. Additionally, the manufacturer's design influences customer behavior. We can choose where we want to start and stop in our analysis and, consequently, decide who influences whom.

In this book, the focus is on designing profitable products by making *good engineering decisions*. Consequently, we will be focusing on the manufacturer's perspective, and we will be focusing on products that require engineering. A manufacturer assesses what the customer wants, encodes this information, uses it to design a product, manufactures, and then markets the product, and the cycle repeats unless a new paradigm-changing product (disruptive technology) enters the market or the manufacturer moves on to another product or goes out of business. Since the general methodology within a cycle is the same, we will consider only a single generation in a product evolution cycle, which starts with a customer needs assessment and ends in the product being marketed. This defines the scope of this book. We will be looking at these steps within the framework of decision based design (DBD). We will be breaking up these steps into various technical and nontechnical tasks and identifying what decisions need to be made to accomplish them in the best possible way.

1.1.1 A Manufacturer Makes Decisions

The tasks within a generation of product evolution are very involved. They are planned and performed by individuals. After all, we need to make the decisions of whether to undertake new product development, collect customer preferences information, perform conceptual design, manufacture, and market. Each of these decisions has a huge impact on the success of a product as well as the manufacturer. It is also seen generally that decisions that are made solely on instinct and experience disappoint in practice. Decision based design takes us away from ad hoc decisions and instead gives us a formal method that is, for a given decision situation, repeatable, reproducible, and most importantly, defensible. It gives us a way to think about an involved product development process by breaking it up into small decision-making situations that can then be rigorously analyzed.

Many people follow a very narrow definition of a decision; they simply consider it as the task of selecting between different alternatives. Formal decision analysis and its counterpart in engineering design (DBD) take us a level deeper. In formal decision analysis, a decision is considered an irrevocable allocation of resources. It is considered irrevocable because backtracking to the status quo will cost money or time or both. It is an allocation of resources because they could be used elsewhere. If there were no resources to commit or if we could revoke decisions without losing anything, we haven't really done anything and there is no real need to analyze such a decision. Decision based design considers all the stakeholders as decision makers in their own right. It enables each one of them to understand the task they have been entrusted with and provides a method to make the decision that best serves their needs as well as those of the larger firm. DBD does not question the decision maker's preferences, but only prescribes a way of making a good decision, given these preferences.

Whether it is a new game-changing (disruptive) product or a mature one such as an automobile, the essence of the interplay between customer and manufacturer is always there. While introducing a disruptive product, a manufacturer has to work under tremendous uncertainty. Manufacturers spend significant effort and money trying to determine whether the customers will purchase the product that they are intending to produce. In mature products also, manufacturers need to continuously improve products by adding functionalities so that they stay ahead of the competition. Sometimes, external factors such as legislation effect a change in a product. Manufacturers should also keep an eye out for fundamental advances in technology that can make an established product obsolete. Classic examples of this situation are the electronic calculator replacing the slide rule and digital cameras replacing film cameras.

Once undertaken, a stage comes in the product development process where a design has to be selected and the manufacturing resources committed to it. Clearly, the manufacturer believed that the amount of effort and resources required in manufacturing the product were justified. This justification should be in the form of a clear order from the customer or, in a majority of cases, market studies which have indicated that many customers are willing to purchase the product. How did the manufacturer come to this determination? Did they have perfect information or were they extrapolating based on what they already knew? The manufacturer must have collected information through surveys or some other means. The questions asked in surveys help determine what attributes customers are looking for in a product and at what cost. Market surveys, as most sources of information, involve uncertainty. The manufacturer is always undertaking risk when committing to make a new product. This uncertainty can be formally incorporated if the manufacturer maximizes the expectation of its utility function, as we shall see in Chapter 3. Uncertainties are significant early in the design process, and decisions makers should be cognizant of this fact. Many product development processes are designed to be flexible enough to incorporate new information as uncertainty gets resolved.

