Recent Advances in Engineering Design: Theory and Practice

Moskalik

Follow this and additional works at: https://scholarworks.wmich.edu/masters_theses

Recommended Citation

This Masters Thesis-Open Access is brought to you for free and open access by the Graduate College at ScholarWorks at WMU. It has been accepted for inclusion in Master's Theses by an authorized administrator of ScholarWorks at WMU. For more information, please contact wmu-scholarworks@wmich.edu.
RECENT ADVANCES IN ENGINEERING DESIGN: THEORY AND PRACTICE

by

Andrew J. Moskalik

A Thesis
Submitted to the
Faculty of The Graduate College
in partial fulfillment of the
requirements for the
Degree of Master of Science
Department of Mechanical and Aeronautical Engineering

Western Michigan University
Kalamazoo, Michigan
June 1994
In the last few years, industry and academia have focused greater attention on the area of engineering design. Manufacturers have implemented new design methods such as concurrent engineering and design for manufacture, and academia has increased research in design-related issues. This paper will attempt to summarize the recent advances, both scholarly and industrial, relating to the field of design. I will examine new methodologies and supporting tools for the design process, both in use and under research. This paper will cover concurrent engineering, design for manufacture, quality methods, design theory research, computer-aided design, expert systems, analysis programs, manufacturing, and other subjects related to design, including engineering education. I will look at the newest advances forming the current state of these areas, the relationships among the areas, and the utility of each area. I will also comment on the future trends in engineering design.
ACKNOWLEDGMENTS

I would like to begin by acknowledging the influence of two men I have never met: Dr. John Dixon of the University of Massachusetts and Dr. David Ullman of Oregon State University. Their enthusiasm for and support of academic work in design theory (and the quality of their own work) inspired me to pursue the subject, and ultimately led to the work contained in this thesis.

Secondly, I would like to thank the people who took time to discuss with me their perceptions of the topics contained herein, specifically Dr. Jerry Hamelink, Ralph Damato, and James Moskalik. I also thank the members of my graduate committee, Dr. Jerry Hamelink, Dr. Dennis VandenBrink, and Dr. Judah Ari-Gur, for taking the time to review my work. I would particularly like to thank Dr. Ari-Gur for helping winnow the wheat from the chaff and bring some cohesiveness to the broad subject material I am presenting. His help in coalescing my ideas into something substantive has been invaluable.

Lastly, I would like to thank my wife, Teresa, for having the patience to watch me sit in front of a CRT and tap keys night after night, with nothing but this stack of paper to show for it.

Andrew J. Moskalik
INFORMATION TO USERS

This manuscript has been reproduced from the microfilm master. UMI films the text directly from the original or copy submitted. Thus, some thesis and dissertation copies are in typewriter face, while others may be from any type of computer printer.

The quality of this reproduction is dependent upon the quality of the copy submitted. Broken or indistinct print, colored or poor quality illustrations and photographs, print bleedthrough, substandard margins, and improper alignment can adversely affect reproduction.

In the unlikely event that the author did not send UMI a complete manuscript and there are missing pages, these will be noted. Also, if unauthorized copyright material had to be removed, a note will indicate the deletion.

Oversize materials (e.g., maps, drawings, charts) are reproduced by sectioning the original, beginning at the upper left-hand corner and continuing from left to right in equal sections with small overlaps. Each original is also photographed in one exposure and is included in reduced form at the back of the book.

Photographs included in the original manuscript have been reproduced xerographically in this copy. Higher quality 6" x 9" black and white photographic prints are available for any photographs or illustrations appearing in this copy for an additional charge. Contact UMI directly to order.
Recent advances in engineering design: Theory and practice

Moskalik, Andrew J., M.S.
Western Michigan University, 1994
TABLE OF CONTENTS

ACKNOWLEDGMENTS ............................................................................................. ii

CHAPTER

I. INTRODUCTION .............................................................................................. 1
   Background ................................................................................................... 1
   Areas of Advancement in Design .............................................................. 3
   Relationships Among Design Subfields .................................................... 4

II. DESIGN THEORY AND METHODOLOGY .............................................. 7
   Descriptive Models ...................................................................................... 7
   Protocol Analysis ....................................................................................... 8
   Creativity in Design ........................................................................... 10

   Prescriptive Models ..................................................................................... 11
   Taxonomies ................................................................................................... 13
   Analysis Methodologies .............................................................................. 15
   Conceptual Design ............................................................................. 16
   Optimization ....................................................................................... 16

   Design Representations .............................................................................. 17

   Issues in Design Theory .............................................................................. 19
   Design Science? ......................................................................................... 19
   Social Issues ........................................................................................ 21
   Response of Industry to Design Theory ................................................. 22

   Future of Design Research ......................................................................... 24

III. LIFE-CYCLE DESIGN AND CONCURRENT ENGINEERING ........... 27
   Design for Manufacture and Assembly ..................................................... 27
CHAPTER

Life-Cycle Design ................................................................. 28
Concurrent Engineering .......................................................... 29
  Teams ................................................................................. 30
  Cautions .............................................................................. 31
Problems With Life-Cycle Design and Concurrent Engineering .... 32
Future of Concurrent Engineering and Life-Cycle Design .......... 33

IV. QUALITY METHODS .............................................................. 36
  Methodologies ..................................................................... 36
    Quality Function Deployment .......................................... 36
    Failure Modes and Effects Analysis ............................... 37
    Taguchi Methods ........................................................... 38
    Methodological Comments ............................................ 39
  ISO 9000 .......................................................................... 39

V. DESIGN PROCESS MODIFIERS ............................................. 42
  Complex Vs. Simple Products .......................................... 43
  Mass Vs. Small Quantity Manufacture ............................... 44
  Metric System .................................................................... 45
  Standards and Codes ........................................................ 47
  Factors of Safety ............................................................... 48
  Effects on Design ............................................................. 50

VI. EXPERT SYSTEMS ............................................................... 52
  Catalog Selection ............................................................... 53
  Advantages and Disadvantages ........................................ 54
<table>
<thead>
<tr>
<th>CHAPTER</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Future of Expert Systems</td>
<td>55</td>
</tr>
<tr>
<td>VII. CAD SYSTEMS</td>
<td>57</td>
</tr>
<tr>
<td>Advantages and Disadvantages</td>
<td>57</td>
</tr>
<tr>
<td>CAD and Concurrent Engineering</td>
<td>61</td>
</tr>
<tr>
<td>Parametric Design and Design History</td>
<td>61</td>
</tr>
<tr>
<td>Intelligent CAD</td>
<td>62</td>
</tr>
<tr>
<td>Future of CAD</td>
<td>63</td>
</tr>
<tr>
<td>VIII. OTHER COMPUTER METHODS</td>
<td>66</td>
</tr>
<tr>
<td>Design Integration and Data Management</td>
<td>66</td>
</tr>
<tr>
<td>Virtual Reality</td>
<td>67</td>
</tr>
<tr>
<td>Analysis Programs</td>
<td>68</td>
</tr>
<tr>
<td>Finite Element Analysis</td>
<td>68</td>
</tr>
<tr>
<td>Other Analysis Programs</td>
<td>69</td>
</tr>
<tr>
<td>Solid Modeling</td>
<td>70</td>
</tr>
<tr>
<td>Other Computer Research</td>
<td>71</td>
</tr>
<tr>
<td>IX. PRODUCIBILITY</td>
<td>72</td>
</tr>
<tr>
<td>Research in Producibility</td>
<td>72</td>
</tr>
<tr>
<td>New Manufacturing Capabilities</td>
<td>73</td>
</tr>
<tr>
<td>Rapid Prototyping</td>
<td>74</td>
</tr>
<tr>
<td>Advantages and Disadvantages</td>
<td>75</td>
</tr>
<tr>
<td>Uses of Rapid Prototyping in Production</td>
<td>75</td>
</tr>
<tr>
<td>Materials</td>
<td>76</td>
</tr>
<tr>
<td>New Directions in Production</td>
<td>77</td>
</tr>
</tbody>
</table>
CHAPTER I

INTRODUCTION

Background

In 1992, America exported more products than any other country (Lacayo, 1993). Companies in the United States are realizing the economic benefits of producing goods intended for sale in foreign markets, and manufacturers are beginning to design products specifically intended to penetrate overseas markets (Baker, 1992). Meanwhile, most American manufacturers have become leaner and more competitive. The United States is the world leader in productivity (Lacayo, 1993), and selling products domestically against stiff competition is more difficult than ever. With the increased competition at home and the drive to sell products abroad, product value is more important to manufacturers.

Product value is a combination of many things: price, quality, utility, and so forth. Product design controls the value of the resulting item. Engineers have recognized for some time that design determines 70% to 85% of product cost (Vogt, 1990; Wingo, 1991), while directly accounting for only 5% of this cost (Yannoulakis, Joshi & Wysk, 1991). Companies have started focusing on the design cycle to cut product lead times, reduce price, and increase product quality and utility. "Design is a key issue in American competitiveness and fundamental to sustaining our competitive advantage" (Weil, 1993, p. 17).

