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Book Reviews

Engineering Design Methods: Strategies for Product Design

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John Wiley, 2000, ISBN 0-471-87250-4

Engineering Design Methods is a relatively short book that presents many of the design methods in common use by industry. It is written in the non-mathematical style of other books such as *The Design of Everyday Things*, by Donald A. Norman; *Fundamentals of Engineering Design*, by William Lewis and Andrew Samuel; *Understanding Engineering Design*, by Richard Birmingham, Graham Cleland, Robert Driver and David Maffin; and even somewhat the lengthier and more classic books, such as *Engineering Design*, by Gerhard Pahl and Wolfgang Beitz; or *Total Design: Integrated Methods for Successful Product Engineering* by Stuart Pugh, all of which were written in the late 1980s and 1990s. These books take a process-oriented cut at engineering design that is almost totally free of mathematics. They present some discussion on what engineering design is all about, the design process, touch upon creativity, and then go on to a discussion of choice among design alternatives. Much of the choice methodology consists of constructing and filling in matrices with checks, x's and o's, and sometimes numbers, and manipulating these in some way. Among the major advantages of this book is that it is written rather concisely, and with a clear style that enables one to glean the gist of the methods with a minimum of effort. It is a worthwhile read if one is unfamiliar with these methods, and is suddenly placed in a design situation that involves a team of engineers who have elected to use the methods.

I believe that the best way to read this book is to accept its content as the author's view of engineering design, and indeed a view that is shared by a large cross-section of the engineering design community, and to accept the principles and processes described in the book as such. I caution the reader not to try to make too much sense of all this as, at least in my opinion, it doesn't make much sense. And this is really the weakness of the non-mathematical approach to engineering design. The methods outlined in the book are largely *ad hoc*; they have been developed without proof or validation of any rigor, and the reader should understand this and what it means.

At the opposite end of the engineering design book spectrum are books that are highly mathematical. A good example is, *Applied Systems Analysis*, by Richard de Neufville. These books tend to have a systems optimization orientation, and they present somewhat complex mathematical concepts that can be quite difficult to apply to complex engineering systems, thus leaving them with limited practical application. There is also the view among many design engineers that design is a creative process, largely devoid of mathematics, and this further leads designers away from the rigors of mathematics and into the fuzziness of methods such as those presented in ***Engineering Design Methods***. Non-mathematical techniques are fine if only they are logical and produce reliable results. If they are logical, they can be understood (I do not know what it would mean to "understand" an illogical concept). But are they? And if they produce reliable results, they can be used with confidence. But can they? These are the all-important questions that I will address below.

To answer these questions in detail would take a treatise much longer than the book itself. So I will confine my remarks here to some brief challenges of only some of the concepts and processes presented. Beginning on page 11, the author tells us that design deals with "ill-defined problems," and he goes on to define in some detail what this means. Let me consider one of the attributes of an ill-defined problem to which the author refers. "Any problem formulation may embody inconsistencies." I challenge you to make sense out of this seemingly innocent statement. Why would a problem formulation embody inconsistencies? If I were designing a commercial product, for example, my goal would be to make money, and there is certainly no inconsistency about that. To be sure, I could not predict precisely how design variations in the product would affect its ultimate profitability, but this is uncertainty in my ability to predict the future, it is not an inconsistency in the problem formulation. I believe that inconsistency and uncertainty are being confused with one another here. So I start from the point of view that the author's view of design is somewhat confused. It may be confusion, but keep in mind that it is also the conventional wisdom, and it is shared by the majority of designers.

The confusion continues into the definition of "design thinking." On page 17, "scientists problem-solve by analysis, whereas designers problem-solve by synthesis..." Again, this statement sounds quite reasonable on the surface, but becomes difficult to interpret when you try to place clear and definitive definitions on words such as "problem." Indeed, analysis may well be the appropriate approach to problem solving, but is that what design is? An alternative view is that design involves decision making, and that synthesis plays a key role in decision making. These little confusions build upon each other and eventually lead us into the major non-mathematical design methods such as Quality Function Deployment (QFD).

Chapter 7 provides a nicely written overview of Quality Function Deployment. QFD is widely used in industry, and it is worth knowing the process and understanding its weaknesses. It begins by placing heavy emphasis on obtaining the voice of the customer. On page 92, Cross talks about the "hall of tests," in which customers are given the opportunity to see, compare and talk about products. The resulting voice of the customer is then taken as the basis for design choices that follow. Again, it sounds good on the surface. But does it work? Let's look at an example.