Let us now delve deeper into the product itself, which the manufacturer is going to manufacture (the one that maximizes the expectation of the manufacturer's utility). Most products involve many components that need to be designed to work synergistically. Manufacturers require technical competency in making these components (unless it is decided to outsource some of them). The technical competency comes from experience and learning of individuals trained in the relevant subfields of science and engineering. Each of these individuals usually has an assigned task to finish given the targets and constraints. Does an engineer designing a small component also make decisions? Undoubtedly! He or she needs to select the material, from many choices, to make the component. He or she needs to prescribe dimensions, the mechanism of operation, materials, source of power, information flow in cases of electronic components, and so on. Each of these design parameters can be selected in many different ways. The engineer needs to decide which one of these will help the component meet the target requirements in the best possible way, while staying within the design constraints. He or she also needs to understand the effect of uncertainty, which in many cases is irreducible. The job of the engineer does not end at designing the component, though; he or she also needs to inform other members about any new information gained.

There are many system-level problems to be solved as well. Someone needs to coordinate the efforts of various individuals involved in the product design and development process. In most engineering companies a project manager is entrusted with this responsibility. He or she needs to ensure that every individual involved understands his or her tasks, that these tasks start and finish at specified times, and that raw materials and parts needed for manufacture arrive on time. Furthermore, project managers also need to act as liaisons between different individuals and recognize and resolve conflicts as they arise. They also need to have a good sense of where the project stands and if more or less money or resources need to be committed.

A project manager must have the technical background to understand the overall working of the product.

Many times a good design is not good enough. A designer must always look for the *optimal* design. An optimal design is the best design given the constraints. Optimality has a specific connotation in engineering design. It refers to the extremization of a *carefully chosen* function while maintaining its feasibility in terms of cost, safety, and engineering constraints. Obviously there should be agreement on what this function should be and how it is defined. For enterprise-wide problems the most commonly used metric is money, since the manufacturer's main motive is to make money. When solving engineering subproblems, the metrics could be engineering parameters like deflection in a beam, torque produced by a motor, money acts more as a constraint. Sometimes other metrics, such as reliability, commonality index, and design for assembly index, are used as objectives. Doing so, however, is advisable only if they do not conflict with the overarching metric of money or engineering constraints. Furthermore, in each case, a utility function must be assessed over the metric(s) selected.

Every decision maker involved in product design and development works under uncertainty. While uncertainty does not take away the ability to make good decisions, it does affect the ability to predict outcomes with confidence. The sources of uncertainty should be identified and their effects on the design understood. In engineering we refer to uncertainty in the context of a mathematically measurable quantity (random variable) whose realizations can be different each time it is sampled. One would prefer an accurate probability density function for these variables, but many times confidence intervals must suffice. Uncertainty gets into the equation through material properties, manufacturing variability, and uncontrollable factors such as increase in cost of raw materials and market conditions.

1.2 Some Examples of Design Decisions

As we have seen in the previous section, decisions permeate all facets of product design and development. Here we provide some examples of design situations where formal decision-making methodology brings tremendous value:

Enterprise-level decisions:

1. **New vehicle line:** When an automobile company decides to pursue a new line of vehicles, there are numerous variables to consider. What kind of demand exists for a new model? In particular, what are the distinguishing features the new vehicles will have? What level of commonality should exist between the current models and the new vehicles? What technical challenges

should be expected? What legislative requirements (fuel economy, safety) must be incorporated and how?

2. **Nuclear plant siting:** Nuclear plants are considered one of the cleanest sources of energy; however, when they fail, the results are catastrophic. This is why they are usually situated outside high population density areas. However, having them too far from the population can increase the resistive losses in power lines. Also, it is hard to find workers for the power plant in remote areas, particularly if basic amenities such as shopping, hospital, and schools are not nearby.
3. **Offshore oil rig:** Many times significant amounts of oil are trapped under the seabed. Preliminary studies can hint at the presence of oil but cannot guarantee it. Offshore oil rigs are commissioned at locations where tests reveal a high probability of the presence of oil. Even so, a decision must be made, involving vast amounts of money, whether or not to build a rig. The rigs must also be designed considering wind and water surge loads to avoid catastrophic failure.
4. **Offering a new cell phone:** To offer a new cell phone, a manufacturer must understand what functionalities customers are looking for in a cell phone and how much they are willing to pay for it. Manufacturers also want to know what technology to use, e.g., Code Division Multiple Access (CDMA) vs. Global System for Mobile Communications (GSM), and how to compete with competitors.