Increased competitiveness has forced manufacturers to change design methods or be left behind. "In order to achieve . . . productivity goals, significant changes in the engineering process must be made--changes that involve new organizational
structures, new ways of working, new approaches to engineering workflow, new systems and techniques, and new ways of managing" (Benassi, 1993, p. 21). Industrial leaders have realized the truth in this statement, and have given top priority to revamping the design and manufacturing process in order to take advantage of shorter development time, lower product cost, and better match of products to customer needs (National Research Council Committee on Engineering Design Theory and Methodology [NRC], 1991). "Competing by improving the product development process is becoming pervasive" (R. Mills, 1993, p. 41).

While trade magazines are raving about the competitive success of concurrent engineering (Baker, 1993) and other new methodologies in the product development process, research work in design has also increased. Within the last 5 years, three new journals have begun publication (Research in Engineering Design, the Journal of Design Engineering, and the Journal of Design Management, Cross, 1993), the American Society of Mechanical Engineers has created a new annual conference (International Conference on Design Theory and Methodology) and the Journal of Mechanisms, Transmissions, and Automation in Design has been renamed as the Journal of Mechanical Design (the title it had previously) to emphasize its new focus on design theory and design-related issues. This explosion in design research in the late 1980s and early 1990s was likely due to the National Science Foundation initiative on design theory and methods (Cross, 1993), which spurred universities to pay more attention to design research.

A later report by the NRC (1991), which has stirred the academic community with its comments on and suggestions for improving engineering design research, practice and education (for example, see Dixon and Finger, 1991), sums up the importance and the goal of the new advances in engineering design. They stated:
Effective design and manufacturing, both necessary to produce high-quality products, are closely related. However, effective design is a prerequisite for effective manufacturing; quality cannot be manufactured or tested into a product, it must be designed in. The United States needs to sharpen its understanding of engineering design theory if it is to realize the competitive advantages of superior engineering design. Significant improvement of design practice requires increased knowledge of the fundamentals of design and increased readiness of firms to adopt new methods. Developing and teaching a coherent body of engineering design principles in this area could help accelerate the changes necessary to maintain the competitiveness of future U. S. manufacturing. (NRC, 1991, p. vii)

Areas of Advancement in Design

In creating new engineering design ideas and supporting greater industrial competitiveness, academic work has ranged across a wide spectrum of issues. Finger and Dixon, in their oft-cited review papers (1989a, 1989b) organized this design research into six categories. These six were: (1) descriptive models of design, which model how engineers do design; (2) prescriptive models for design, which model how engineers should design; (3) languages, environments, and representations for design, which are descriptions of design artifacts and the environment surrounding the engineer; (4) computer-based models of design processes; (5) design analysis; and (6) life-cycle design.

While academia has been increasing design research, industry has been formulating and employing new methods of design also. Concurrent engineering and life-cycle design methodologies have rapidly spread throughout industry, and are common enough now to require no definition when used in trade magazine articles. Quality methodologies have increased in popularity, spurred by the quality push of the 1980s. These methodologies need to be modified by applicable design process modifiers, including product complexity, lot size, the existence of standards, codes, or factors of safety, and the affect of the metric system.
The use of computers in design has increased rapidly at the same time. Computer-aided design (CAD) and finite element analysis (FEA) systems have been in use for years, doing design work that is difficult or tedious for engineers to do unaided. Recently, however, computer hardware has gotten small enough, fast enough, and cheap enough that engineers can use these programs much more extensively and effectively. Computer networks are furthering the ease of information exchange in concurrent and other projects. Other programs developed to aid design have been added to the repertoire of the engineer, including design-related expert systems, product databases, data managers, solid modelers, engineering analysis programs, and others.

Technology in general, as well as computer hardware, has also improved. Designers can now depend on new materials and manufacturing processes. Rapid prototyping has helped designers look at products in the first stage of development. There have also been advances in materials and production processes.

To keep up with the changes in industry, engineering education has also changed. Design now forms a more basic part of education, reversing the trend emphasizing engineering science begun in the 1950s. Engineering educators have also begun to stress team design and other procedures used in industry, in order to better prepare their students for a career in the industrial world.

Relationships Among Design Subfields

Academic researchers are constantly modifying and refining the methodologies that are now in use in industry (concurrent engineering and design for manufacture and assembly being the most well-known examples). These methods (including quality methods, which can be thought of as "design for quality" procedures), can be affected
by other considerations. The type of product being manufactured (complex or simple item, large or small lot), applicable standards and codes, and the management philosophy of the company play a role in the formation of design teams and the concurrent engineering strategy. Additionally, the available production procedures can affect concurrent methodology and the design process in general, as can the way in which computers are utilized in the engineering environment. Some programs, such as expert systems, informational managers, and intelligent CAD, are written specifically to support concurrent engineering.

CAD systems not only affect the workings of concurrent engineering, but, being a basic engineering tool, are also the points around which other computer-based technologies are arranged. Developers create some computer products to work hand in hand with a CAD system, such as product information managers or finite element modelers. Other applications are created as add-ons to CAD systems, such as solid modelers or format-changing software. Rapid prototyping production systems depend on the solid modeling capabilities of CAD systems. The representation and modeling of design artifacts is a basic topic in design theory, and the representation of objects is important to CAD manufacturers (particularly in parametric, feature-based systems) as well as to designers of production systems and expert systems. Expert systems can be combined with CAD to create intelligent CAD systems, where the computerized expert optimizes parts in a CAD-like environment.

Researchers often model expert systems on the cognitive processes of a human expert. Major areas in design theory research are the formation of descriptive models to describe how human designers complete the design process, and prescriptive methods to describe how design should ideally be performed. Other aspects of design theory research include the role of computers in design, the formation of analysis...
methodologies, and investigation into how engineers learn (and thus, how to teach them). Design education is changing as academia reinvents the engineering educational process to make academic training more relevant in industry.

Manufacturers are interested in these design procedures because of the benefit they expect from making products less expensive, faster, and of better quality. Concurrent engineering and life-cycle design accomplish these goals, but there are also aspects of marketing and production that directly affect the design. Designers need to consider standards and codes in the product realization process. In addition, adherence to general quality standards, like ISO 9000, can be the determining factor in the award of contracts, especially overseas. Manufacturers selling abroad also need to consider the application of the metric system to their products. The complexity of the product and the manufacturing lot size also affect production methods and engineering design.

All these subfields of design heavily influence one another. This is not surprising, as design is a complicated process that encompasses all of these topics. Indeed, as design and design methods increase in sophistication, the design process will become more concurrent and what are now distinct steps and methods will become blurred together. The subtopics discussed in this paper will then begin to intertwine even further into a complex product realization process.
CHAPTER II

DESIGN THEORY AND METHODOLOGY

The most basic research done in design is grouped into a category entitled design theory and methodology. This is the branch of research devoted to the modeling and formalization of the methods used by engineers (Salustri & Venter, 1991). The rationale for formalizing these methods is that, because much design work seems intuitive or is based on poorly understood rules, researchers need a more concrete description of the entire design process. A more completely described design process will help researchers categorize their work, help practicing designers produce well-engineered products, and help engineering educators teach consistent, concrete processes. This chapter covers four of the six basic research areas described by Finger and Dixon (1989a) and cited in Chapter I: (1) descriptive models, (2) prescriptive models, (3) design analysis, and (4) design representations. The other two areas are life-cycle design (covered in Chapter III) and computer-based models (covered in Chapters VI, VII, and VIII).

Descriptive Models

The main thrust of design theory research is in modeling all or part of the design process and investigating the correctness of the model (Smith, Eppinger & Gopal, 1992). One approach to modeling the design process is to investigate and describe how engineers create designs; that is, studying "what processes, strategies, and problem solving methods designers use" (Finger & Dixon, 1989a, p. 52). From this information, researchers can develop a cognitive model of the design process. The benefits of understanding the human design process are clear: (a) If the design process
is well understood, researchers can avoid creating methodologies that conflict with the natural cognitive process (Condoor, Shankar, Brock, Burger & Jansson, 1992); (b) the differences between experienced (and, presumably, good) engineers and naive engineers can be pinpointed; (c) better comprehension of the cognitive design process will improve engineering education and training by detailing the best ways to design; and (d) computational programs, such as expert systems, that are intended to aid or mimic the design process, can be built more like the engineers that they imitate.

Research in descriptive methods has ranged over many different subjects. Smith et al. (1992), for instance, modeled the entire design process to determine the amount of time needed to solve each stage of a design problem, and thus give managers a tool to improve control of these projects. Other researchers have attempted to model specific steps or aspects of design. Ullman (1993) examined how conceptual descriptions of function (what a device should do, or its ultimate purpose) and behavior (how the device performs this function) evolve over the course of a design.