Suppose 100 potential customers are presented with five different design alternatives – we'll call them *A*, *B*, *C*, *D* and *E* – and asked which they prefer. There is on the order of 10 million possible results one could get from such a survey. Let's look at one of them, the case where 45 people respond that *A* is their preferred design, 25 for *B*, 17 for *C*, 13 for *D*, and zero for *E*. Given these results, one is inclined to say that the customers' preference ordering is *ABCDE*, and indeed even conclude that no one wants *E*. But this would be a hasty conclusion. To validate such a conclusion, we would have to examine the individual underlying customer preferences from which the survey results derive. There are some 10^{62} sets of possible individual preferences that could result in exactly the stated survey results. One of these is the following:

45 people have the preference ordering *AEDCB*;
25 people have the preference ordering *BEDCA*;
17 people have the preference ordering *CEDBA*;
13 people have the preference ordering *DECBA*.

It is easy to see that this set of customer preferences indeed yields exactly the stated survey result. Yet, by pairwise comparisons, we see that *E* is preferred to *A* by 55 to 45. Likewise, *E* is preferred to *B* by 75 to 25, *E* is preferred to *C* by 83 to 17, and *E* is preferred to *D* by 87 to 13. Indeed, *E* is the most preferred alternative, and one can show that the real group preference is *EDCBA*, precisely the opposite of the initial conclusion. So, if one were to select the one design most preferred by this group of customers, it would be *E*. But is my example a rare event? This is a difficult question to answer because the number of possible cases is too large to simply count the times that such anomalous results occur. The problem has been studied by the mathematician Donald Saari, and he concludes that such anomalous cases dominate, such that one is practically guaranteed that simple survey results are misleading – let's say wrong.

In the above case, the customer survey did not solicit the underlying preference data, but rather obtained aggregate data in the condensed form *A*(45), *B*(25), *C*(17), *D*(13), *E*(0). It would appear that we could salvage survey methods by collecting the raw preference data and aggregating them only in the case of a specific decision. In theory, this could work, but in practice, it has problems. We can see this from another example.

Suppose we are designing a customer product for three potential customers, let's name them Tom, Pam and Jan. The product has three attributes, *X*, *Y* and *Z*, of interest to the potential customers, and two possible instantiations of each, X_a and X_b, Y_a and Y_b, and Z_a and Z_b. Furthermore, we will consider the case where the customers' preferences are such that they are attribute independent (the most favorable possible case for our analysis). Now, suppose the customers' preferences for each attribute are as given in the table below.

The preference notation here is the following: "Hate" means that the customer intensely dislikes this attribute instantiation and would not buy the product with it, "Like" means that the customer is satisfied with this instantiation, and "Favor" means that this is the preferred instantiation. A quick inspection of the table shows that, for each attribute, the customers prefer X_a, Y_a and Z_a by a majority of 2 to 1. As in the QFD procedure (and as with many other methods), one is then directed to conclude that the optimal product (or the recommended product) is the design X_a, Y_a, Z_a. However, once again this conclusion is a bit hasty. Full examination of the customer preferences indicates that none of the customers would buy the product X_a, Y_a, Z_a. Indeed, every customer prefers the product X_b, Y_b, Z_b to the QFD-recommended product X_a, Y_a, Z_a.

What this example illustrates so emphatically is the well-known result from economics that the optimal product is not the product comprised of the optimal instantiations of each attribute taken independently. Furthermore, this disparaging result obtains even in the most favorable case of attribute independence; it can only be worse in more realistic cases. Because of this result, any customer preference orderings that we seek as input data

Customer	*Consumer preference*					
	X		*Y*		*Z*	
	X_a	X_b	Y_a	Y_b	Z_a	Z_b
Tom	Hate	Favor	Favor	Like	Favor	Like
Pam	Favor	Like	Hate	Favor	Favor	Like
Jan	Favor	Like	Favor	Like	Hate	Favor

to our design selection methodology must be collected across the full spectrum of design alternatives, not merely across independent attributes. Herein lies a big problem. Any reasonable consumer product might have 10, 20 or even 100 or more attributes of interest to the consumers. And each attribute might have five, 10 or 20 possible instantiations. Let's take a simple case where there are 10 attributes, each with five possible instantiations. This leads to 5^{10} or roughly 10 million different products for which each customer whom we survey must supply a complete preference ordering. I contend that no potential customer will volunteer to rank-order 10 million different products, even if it were within his or her mental capacity to do so. Further, the QFD method fails to address adequately the issue of product cost as a function of design and it largely neglects product demand as a function of price, both of which are obviously critical to design choices. Lastly, it assumes that there are indeed preferred instantiations of attributes. But Nobel laureate Kenneth Arrow clearly demonstrated that this is generally not the case.

The result of the issues brought to light in the above examples is that the methods advocated in ***Engineering Design Methods*** are neither logical nor reliable. Indeed, we see in these examples that the methods are perfectly capable of selecting the worst alternative from among the set presented and that, at best, the selection that such methods provide is random. Given this disparaging result, one has to wonder if any insights at all can be gleaned from the application of such methods. Indeed, if in the generation of design alternatives, reasonable care is provided to eliminate obviously deficient designs from further consideration, then methods such as QFD are truly no better than random selection.