Engineering decisions:

1. **Material choice:** What material one should use to make a connecting rod for an internal combustion engine is an engineering decision. The material should be rigid, lightweight, and able to maintain its strength even at elevated temperatures inside the engine. Many times special alloys must be developed to increase performance and reliability.
2. **Engine variants:** Market forces sometimes require that a manufacturer make many variants of a product to capture enough demand. For example, a car can be offered in a 2.4 L four-cylinder engine version or a 3.2 L V6 engine version. These differences may require changes in the drivetrain, engine control modules, chassis, and even brakes. The designs should be such that they minimally interfere with the rest of the car, but at the same time provide enough distinction in terms of power to the customer.
3. **Cell phone processor:** Cellular phones today can outperform computers from a decade ago in processing power. The architecture is similar to computers in that there is a central processor

whose speed determines the overall speed and "experience" of the cell phone. However, increased speed in the processor requires compatible memory and video processing units. A faster processor will also drain the battery more rapidly. These factors must be considered when choosing one processor over another.

4. **Conversion of rotary motion to linear:** When converting a circular motion to a linear motion, many different mechanisms, such as the scotch yoke, crank-slider, or rack and pinion, can be used. Each engineering application has different power, speed, and reliability requirements, making one of these implementation options preferable to the others.

1.3 Roadblocks to Engineers Thinking about Product Development

Engineering acts as an interface between science and society. Progressively, it has become highly technical, requiring in-depth understanding of many concepts even while making marginal improvement in products. The result of this is that engineers sometimes tend to focus too much on their engineering subproblems and miss the big picture of profitable product development. While some of the roadblocks to engineers thinking about product development are attributable to engineering becoming highly specialized, others are more systemic and motivational. The engineering curriculum has only recently started acknowledging that in industry, monetary issues often outweigh engineering concerns. A design must be financially feasible (even optimal) to be pursued, regardless of how novel it is. There is also a general motivational aspect attached to engineering. Most engineers enter the field intending to do engineering. They consider financial and managerial aspects of product development to be too boring or nontechnical. This is highly ironical because most successful managers in industry started out as engineers. The good news here is that these roadblocks are being noticed, and most educational institutions offer courses in management and entrepreneurship to engineering students. In Chapter 7, we will revisit these roadblocks to engineers thinking about product development and discuss some additional ones.

1.4 Decision Based Design and Product Development

In this book, we employ the premise that decision based design mirrors product development. We argue that instead of studying the two separately, we should consider an amalgam of the two topics. Product development traditionally is considered to be the sum total of all the activities that together go into making a profitable product. Therefore, the product is the key focal point of the process. Decision based design also gives us a formal way of product realization. However, the contribution of DBD is that it realizes that many decision-making entities are involved that are trying to maximize their own satisfaction, while working toward a common goal of a profitable product. Decision based design therefore puts a human decision maker at the forefront. Not only does this change in perspective better reflect the workings of most companies, but it also provides for a richer understanding of product realization and how it can be accomplished in the best possible way, that is, by making good decisions.

1.5 Why Study Decision Based Design?

As we have discussed in this chapter, products over time have become complex, and their design and manufacture more difficult. More and more features are packed into a product, each of which poses significant technical and nontechnical challenges. Traditionally engineering approached design subproblems separately with very different focuses for each. Many subfields, such as design optimization, reliability engineering, simulation, product development, and decision analysis, were developed to address these needs. Since there is significant overlap between these subfields, a unified framework like decision based design helps by providing context to each design decision. We identified in this chapter, with many examples, that there are decisions being made at each step of product development. As opposed to using intuition, which involves subjectivity (and many concomitant risks), is there a formal methodology for making engineering decisions in the best possible way? Decision based design allows us to do that.

This book stems from a palpable void in the area of engineering design. In the author's time as a graduate student and later as a researcher in the decision based design area, many disparate books needed to be consulted to clarify a simple concept. Books that tended to be somewhat complete in a particular subtopic were so comprehensive that it was hard to find what one was seeking. Discussions with many a new researcher have revealed that they face similar issues; many times they are simply looking for a context in which to put their engineering knowledge. Decision based design provides that context.