Protocol Analysis

Techniques borrowed from artificial intelligence investigation, most notably protocol analysis, form the basis of most descriptive research (Finger & Dixon, 1989a). In protocol analysis, researchers record the actions of engineers during a design session and dissect the recording to ascertain the design processes used. For example, Takeda, Hamada, Tomiyama, and Yoshikawa (1990) used this procedure to analyze an example of the complete design process. They identified what aspect of the design problem the engineer worked on at any time and how the form of that aspect changed over time. From this information, they traced the path of the design process.
itself as the engineer considered different solutions and studied the impact of each of them on the design.

Researchers have also used protocol studies to pinpoint what actions experienced designers undertake that naive designers do not. The focus in these studies was on what experienced engineers have learned that makes them better designers. The studies have shown that experienced designers asked for more initial information and decompose the problem less (Christiaans & Dorst, 1992), and used inverse reasoning more (Waldron, Waldron & Abdelhanied, 1989). In a related study, Chovan and Waldron (1990) examined the differences in the way that engineers interpret drawings. They found that the meaning of the drawings varies significantly depending upon the experience of the designer; therefore, in order to completely describe a design, CAD systems must carry information about the experience level of the designer.

The evaluation of group design is another important area where protocol studies are useful. Because design is most effective when performed as a group (and, indeed, is most often performed in that manner in industry), the study of individual designers offers an incomplete view of the design process. The dynamics of a design group influence the design process in ways that are not seen when only a single subject is studied. There is little research that focuses on group design; most protocol studies involve only single designers. One study focusing on group design tracked the design actions performed by the group (how much and at what point in the design was time spent on various design-related tasks) and how the individuals interacted (Radcliffe & Slattery, 1992). McMahon (1991) looked at the utility of computational support for group design using an engineering manager program that controlled and tracked design activities and actions. Although the recording of design activity in this study
was admittedly not as complete as desired (in that gestures and other nonverbal communication could not be recorded), the study found that clear and frequent direction by the manager is important. A third, similar paper described research in controlling information flow in the group through the use of intelligent agents (Kannapan, Bell & Taylor, 1993).

Descriptive methods will become more valid when analyses focus more on group design. The study of individuals is important only in that individuals must be understood in order to completely understand the workings of the group. However, design really is a group process. The investigation of groups, although more complicated, is closer to the real process of design.

Creativity in Design

An area of design research that is heavily individual is the investigation of the creative aspects of the design process--how ideas are generated. Modeling the creativity of the design process may help engineers understand and harness creativity. J. J. Shah, Nico, and Kraver (1993) concentrated on the steps designers go through to generate an idea. They showed how experience is an important factor in idea generation, and commented on the use of "analogical" design. Analogical design (that is, using a familiar concept in a novel way to solve a problem) is a common way of generating ideas. Adelson (1990) modeled the process of a designer progressing through the steps of an analogical design. French (1992) showed that engineers often leap to conclusions from instinct, rather than using skills they have been taught in school. Robie, Kicher, and Wolfe (1992) demonstrated that different personality types perform differently in generating concepts (also see Chapter X). Radcliffe and Lee (1990) showed that sketching, although an important engineering tool, can also be a
block to the generation of ideas, and novice designers are often constrained in their
design by their sketch.

The group of creative methods in design, although not strictly a subject in
design theory research, bears some mentioning here. B. S. Thompson (1992) gave a
long list of techniques used in industry to stimulate creative design. This list ranged
from analogical design and brainstorming to morphology (listing and combining all
possible solutions) to use of significant technological advances.

There is some indication that novices or individuals unfamiliar with a particular
engineering field can be invaluable in forming creative solutions to seemingly
intractable problems (B. S. Thompson, 1992). B. S. Thompson also added that "these
individuals are not constrained to seek solutions using traditional approaches
employed by the more conventional experts in the field, and they can typically provide
fresh insight without prejudice against what can be achieved and what cannot be
achieved" (pp. 35-36).

Creativity is the portion of design that is the least scientific. Researchers can
formulate analysis methods and codify descriptive and prescriptive methodologies, but
creativity cannot be formalized in any way other than to create the techniques that
seem to stimulate creativity the best.

Prescriptive Models

Prescriptive models describe how the design process ought to proceed. They
are methodologies describing (according to the researchers) the steps required to most
efficiently complete the project realization process. Unfortunately, there is little
agreement among authors of prescriptive methodologies on how engineering design
should be performed, and there are nearly as many prescriptive design models as there
are authors to present them. Additionally, as Finger and Dixon (1989a) rather pointedly commented, "an implicit (and occasionally explicit) assumption of [prescriptive] research is that if designers follow the prescribed process, better designs will result. The authors of this article are unaware of any research in which this assumption is tested scientifically" (p. 55). With one exception (Ennis & Gyeszly, 1992), I have found no papers describing the testing of prescriptive methodologies. The one exception was a controlled experiment rather than a field test. Among the wide array of academic methodologies, not one has undergone a serious test in an industrial setting. This lack of field testing of prescriptive methodologies seriously undermines their collective potential worth, whatever the worth of the individual methodologies (Gill, 1990).

Various researchers have proposed these methodologies for use in different portions of the design process. For instance, in one paper Kusiak and Szczerbicki (1992) presented a methodology for the specification stage of conceptual design. Srinivasan and Allen (1989) proffered a method for preliminary design. In a third paper Shanmugavelu, Esterline, Riley, and Erdman (1991) presented a prescriptive methodology for conceptual design. Krishnan, Eppinger, and Whitney (1991) described designers working together in a cooperative manner, where the object was to obtain the best quality product when each designer is concerned with optimizing his own portion of the product. These researchers and others have been creating methods to complete different portions of the design process, but the methodologies are generally not compatible. The incompatibility of different prescriptive methods is probably the biggest problem with design theory and methodology; I will further discuss the consequences later in this chapter.
Another area of investigation of the design process is the examination of management of the design process. Traditional management methods neither account for the technical structure of the problem nor allow improvements in the management process (Eppinger, Whitney, Smith & Gebala, 1990). Because of the demands on management made by concurrent engineering, these improvements are sorely needed. The manager must ensure that requirements generated by various concurrent design groups are reasonable (Ward, 1990).

The biggest problem with prescriptive methodologies is that they have no practical worth until they are proven to be robust design practices in an industrial setting. Field tests of various prescriptive methods will weed out the less vigorous of these methodologies and give industry an incentive to utilize them (this subject is covered in greater detail later in this chapter).

Taxonomies

A basic idea in design theory, important to both prescriptive and descriptive methods, is the creation of taxonomies. Taxonomies are ways to subdivide the design process and categorize design problems. They are important in design research in that they assign each design problem to a specific place using a pre-established terminology. Under a consistent taxonomy, design tasks can be grouped with other similar tasks in order to solve them in a consistent manner. Taxonomies are useful in design practice also; they group design tasks in a consistent manner and provide a framework around which to establish a plan for completing the product design process.

Engineers are familiar with the traditional taxonomic divisions created by program management and used in product design: specification design, conceptual
design, preliminary design, detail design, and the like. This traditional division, however, is inexact and gives no information as to what is being accomplished and who is doing it (Ullman, 1989). Thus, an accepted, exact taxonomy is necessary to prevent confusion of meaning.

The most widely cited taxonomy is that created by Dixon, Duffey, Irani, Meunier, and Orelup (1988). They proposed that design problems be classified according to the initial and final states of knowledge. They listed six states of knowledge, which were, in order of increasingly specified detail: (1) perceived need, (2) function, (3) physical phenomenon, (4) embodiment, (5) artifact type, and (6) artifact instance. Each type of design was specifically defined as starting from a particular state and proceeding to some higher state. Thus, conceptual design, for example, would be described as beginning in a function state and ending with an embodiment.

Ullman (1989) expanded on the concept begun by Dixon et al. (1988) in order to create a more exact taxonomy for research. He included in his taxonomy a number of additional descriptors to further refine the classification of various design problems. The most obvious variables included were a description of who performs the design (individual, group, and/or computer) and their characteristics (expertise and so forth). Ullman also added a description of the design process (fixed plan, selection from list, and others, as well as modifiers to these plans) and a description of the research approach.

Although the taxonomy created by Dixon et al. (1988) seems to be the most widely accepted among other researchers (often with the modifications proposed by Ullman, 1989), other proposed taxonomies are in existence, such as the one J. J. Mills (1993) suggested. He differed with Dixon in suggesting that each step of the design
process be categorized differently rather than using the starting and ending states to
mark the type of design project. Thus, J. J. Mills did not group design projects
according to their starting and ending states, but rather paid attention to the various
states the design passed through. These steps are then individually compared to
similar steps in other design problems. J. J. Mills also differentiated between design
projects by including product complexity, originality of design, domain (electrical,
mechanical, etc.), specific activity, and experience level of participants as taxonomic
divisions. He expanded his taxonomy by specifically including production and product
support as issues in his taxonomy.