Given this alarming and rather contrary result, one has to wonder why the use of such methods would be considered at all. First, the methods presented in ***Engineering Design Methods*** are essentially those presented by many other publications. Unfortunately, however, neither in ***Engineering Design Methods*** nor in any of the other publications have the authors ever sought to validate the methods in a mathematically acceptable way. The danger in this naivety is obvious. But even among engineers who have seen the flaws of these methods, there is still a strong impetus to continue with their use. One explanation frequently given is, "These are special cases, they don't happen to me." But the work of Saari should put this argument to rest once and for all. Second, when such methods fail and produce blatantly bad decisions, we rarely hear the complaint that the bad design decision method used is at least equally culpable. Cases of failed methods are the rule, not the exception, and the probability that in any real design situation such methods will give valid results (that is, results that do not contradict the data upon which they are based) is vanishingly small. Third, and this is quite unfortunate, engineers use formal methods to obviate themselves of any possible blame for bad decisions made. If a company adopts a method such as QFD, and if the design engineers adhere strictly to the methods, then they cannot be blamed when they make bad design decisions. Finally, the non-mathematical methods are "easy" to learn and apply. Unfortunately, easy does not equate to reliable.

Thus, to sum up, I find ***Engineering Design Methods*** a book that is considerately and concisely written, and that provides a nice survey of engineering design methods in widespread use in a clear and accessible form. If your purpose is to gain an understanding of what these methods are, I can recommend this book. But if your purpose is to become a good designer, that is, if you really care that you make good design decisions, alas, the methods presented at best leave much to be desired and at worst lead to bad design decisions.

Reviewed by George A. Hazelrigg

Contributed by the Book and Software Review Department

Air-conditioning America. Engineers and the Controlled Environment, 1900–1960

Gail Cooper

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The development of air-conditioning served as one of the underlying factors to affect dramatically American society and the practice of engineering during the 20th century. The present work delves into not only the technological aspects of indoor climate control but how these shaped social and political policies and the economy.

Indoor climate control efforts began at the end of the 19th century in tobacco and textile factories as a means to improve production processes. The efforts soon devolved into a struggle between the technological elite who controlled the machinery and the craftsman who controlled the windows. The conflict would eventually give rise to industrial engineering and play a major role in the scientific management movement. The conflict would also change the management of engineering from a professional practice by a small group with esoteric knowledge to a situation where engineering was part of a broader manufacturing service to customers. This conflict continues today and is at the root of a significant cultural divide among engineers. Aside from its delineation of the social impacts of the controlled environment, the book's major value lies in defining and exploring that conflict.

Air-conditioning began to have a much wider effect on urban populations when cinema theater owners began to install cooling and dehumidification systems. By the onset of World War I, all the major theaters in the big metropolitan areas had installed systems. Soon, competition forced the spread of climate control (and differing approaches to solving the problem) even to small town movie houses across the country.

Sociologists tell us that the movies have had a profound effect upon American society in this century. Little have most realized that without climate control, none of this would have been possible as theaters would have been uninhabitable for up to half a year in most locales.

The progressive social and political movement that characterized much of US society up to the onset of the Great Depression incorporated an active effort to improve air quality in schools and public buildings. Proponents of "fresh" outdoor air went to bizarre lengths – holding classes on the roof of a grammar school in Chicago during one winter – to show the advantages over filtered and dehumidified air. Standards were developed during this period that continued to affect school construction and operations budgets decades later, long after anyone remembered why.

Air-conditioning had perhaps its greatest visible impact upon the American landscape in the post-World War II period. The modern skyscraper without interior ventilation shafts or windows, with shear, all-glass walls, would have been impossible without a/c systems. Likewise, the large expanse of relatively cheap tract homes depended upon the potential for air-conditioning to make them habitable. A need for massive increases in the housing stocks in the 1950s and 1960s to hold a burgeoning population changed land use patterns, led to suburban sprawl, and accelerated highway expansion.

Perhaps the most insidious impact was that upon energy consumption. As air-conditioning use increased, so too grew electrical load. Coal and petroleum consumption increased at a similar rate, bringing the first large-scale dependence upon non-domestic sources of petroleum. Nuclear power was viewed as a relatively inexpensive alternative to service this demand.

Even our modes of transportation incorporated climate control as motor vehicles and railroads added air-conditioning systems. This increased the mechanical loads upon engines and with the longer driving distances associated with sprawling housing developments, increased the petroleum requirement.

The present work reveals the inter-relationships of these factors for change in modern society. It is an important book for these who seek to understand why.

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