There is no shortcut to learning engineering design. Just like the process itself (of engineering design), learning it is also iterative. At every pass one internalizes some concepts, while learning other new ones. This book was intentionally written to be approachable and short enough to be read from cover to cover. Most researchers will find what they are looking for in decision based design and, if not, where to look and, most importantly, what to look for. It will make them comfortable with many important concepts with lucid presentation and solved examples.

1.6 What This Book Does Not Cover

It is important to point out what this book does not cover. This book is not meant to be a compendium of knowledge on engineering design. The book is about what the title suggests, decision based design. It provides a basic framework that helps put accomplishment of engineering tasks in the context of decision making by the stakeholders involved. While enough discussion is provided in the relevant fields of optimization, reliability engineering, simulation, and uncertainty modeling to introduce the reader to these fields, it is not meant to be as exhaustive as dedicated textbooks in these areas would be. The reader hopefully will have developed enough background after reading the book that he or she can decide what aspect of engineering design he or she wants to pursue further. The book is one of the first attempts in presenting these seemingly disparate ideas in an integrated way. The book can be a great starting point in any of these research and practice areas. The interested reader can go about reading dedicated books or publications on the topics covered, if he or she is so interested. This book, however, does provide a comprehensive treatment on engineering design, decision analysis, and product development.

Many basic topics in mathematics and engineering are not covered, and the reader is assumed to be conversant with them. The reader is expected to be comfortable with random variables and their distributions, basic calculus (derivatives and antiderivatives of common functions), probability calculation of compound events, trigonometry, as well as commonly encountered engineering design problems. Where relevant, however, sufficient explanation is provided.

This book also steers clear of a dogmatic approach to decision making in engineering design. We contend that engineering design can never become a pure science. It is repeatable and reproducible for a given set of preferences, in given market conditions, and for a given product type. Even so, there is always room for subjectivity. A rigorous step-by-step approach to decision making in design will assume uniformity in all design problems and the challenges they pose. While seemingly lucrative, it can work flawlessly in one situation and disastrously in others. This is not to say that a proper approach is not beneficial; *it is* for the most part, as the next chapter shows. The rigor and constancy should be more in the way of thinking than in the process itself. The author's work is completed if, after reading the book, the readers feel that every design endeavor is simply the result of a series of informed good decisions made by the stakeholders.

1.7 For Students, Practitioners, and Researchers

The book is primarily a teaching resource, but can be equally valuable for both practitioners and researchers. Practitioners will learn the systematic method to engineering design that has been developed over the years. They will be introduced to the fundamentals of not only the relevant techniques, but also the philosophy of engineering design in the decision-making context. As we have mentioned many times in this chapter, decisions can and must be analyzed formally. A decision made in an ad hoc fashion, more often than not, disappoints in practice. Decision based design helps us think about decisions as allocation of resources, and every decision situation presents an opportunity to minimize the resources consumed and maximize the benefit realized. If practitioners internalize the basic ideas presented here, they will be better prepared to effect positive changes in their organization's best practices.

For seasoned researchers, this book can be a quick resource on engineering design, particularly on the topics with which they are not conversant. The book provides enough background in the topics of engineering design that they can quickly complement their knowledge. A particularly important addition to their repertoire will be decision making under uncertainty, particularly the topics in Chapters 3 and 6. For researchers new to the area of decision making in engineering design, or even just engineering design, this book can be a valuable resource. Unlike a dedicated book on decision analysis, or optimization, this book stays rooted in design. The book provides the most value for students—both graduate and undergraduate. If introduced early to DBD, they will be able to shape their education and learning in a way best suited to their interest, while being fully conversant in formal normative decision making.

Problems and Exercises

1. Comment on the interplay between customers and manufacturers when designing
   a. A new product
   b. An improved already existing product
2. How does uncertainty affect engineering design decision making?
3. Enumerate different decisions a manufacturing firm has to make for successful realization of a product.
4. How are enterprise-level decisions different from technical decisions?