Analysis Methodologies

Another area of design theory investigation is the analysis of designs. Finger
and Dixon (1989b) pointed out that "traditionally, the distinction between design and
analysis has been blurred, and analysis often subsumes design" (p. 126). Until
recently, even design textbooks were really analysis textbooks (for instance, Shigley &
Mitchell, 1983), teaching the mathematical treatment of gears, beams, and belts rather
than design methodologies and processes. Currently, engineers are learning the
difference between analysis and design. Analysis is not design, but it is a part of the
design method, and useful in the product realization process. Researchers are
expanding the realm of knowledge in analysis methodologies. There are three main
areas of new research in analysis methodologies (as described by Finger and Dixon,
1989a): (1) optimization, (2) finite element analysis and numerical methods (which I
will cover in Chapter VIII), and (3) support of conceptual design.
Conceptual Design

One area of design analysis is creating methodologies for the evaluation of competing designs. Design evaluation is most useful, but also most difficult to do, in the earliest, conceptual stage of design. Welch & Dixon (1991) pointed out that the determination of the conceptual design fixes 60% of all life-cycle costs. With that in mind, they concluded that engineers will create better designs if methods are developed to evaluate system behaviors before explicit embodiments of the design are formulated.

To that end, researchers have been investigating the evaluation of conceptual design. Research in conceptual design analysis ranges from specific evaluation methodologies (Iyengar, Lee & Kota, 1992) to computational support (Diteman & Stauffer, 1992) to bond-graph representation of the design (D. A. Bradley, Bracewell & Chaplin, 1993) to measurement theory (Otto, 1993).

The most difficult problem in the evaluation of conceptual design is basing decisions on the imprecise information that critical design decisions are based on. Reddy and Mistree (1992) conducted research modeling this uncertainty in order to obtain the best solution with uncertain and potentially inaccurate information. The problem of inaccurate information is further compounded by the natural probabilistic uncertainty of design information. Otto and Antonsson (1992) have studied how to pick the best parameters in the face of the overall noise in the system using a method of probabilistic uncertainty.

Optimization

Another design analysis procedure is optimization. Optimization is a process whereby a design is fashioned to minimize or maximize a certain variable (weight, for
example), considering constraints placed on other design attributes. Optimization procedures can be a computer-intensive process. Because optimization is normally an iterative process, obtaining the best solution can take a long time. Some optimization research has focused specifically on improving optimization procedures (Yerramareddy & Lu, 1993), or refining the initial state of a design (Ramachandran, Langrana, Steinberg & Jamalabad, 1992) in order to decrease solution time.

Optimization algorithms are limited in that they are normally carried out with respect to only one variable. For example, a bracket may be optimized with respect to weight, with the understanding that it must meet some arbitrarily predetermined strength and cost targets. Thurston, Carnahan, and Liu (1991) created a methodology where a part can be optimized for many attributes at once. This offered an advantage in that the part can be optimized for the same variables that it will ultimately be evaluated for.

Optimization software has made the jump from academic labs into industry (Puttré, 1993c). Optimization is ideal for simple problems where one aspect of the design is distinctly more important than others or where there is a clear boundary (maximum stress, for instance) that cannot be crossed. Optimization packages can also be useful as add-ons to finite element analysis programs (Puttré, 1993c).

Design Representations

The representation of the physical and functional attributes of mechanical designs is another area of research in design theory. Standard representations of features and behavior can be used to create a library of parts accessible from CAD programs. Additionally, storage and retrieval of design information is easier when the information is stored parametrically in a feature data base (Peters, 1992). When stored
in this manner, engineers can perform design evaluations quicker and more easily (Rosen, Dixon & Finger, 1993). Simple geometrical representation systems are widely available, although there is not a standardized system for part representation (Finger & Dixon, 1989b). Complex representations of feature and behavior connectivity are few, however.

The bulk of the behavior representations has been created to describe the function of mechanisms. For example, Neville and Joskowicz (1993) created a representation language for describing the behavior of fixed-axis mechanisms. Their purpose was to develop a computerized mechanism designer that uses this representation language. However, there are few behavior representations that do not in some way involve mechanisms.

Simple feature representation, however, is a well-researched topic. A feature is "any particular or specific characteristic of a design object that contains or relates information about that object" (McGinnis & Ullman, 1992, p. 3). The recognition of features of parts can lead to better manufacturing processes; with feature recognition, intelligent process planners can automatically design production methods. Recording parts using features can capture the intent of the design (De Fazio et al., 1993). Some commercially available parametric CAD engines already exploit the use of features (Walske, 1993). Research on features covers several different subjects. Y. Chen and Langrana (1992) developed a feature recognition system to translate CAD data; Peters (1992) analyzed the extent to which feature recognition systems could capture geometric part data, assuming a large domain of possible feature combinations. De Fazio et al. explored the uses of features in the support of DFA methodologies.
Issues in Design Theory

Design Science?

Although some subtopics in design have been studied for decades (analysis, for example), design theory as a cohesive field is only 30 years old (Cross, 1993), and has developed strongly only in the last ten years (at most). One issue that has plagued design theory since its inception is the distinction between design and science. In the early, first-generation approaches to design methodology, researchers applied scientific principles to design in an attempt to create an all-encompassing "design law" that would be applicable in all circumstances (Cross, 1993). Most researchers have since abandoned the idea of a completely, scientifically structured design methodology in favor of a "softer" concept of design that includes scientific elements, but does not require a completely structured methodology. Cross defined design science currently as "an explicitly organized, rational and wholly systematic approach to design: not just the utilization of scientific knowledge of artefacts, but design also in some sense as a scientific activity itself" (p. 66).

There is still disagreement now, however, as to in what sense design should be a scientific activity. Konda, Monarch, Sargent, and Subrahmanian (1992) argued that emulation of natural sciences by attempting to formulate universally applicable design methods is meaningless, because contextual information is extremely important in engineering design. They called for the expansion of design research to include "individual, organizational, and social elements, which help designers collaborate by creating shared meaning and maintaining it as shared memory" (Konda et al., 1992, p. 40). Eder (1990) added that models and methodologies cannot be represented as a rigid sequence of work, but must rather be a flexible tool that changes with the
application. Eder also stressed the importance of creating methodologies with the
tasks of the engineer in mind. Willem (1990) acknowledged that design and science
are interdependent, but went so far as to say that "science and design . . . have little in
common" (p.323). He then added that "at its heart design is a creative act. . . . It is the
'creative leap' that is the 'crux' of design" (p.324).

Dixon (1991b) argued that this notion of design is incorrect, and design is
really a cognitive process. Dixon disputed the idea that engineering design is an art or
a skill. Designers get better with experience, but this is because of their knowledge
acquisition, not through an innate increase in their skill level. He claimed that the
argument that design is an art "has been used effectively to oppose design science
research and thus to keep design and practice stagnant and ineffective" (p. 66). Dixon
stated that the reason design is difficult to describe in precise scientific terms is not
because it is an art, but rather because some design knowledge is not yet fully
articulated.

It should be clear that design is fundamentally different from the "harder"
sciences of physics, mathematics, and engineering sciences (mechanics, heat transfer,
etc.). Research or practice in these harder sciences produces a concrete answer that
can be objectively judged: Is it right, or is it wrong? Design, however, produces a
product whose usefulness can be judged only subjectively: It works, but how well?
Design metrics have been used to "objectively" compare products, but ultimately the
metrics themselves are created subjectively, whether by customers, management, or
the engineers themselves.

This is not to say that design is an artistic activity. While the quality of an art
object is measured by the aesthetic pleasure it gives the viewer (or listener), design
quality is judged by the usefulness of the final product. This usefulness is quantifiable:
The product will work for a certain period of time, at a certain maximum voltage, under a certain load, and so on. The overall utility of a product is based on these hard data (but, because of the subjective importance of each attribute, is still a subjective judgment).

So what is design? It is neither a hard science nor a completely artistic endeavor. Design is a soft science that employs rules and methods, but cannot be totally quantifiable. The utility of a product is a subjective, but quantifiable, assessment. The practice of design can be improved by the application of new methodologies and the use of new tools, but it can never become a totally automatic process. The design must be responsive to issues included in the context of the design problem.

Social Issues

The idea of a contextual component of design proposed by Konda et al. (1992) implies that there is a social aspect to design that the engineer must consider. Blockley (1992) argued similarly to Konda et al. that engineering is not all technical rationality (and, indeed, he agreed with Willem, 1990, that design is distinctly different from science). Engineering science needs to be tempered with an "engineering wisdom" that includes philosophical values. Blockley supported the role of the engineer as a reflective practitioner (RP). The central concept of reflective practice is that the engineer has a responsibility to both his client and society in general. Blockley explained:

The RP is not concerned principally with the degree of truth of a theory or model, rather the RP is concerned with the taking of responsibility to act on the basis of the theory or model. The taking of responsibility implies not that one has earned the right to be right or nearly right but that one has taken precautions that one can reasonably be expected to take against being wrong. (p. 17)
Thus, Blockley emphasized that the job of the engineer is not to be scientifically correct, but rather to maximize the success of his or her designs. This is the responsibility of the designer to society, which transcends any other obligation the engineer might have. This is really not a new idea; the concept of engineering ethics has been in existence for quite a long time. Engineers are professionals like doctors and lawyers; they have a responsibility to their clients and to society in general.

In addition to the external society that the engineer is responsible to, there is also an internal, engineering society. French (1991) argued for a science of functional design, where all disciplines of engineering are combined into one society. He suggested that all design ideas developed over the centuries should be ordered into a coherent system. Because of the relatedness of different ideas, engineers can then draw on this codified knowledge and make analogies to their own products. With the advent of computers that can store vast amounts of data for immediate retrieval, the codification of knowledge will become easier.

Response of Industry to Design Theory

Despite the wealth of research that has been done in design theory and methodology, industry has largely ignored the field, particularly regarding the methodological studies of the design process. Manufacturing firms have enthusiastically adopted concurrent engineering and life-cycle design, but have paid little attention to any of the new academically-generated prescriptive methodologies or taxonomies. Finger and Dixon (1989a) agreed with Gill (1990), who suggested that the reluctance of industry to utilize systematic design methodologies proposed by academia stems from the differences among academically-produced design methodologies in their descriptions of the design process. He pointed out that (a)
current writings lack coherence, (b) the field has no standard vocabulary or taxonomy, and (c) there is no detailed overall systematic design methodology. In order to make the field of design research more relevant to industrial uses, Gill proposed a period of consolidation, where an international forum can make the message of design theory more cohesive and more accessible to users in industry. He also suggested more field trials to prove the efficacy of various methods.

Whitney (1990) believed another reason for the disregard of academic design theory by industry is that design research (and design education) is out of touch with industry. He pointed out that the research community has no consensus on what the pressing research needs are. With that in mind, Whitney suggested three definitions of design that could be used to focus research around. He stated that design is (1) a part of the product realization process, (2) the process of obtaining a robust product, and (3) the process of recognizing and resolving conflict during the creation of a product that meets a set of goals. With these definitions, academia can focus on the research and education issues that are most important.

The NRC (1991) agreed that, to some extent, engineering schools are out of touch with industry. They pointed to design education that fails to meet the needs of industry (which I will discuss in Chapter X), lack of research, and limited interactions with industry. However, they also faulted industry for not adopting the best design practices. They placed the blame not on engineers, but rather on company management, which does not adequately understand the product realization process.

I think that the main reason industry ignores methodological advances in industry is the lack of proof that the new prescriptive methodologies work. Industry is enthusiastically converting to concurrent engineering, which is a prescriptive methodology that has proved its worth. New prescriptive methodologies need to be
tested before industry will use them. During a cycle of testing, the less robust methods will fail and the lack of cohesion among methodologies will disappear as the methodologies best suited to industrial use survive. Requiring field tests for potentially useful methodologies might seem to lead to a vicious circle, where no companies are willing to experiment with design methodologies unless another firm does first. However, companies do realize the worth of experimentation to gain a competitive edge (else how would any new products be sold?). It is up to academic researchers to seek out industrial partners to enhance design knowledge. Engineers and even managers can easily be taught the usefulness of design research and new design methods if they have a chance to contribute to the formalization of these methods. I will discuss this further in Chapter X.

Future of Design Research

The biggest problem facing design researchers is the noncohesiveness of their body of research and the seeming irrelevancy of research to industrial practice. Design research is not considered a "mature" field of research because of the division of its message. Research is fragmented and the coverage of the entire realm of design is spotty. This is true of the harder portions of design research (analysis methodologies and feature research, for example), and more so for the softer areas like descriptive and prescriptive methodologies. Gill (1990) advanced an important idea when he called for "a period of consolidation . . . during which exponents can impose erudition on what is now an incoherent if not totally confused message" (p. 295). It is naive, of course, to expect this consolidation of knowledge to produce anything like total harmony in the field of design research.
However, it is not unrealistic to expect some agreement on principal questions for future design research and taxonomic divisions of the design process. Dixon, the primary author of the most widely used taxonomy (Dixon et al., 1988), admitted that "no widely recognized taxonomy of design problems has yet evolved" (Dixon, 1991a, p. 58). A common taxonomy would allow research to be grouped and compared. LaFleur (1992) further proposed that the research community should identify the principal questions in design theory. Identifying these questions should "bring cohesiveness to splintered research topics, establishing well-defined goals as well as serving as a common informational framework by which to express problems, methods, and solutions" (LaFleur, p. 89). The NRC (1991) recommended that all design researchers should at least be aware of how their research fits into an overall research agenda; identification of research issues and a specific, detailed taxonomy should help accomplish this.

Once a taxonomy is established, researchers need to focus on procedures that are directly applicable to engineering practice. The "best" methodologies may vary from company to company, product to product, and project to project. Because the primary function of design research is to supply industry with usable design tools, methodologies must be field tested to determine efficacy. To understand the design process better, descriptive methodologies must be formulated for group design. Design researchers, particularly in the field of descriptive and prescriptive methodologies, must develop closer ties with industry.

Design does include some social content and must be flexible. Design researchers, however, walk a thin line. On one hand, they must realize that design cannot be completely codified into one universal design scheme. On the other hand, there has always been some amount of suspicion of design by other engineering
academics because design is perceived as not being a rigorous discipline (Dixon, 1991a). In order for the present robustness in engineering design research to continue, researchers need to step back and formalize their concepts of the mission of design research. With an explicit representation of the principles and goals of engineering design, researchers can concentrate on the most important areas of research and define their own place in the engineering world.

Will design researchers actually follow the advice of Gill (1990) and formalize their methodology? Perhaps more importantly, will they develop closer ties with industry in order to prove the applicability of new methodologies? Unfortunately, I am pessimistic about the direction that design research seems to be headed. Although a few researchers agree with Gill, there seems to be too few of them (or they are not vocal enough) to create the kind of change of focus that is required.
CHAPTER III

LIFE-CYCLE DESIGN AND CONCURRENT ENGINEERING

The design portion of the product realization process determines much of the cost of the end product. Sequential engineering, where engineers design a product and throw it "over the wall" to manufacturing, costs a company time, money, and product quality. Industry and academia, realizing this fact, have begun utilizing and researching concurrent engineering, design for manufacture (DFM) (O'Donnell & Gomba, 1992) and design for assembly (DFA) (Lee & Melkanoff, 1991), related methodologies that force consideration of manufacturing costs early in the design stage.

Design for Manufacture and Assembly

The principles of design for manufacture and assembly are well-known enough that nearly every engineer is certainly aware of their utility. The idea behind DFM/DFA is simple: early in the design, explicitly consider how to manufacture parts at least cost and how to combine those parts into assemblies using the least labor (Vogt, 1990). By designing with these attributes in mind, engineers can substantially reduce the cost of the product. Proper consideration can reduce the number of parts in an assembly by as much as 90% and save up to 94% of assembly time (Vogt, 1990). Although occasionally the implementation of DFA or DFM leads to increases in product cost (Huthwaite & Schneberger, 1992), these methodologies, used with care, can be very efficient.

Many references give rules of thumb to accomplish DFM/DFA goals, such as combining parts and assembling bottom-to-top (Huthwaite & Schneberger, 1992).
However, there is rarely an objective rating system to compare strategies. Lee and Melkanoff (1991) created a methodology to rate designs on ease of assembly. O'Donnell and Gomba (1992) formed a method to examine the manufacturability of a design, and Heng and Gay (1991) researched a system that gives actual assembly costs. Although these rating schemes are necessarily subjective, in that they reflect the prejudices of the authors, they are still useful. They are a form of prescriptive methodology that describes the utility of products designed for assembly.

Life-Cycle Design

With the success of DFM/DFA methods proven by reduced-cost, higher quality products (Green & Reder, 1993), industry focus has widened from manufacturing and assembly costs to other costs in the product life cycle, in particular relating to postmanufacturing issues. Newer methodologies include design for serviceability (DFS) (Bryan, Eubanks & Ishii, 1992), design for the environment (DFE) (Ashley, 1993), and design for diagnosis (Ruff & Paasch, 1993), among others. The newer methodologies have not attracted as much attention as DFM/DFA (Ishii & Mukherjee, 1992), possibly because the benefits are not as visible (and do not directly impact product cost). All these methodologies, including DFM and DFA, are individually known as members of the DF"X" family, or collectively as life-cycle design.

Life-cycle design recognizes that issues such as disposability and service do indirectly affect the cost or utility of the product. As such, these concerns are worthy of consideration in the design along with manufacturing and assembly concerns. The methods used to evaluate a product for any particular aspect are fairly straightforward; the methods generally simply prescribe analyzing the personnel and time required to
perform tasks (such as recycling or service) in the product life-cycle (Ishii & Mukherjee, 1992). The above-listed references give examples of life-cycle design methods.

**Concurrent Engineering**

An effective tool for implementing life-cycle design is Concurrent Engineering (CE). According to the most widely quoted definition (from an Institute for Defense Analysis Report written by Winner, Pennell, Bertrand, and Slusarczuk), CE is

a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements. (cited in Benassi, 1993, p. 20; Karandikar, Rao & Mistree, 1991, p. 361)

The goal of concurrent engineering is to integrate all development stages into the design stage, and thereby reduce the cost and increase the utility of the product.

The procedure in concurrent engineering is to assemble personnel from all disciplines and all stages of the life-cycle into a team. All team members add their ideas into the design. The earlier in the design that the designers consider all facets of the life-cycle, the better the overall design will be.

There is ample evidence that concurrent engineering works. Trade magazines are full of articles praising concurrent engineering ("Design: The Power," 1993). The implementation of CE will typically save 40% in manufacturing costs while cutting development cycle times up to 60% (Benassi, 1993). Although the use of concurrent engineering normally imposes higher up-front costs than traditional, sequential engineering methods, studies have shown that this investment is relatively small compared to the potential overall savings (Belson & Nickelson, 1992).
Teams

Concurrent engineering is widely used as a vehicle to improve product design. The central component of concurrent engineering is the team. A good team can produce impressive results. A bad team can sink a project. Possibly the most important aspect of a good team is a strong team leader. A good leader needs to be a "people" person rather than a technical expert (Huthwaite & Schneberger, 1992), and must be an effective liaison between the team and upper management (Ashley, 1990). In addition, the leader must be clearly in charge of the project and willing to make decisions (Barr, 1990), lest the team becomes a committee.

Another important team characteristic is attitude and team dynamics. The best teams do not contain the most technically capable members. Rather, they are carefully constructed to contain members who work well with each other (Huthwaite & Schneberger, 1992). There is also some indication that team containing members with different educational or social backgrounds produce better results than those with members of similar backgrounds. In addition, all team members must be equal no matter what disciplines they hail from (Ashley, 1990). How decisions are made and how conflicts are settled must be clearly understood (Huthwaite, 1993). It has been noted that teams work most effectively when members are physically close to one another (Barr, 1990). Additionally, though, team members must be devoted to the project to work effectively. If members are not devoted to the team, but rather are required to "fight fires" on other projects at the expense of the team, the team is in jeopardy (Huthwaite, 1993). "How closely and how well team members collaborate can often spell the difference between making the deadline or blowing it" (Barr, 1990, p. 50).
The team design process can be as important to project success as team personnel. A team with more responsibility for the product and less time commitment to other projects will produce the best results (Huthwaite & Schneberger, 1992). Teams also work better when faced with smaller tasks. Large projects need to be split into smaller subtasks, each with its own subteam. The ability to focus on just one aspect of a larger problem enhances the creativity of the team (Huthwaite & Schneberger, 1992).

The team also needs a clear goal to function well. The specification of the end product must be clear, and the importance of various characteristics must be firmly established (Barr, 1990). Team members must understand all the project goals (Huthwaite, 1993), and communication with management must be open.

Cautions

The corporate culture that the team operates in is also important. Upper management must be supportive of concurrent engineering, giving the team a free hand to design the product (Huthwaite & Schneberger, 1992). Huthwaite and Schneberger cautioned, however, that a company cannot view CE (particularly when first implemented) as a cure-all for the company ills. This puts too much pressure on the first CE projects to "make good." However, the first implementation of concurrent engineering is bound to have some difficulties.

The aspect of concurrent engineering most fraught with difficulty is the implementation. Bringing any sort of change to a corporate environment will inevitably meet with resistance. Ringlein (1994) identified six problems that may occur during the implementation of any change in the product development process: (1) stagnation, (2) misunderstanding, (3) resistance to change, (4) lack of ownership (5)
distrust and jealousy, and (6) resource conflicts. A design team can overcome the first five problems if management fully supports concurrent engineering and correctly follows the suggestions to create good CE teams.

Resource conflicts, however, require some creative management to deal with. Because one expectation of CE is that the number of personnel time required to bring a product to market will decrease, management all too often overlooks the critical short term requirement for increased personnel (Ringlein, 1994). CE emphasizes dedication of resources at the beginning of projects, so during the phase-in of a company-wide CE effort, those personnel working on the front end of concurrently-based projects and the tail end of non-CE projects will be overwhelmed. During this labor crunch, the company may need to send some work to outside vendors, delay projects, or eliminate some goals to successfully implement CE (Ringlein, 1994).

Problems With Life-Cycle Design and Concurrent Engineering

Once past the initial implementation, the benefits accruing from the use of DF"X" methodologies and CE are abundantly clear and need not be repeated here (for examples, see Belson & Nickelson, 1992 and Karandikar et al., 1991). It is becoming apparent, however, that due to the extensive and sometimes contradictory goals of the various life-cycle methodologies, the aims of CE are becoming increasingly difficult to meet (Constance, 1991; Gershenson & Ishii, 1991). Research devoted to DF"X" has focused on improving only one or two members of the family at a time, rather than investigating and promoting a comprehensive view of life-cycle design.

There has been a recent realization that all life-cycle aspects need to be examined simultaneously (Marks, Eubanks & Ishii, 1993). However, there is little current research in this area, and existing subject treatments are little more than a
repetition of life-cycle design goals (Keys, 1988) or simplistic multiattribute optimization (Thurston et al., 1991) rather than an exploration of explicit methods. The lack of guidance in design practice results in either a disregard for particular life-cycle goals, or a sequential treatment of these goals—a "sequential concurrent design." This can lead to iterations through each different life-cycle goal, often leaving the design in whatever form it takes when production begins (Ward, 1990).

To compound this difficulty, the stated goals of concurrent engineering are more expansive than engineering teams can realistically accommodate. "Ideal" concurrent engineering (as defined above) requires that all development tasks be considered as early in the design process as possible. However, in concurrent engineering as normally performed, there is no consideration of labor, time, or engineering cost (the programmatic, upstream tasks) (J. Schmitz & Desa, 1992). Some published material on concurrent engineering included discussion of the role of marketing in concurrent development, but only a few papers included management in the concurrent scheme or emphasized the importance of including all departments of the organization in the concurrent design effort (Gujrati, 1992). In practice, the constraints on the upstream tasks are imposed by upper management at the beginning of the design project, and the design process lacks the flexibility of concurrently reallocating money and personnel for design tasks.

Future of Concurrent Engineering and Life-Cycle Design

The concurrent engineering now practiced in industry is an approximation of ideal concurrent engineering. The next step in the development of CE is to integrate all development tasks with design and manufacturing to create a "total concurrent life-cycle design" methodology. In other words, concurrent product design must be
expanded into concurrent project design by including both upstream and all
downstream development stages and concerns into product design. The constraints
imposed on design by upstream functions (minimum design time, minimum design
cost) should be treated the same way as constraints imposed by downstream functions
(minimum product cost, maximum product utility), and each constraint should be
handled in a fully concurrent manner. Project management needs to be changed from
a static process to a dynamic process that can handle issues raised by concurrent
design (Eppinger et al., 1990).

Accomplishing the realization of total concurrent life-cycle engineering is a
two-step process. First, the methodology must be developed. It will be necessary to
include, early in the design phase, the impacts of various design decisions on the
diverse goals of life-cycle design. However, representing all aspects of the life-cycle
will be very complex, in particular in the first stages of the design process. To develop
a system that can be used, industry will need computational support that can track the
status of life-cycle goals and the effect of design changes on all aspects of the product.

The second task will be to implement this methodology in a form that is usable
in industry. Some attempts have been made to support life-cycle design with
computer programs (Bowen & O'Grady, 1990), but the technique has been to
comment upon fully detailed descriptions rather than to support investigation in the
early design effort (concurrently, in other words) where the representation of the
product is necessarily amorphous. There are programs that support concurrent
engineering (see Chapters VII and VIII), but these have supported CE by
disseminating information or aiding individual designers rather than specifically helping
the concurrent process. It has been shown that in the early design stage,
communication using sets of possibilities will allow representation of the design
without the need to specify particular details (Lin & Ward, 1992). To meet the goal of total concurrency, the computational support will have to be in this form to support representations where decisions are not yet made.

Although it appears now that there is little if any progress towards implementation of a total concurrent life-cycle design, I believe that this accomplishment is not far off. Companies that have used concurrent engineering and DFM/DFA methodologies have seen impressive results. As the other members of the DF"X" family become more popular, engineers will quickly see the advantage of combining them into a total methodology. From there, concurrency will spread throughout the organization. There will be some resistance from individuals who see their autonomy being threatened (and by those who simply resist any change), but, as concurrent product development spreads, the entire organization will eventually be affected.
CHAPTER IV

QUALITY METHODS

Product designers have been making more use of the group of quality-based methodologies. The quest for quality started in the early 1980s; the attention now being paid to design methods can be seen as a direct outgrowth of this search for quality. Quality methods can relate to production, or, as in the methodologies presented in this paper, to design. Taken as a group, they can, as suggested by Swift and Allen (1992), be considered as another member of the DF"X" family—design for quality (DFQ).

Methodologies

Quality Function Deployment

One such method is called Quality Function Deployment (QFD), which is "a systematic approach for translating customer requirements into appropriate technical design requirements for each stage of product and process development" (Steiner, 1991, p. 191). The QFD method relates characteristics of a product to the customer needs in a matrix form. QFD is a method that specifically accounts for the desires of the customer (Hauge & Stauffer, 1993). The design team rates and weighs product attributes according to these customer needs. They then design the product to maximize the overall quality and utility. Hauge and Stauffer created a methodology for use with QFD (although it can also be used alone) that increased the depth and breadth of the requirements elicited from customers. This helped engineers understand exactly what customers prefer in the product, and aided in trade-off studies.
Liner (1992) described her experiences using QFD in conjunction with concurrent engineering. Although there were some problems in the implementation of QFD, she concluded that QFD helped her team design a quality product. Steiner (1991) noted that it is easier to implement QFD when a team works well together and understands its customers' requirements. Swift and Allen (1992) stated that the primary problem with QFD is the difficulty of properly defining the appropriate terms in the matrix, although they admit that this is largely overcome with sufficient training and experience.

A method similar to QFD is the House of Quality. This method weighs capabilities of a product in relation to each other (as well as in relation to customer needs) and accounts for coupling of attributes (i.e., increasing motor size to increase horsepower also increases weight). The name of the method is derived from the shape of the chart (a rectangle surmounted by a triangle) required to list attributes and coupling factors. Ramaswamy and Ulrich (1992) have defined a more accurate version of this methodology that accepts complicated links among attributes.

**Failure Modes and Effects Analysis**

Failure Mode and Effects Analysis (FMEA) is a reliability-based method that attempts to formalize the thinking of the design engineer in the avoidance or guidance of product failure. FMEA can be twinned with QFD, as a reliable product is nearly always an important customer concern (Swift and Allen, 1992). As described in Fuqua (1987), FMEA is an iterative process that occurs simultaneously with the design procedure. The method begins as a failure analysis at the part level. The design team examines and ranks all failure modes of all parts as to the likelihood and severity of the potential failure. Design engineers focus on the most severe failures...
and design to eliminate them. Although FMEA requires a large up-front cost in terms of labor involved, it has a number of distinct advantages. Design teams using FMEA will select a design with a high probability of operational success, and using the method will automatically provide a list of potential failures that can be the basis for later troubleshooting (Fuqua, 1987).

Taguchi Methods

The Taguchi method is "a statistical experimental technique aimed at reducing the variance of a product performance characteristic due to uncontrollable factors" (Michelena & Agogino, 1991, p. 13). Quality in the Taguchi method is measured by the performance of the product in society. A high-quality product is defined as minimizing the extent to which society loses from utilizing the product. Thus products that cause "any sort of problems--from environmental damage to personal dissatisfaction--are considered to be lacking in quality" (Huthwaite & Schneberger, 1992, p. 74). The more robust a product is under varying conditions, both external and internal, the higher its inherent quality (Michelena & Agogino, 1991). It is obvious that a more robust design is preferable to one less robust; in fact, other researchers have approached this problem using methods dissimilar to the Taguchi method (Otto & Antonsson, 1992).

Portions of the Taguchi method are somewhat controversial, however. Not everyone agrees that the Taguchi method describes a way of truly obtaining a more robust product. Perhaps because of this (or perhaps because of the large number of examples already in existence), there has been relatively little research in this area. Research into improvements in the method and comparisons to other methods is sparse (Otto & Antonsson, 1991). In a design environment, full Taguchi experiments
tend to consume a significant amount of resources and so are used only sparingly (Swift & Allen, 1992).

**Methodological Comments**

None of the quality methods are really new inventions. They merely take a common sense approach to product design by increasing the worth and quality of the product (Steiner, 1991). This can be accomplished by specifically matching customer needs, eliminating failure modes, or creating a more robust design. Use of these methods can eliminate poor quality products and cyclical design revisions that solve old problems only to introduce new, unexpected problems (Clausing, 1994).

Although presented separately, these methods are not necessarily unrelated. They can be used simultaneously during the design effort, and, far from interfering, can complement each other quite nicely. These methods can also be utilized in conjunction with concurrent engineering and life-cycle design; indeed, they fit nicely within the spirit of the DF"X" methodologies. However, quality methods have the same subtle deficiencies as CE and related methodologies: they have broad goals and no explicit command of the personnel and scheduling aspects of the program.

These methodologies eventually will be used with concurrent engineering as more companies use CE more extensively. They will be subsumed into a total concurrent life-cycle design as a DFQ method.

**ISO 9000**

Although strictly not a design quality method, ISO 9000 guidelines deserve some mention. ISO 9000 is a set of standards created by the International Standards Organization for establishing quality throughout a company (Korane, 1993). Standards and codes in general are covered in Chapter V. Governments and overseas
manufacturers are requiring their suppliers to adhere to ISO 9000 (Valenti, 1993), so American companies planning to be globally competitive are obtaining certification to keep on equal footing with their overseas rivals. Although the standards primarily affect production, there are some requirements that pertain to design engineering, and the guidelines are especially important in a concurrent environment.

Companies adhering to ISO 9000 have increased their quality, in particular lowering their scrap rate, creating fewer rejects, and increasing their percentage of on-time delivery (Valenti, 1993). Valenti added that ISO 9000 allows manufacturers to monitor and improve the quality of their business. "The main benefit [of ISO 9000] we see is a better understanding within the company of who does what," says a quality manager (Korane, 1993, p. 74). ISO 9000, because of its standards of quality, makes industrial customers more comfortable with the products they are supplied.

Not everyone agrees that ISO 9000 is beneficial, however. Line (1993) pointed out that while companies with little or no quality management will certainly benefit from ISO 9000, companies with sophisticated quality programs might see little value added to their products. Lohrer (1993) stated that "apparently the dictum for [ISO standards] is thou shalt document ad nauseam. The naive belief is that more is always better, which is as far off the mark as it can be" (p. 14). ISO certification can be a costly, unnecessary set of guidelines that imposes unneeded requirements on the company.

ISO 9000 guidelines can be useful, but they must be applied with care. The standards are not strict in their requirements, but they require consistency in internal policies, traceability of designs, procedures, and material, and accountability for actions. All of these can be useful, but companies need to implement the ISO standards with care. Often the companies being certified create new procedures that
are not well thought out. Poorly constructed procedures and company standards can discourage innovation. These procedures lack flexibility in regard to uncommon requirements, and can be a hindrance to product design.
CHAPTER V

DESIGN PROCESS MODIFIERS

In industry, the methods of design vary from project to project depending on the circumstances. As mentioned in Chapter III, project budget and available personnel are important factors in determining how a design progresses and what amount of effort the design team will put into each step of the design. The complexity and lot size of the product, in turn, determine the amount of resources to be allocated to the project. If the product is an established, widely used part, or if reliability is critically important, there may be standards or codes describing some aspects of the product. Existing standards and codes that govern the design of a product may have positive or negative effects on the design process. If the product is sold overseas, there may be foreign standards to consider, such as ISO 9000 standards (covered in the previous chapter) or requirements for adherence to the metric system.

Unfortunately, there has been little specific research about the effects of these modifiers on the design process and the necessary differences among the design strategies for various products. Most authors assumed that methodologies can encompass all types of products, without making allowances for variations in complexity, volume or standardization. However, product design cannot operate in a vacuum without consideration of these issues (design, after all, should be a concurrent process), and all these factors influence the design method.
Complex Vs. Simple Products

Most prescriptive methodologies are written with a moderately complex part in mind. The items that are either extremely simple or extremely complex will require modifications to any methodology.

Very simple products (for example, a nail or other type of fastener) are likely to have predecessors that are similar to the item in question. Additionally, the product itself is conceptually simple, and unlikely to require more than one design engineer on the development team. The challenge to the team designing a simple product is normally to design it specifically for ease of production. A simple, limited-production part should be engineered as quickly as possible to limit the amount of engineering time amortized over each product. High volume parts need to be carefully designed for inexpensive production.

Complex products present their own problems. An extremely complex product, like an airplane, can never be fully understood by one person. In this case, a large team is required, and the juggling of design priorities is quite important. With a large team and a complicated product, good data management is a necessity, so that each member of the team fully understands the ramifications of any design changes.

A special case of complex products is the small-quantity (often one-of-a-kind) made-to-order (MTO) product. Cleland and King (1993) studied the design process of an offshore oil production platform. They offered some conclusions that show differences between the design of complex MTO products and more traditional products. Foremost, they concluded that prescriptive methodologies generally do not apply to MTO products. This could be a result of the general noncohesiveness of the body of prescriptive methodologies, but more likely it is simply a result of the
narrowness of most methodologies concerning product complexity. Cleland and King also noted that, because of the "top-down" nature of MTO design (where information representation is very crude early in the design), the two-stage conceptual and embodiment stages of design collapse into one stage, and the generation of alternative designs seldom occurs.

Mass Vs. Small Quantity Manufacture

There are also distinct differences between products manufactured in mass and small quantities. Mass manufactured products can (and must) be carefully designed to reduce the cost of the final product by decreasing part and assembly cost. The manufacturer can afford to amortize an extensive engineering effort over the large number of parts built. However, the manufacturer must realize that competitors are likewise designing to reduce assembly costs. Therefore, the management challenge becomes specifying the necessary and sufficient engineering effort required to turn out a quality product in a timely manner.

With small quantity products (in particular very low quantities of one to ten), manufacturers do not have the luxury of a large quantity to amortize the engineering cost over. Extra engineering effort spent in optimizing the part and assembly cost may (and, in low quantities, will) outweigh any savings gained. In this case, the engineering manager must decide how to trade off engineering effort with performance and cost of the final product.

There is also the case of small-batch, high-volume production. In this instance, manufacturers carry a line of similar products that can be configured in different ways depending on the needs of the customer. These small quantity lots require machinery and personnel that are highly flexible, because configuration changes are frequent.
Products created with this form of manufacturing can be easily improved by applying design for assembly rules to make model transitions easier on the production line (Bak, 1992).

In reality, a design team must ascertain where the product to be designed fits along the spectrum of manufacturing lot size. Coupled with product complexity, this will determine the design strategy. The four extremes are: (1) simple, small quantity product; (2) complex, small quantity product; (3) simple, mass quantity product; and (4) complex, mass quantity product. As noted previously, prescriptive methodologies do not cover the complexity of the product. Nor do they cover the lot size. Even concurrent engineering (the most common prescriptive methodology) does not cover these issues. The level of engineering effort is normally left to the engineer (with no concurrent guidance) or, more usually, dictated by management before the beginning of the design program.

In my own experience designing moderately complex, low-quantity (lot size of six) products, I have often had to decide when an assembly was "good enough" to be produced. These decisions were based on diminishing returns: A system can always be improved, but is it cost effective in terms of engineering labor? This highlights the importance of these design process modifiers; rarely do engineering methodologies account for them. Creating a total concurrent life-cycle engineering methodology will automatically include these issues as part of the concurrent decision process.

**Metric System**

Manufacturers who produce products for sale overseas must also consider the importance of producing goods that are designed in metric units. Most American manufacturers currently use United States Customary System (USCS) units. Some
years ago there was strong momentum in this country toward changing to the metric system; the general public was exposed to liter beverage bottles, Celsius temperatures, and km/h speed limits. Now, however, the conversion process has slowed to a halt, and has even reversed in some areas (Dalphin, 1993).

Currently, there is some inertia built up in the United States resisting the switch to the metric system. Companies must balance the demand for USCS products at home with the demand for metric products abroad. Manufacturers dealing in foreign countries now have two choices: (1) They can sell non-metric products abroad and risk lower sales and potentially exclusive standards (Young, 1993); or (2) they can design metric products at potentially higher cost, with personnel unfamiliar with the metric system.

Because the United States is the only major industrial country that has not adopted the metric system, some worry that American manufacturers selling products abroad may be at a disadvantage. Another concern about the use of the USCS in the United States is the potential that foreign countries may adopt standards that exclude non-metric products (Young, 1993). To encourage the adoption of metric products, the federal government has required that its purchasers procure metric standard material (Young, 1993). However, this action will not hasten the advent of metrification in America. Rather, when American companies think it is financially advantageous to switch to the metric system, they will, and the rest of the country will slowly follow (Dalphin, 1993).

There is some support for the government to force the country (as much as it is able) to switch to the metric system. Proponents argue that U. S. industry will be more competitive if the incentive to stay with USCS units is removed. There is also resistance to the move, from people who fear a forced change will cost too much
money (and not be well received by the general public). I think that at the present time the USCS is too entrenched to change easily. Although remaining non-metric might hurt American competitiveness some, I agree that American companies will switch when they think it is advantageous to do so. America will eventually become dominantly metric, but this will take a long time. Even when that happens, there will be some areas where the USCS will remain as the primary unit system.

Standards and Codes

Loosely defined, codes and standards are regulations, either voluntary or enforced, that affect products and/or product functions. There is, however, a subtle difference between the two. Codes deal with the safety of the product. Standards allow similar products to be compared or govern the interchangeability of products.

Standards can be thought of as "documents of trade" (O'Grady, 1990, p. 24). O'Grady explained that standards can be used to facilitate trade by describing complex products in a uniform way. However, standards can also be used as regulations to prevent products from being sold. ISO 9000 standards are a good example of this dilemma. ISO 9000 certification makes company customers more comfortable with product quality (Korane, 1993), but requiring certification can be seen as requiring unnecessary documentation (Lohrer, 1993), in effect weeding out competition.

The nature of standards has changed in the past few years. Previously, standards for new products were developed after the products had been on the market for years. With the complex, high-cost products available today, consumers demand the adoption of standards before products are sold to ensure future compatibility (Line, 1993). The recent effort to define a standard for high-definition television is a good example. Line added that because of the push to describe standards before
products are built, standards hasten the implementation of technology, as the latest
technological advances are often included in the standard.

Codes and standards affect product design in a number of ways. Product
development, in particular in areas where the technology is still new, is risky without
consulting applicable standards (Line, 1993). Sony's BetaMax system is a good
example of what can happen if a company decides not to adhere to an industry
standard in an area where other companies are making standard equipment.

Standards, however, can be dangerous to the design engineer. As G.
Thompson (1993) pointed out, "the unthinking use of company and international
standards is the single most inhibitor [sic] of original thought" (p. 1). Standards can
stifle creativity and penalize the novel solution to a problem. Designers should
consider standards to be guides to common good practice rather than rigid constraints
that smother creativity.

With the recent rise in the number of product liability lawsuits, safety codes are
becoming more important. If a company is sued over the performance of a particular
product, and a safety code for the product exists, the company will certainly be called
upon to prove adherence to the code. Ignoring the directives contained in the code (or
even ignorance of the code) will cause the company to lose the suit.

Factors of Safety

Responsible engineers invariably use factors of safety in determining their
designs. The safety factor is defined as the ratio of the limiting stress (or other
characteristic) of a part to the working stress (Pahl & Beitz, 1977/1984). The value of
the safety factor will depend on uncertainties in the loading, part size, calculation
method, and manufacturing, as well as the importance of possible failures. However, as Pahl and Beitz added:

The determination of safety factors still lacks generally valid criteria. . . . Tradition, figures based on one-off and often inadequately explained failures, hunches and experiences are often the basis of numerical data from which no generally valid statements can be derived. What figures are given in the literature must therefore be treated with circumspection. (p. 191)

This is the area where codes and standards can aid the engineer, because they presumably prescribe an adequate, well-tested factor of safety. However, due to economic pressures, designers often provide just the regulated factor of safety and no more. This leads to design as "more a matter of satisfying the regulations than thinking fundamentally about the safety of the design" (Wolfram, 1993, p. 5).

A new concern in dealing with factors of safety arises from the increasing use of computer analysis in design, in particular finite element analysis. While FEA software developers are quick to point out the accuracy of their programs ("Algor Accuracy," 1994), the correctness of the output is only as good as the competence of the operator. As engineers understand less and less of the analysis methods used to judge their design, it becomes increasingly difficult to reliably establish an acceptable risk factor. Additionally, the apparent precision of computer output (not to be confused with accuracy) can give engineers "an unwarranted confidence in the validity of the resulting numbers" (Petroski, cited in Ferguson, 1993, p. 19). In particular when engineering students (who are used to relying on computer models) begin engineering practice, their lack of hands-on experience provides no reality check when an error occurs (Ferguson, 1993).

Engineers must be careful in choosing the factor of safety that they use. Factors of safety are really "factors of ignorance" that should be chosen based on the amount of knowledge the engineer does not possess. The designer still has a
responsibility to design a product to be as robust and safe as reasonably possible. Engineers should strive to understand as much of the analysis process as possible. More importantly, however, they must be aware of exactly how much they do not know.

Effects on Design

Factors of safety are often poorly understood, and engineers be wary lest they produce designs with a low safety factor. Engineers must be cognizant of how much they do not know. Standards and codes must be formulated and used with care. They will protect both the consumer, who can be sure of the product quality, and the manufacturer, who can bring the product to market with more assurance. However, it is possible to overspecify a product, stifling creative design.

As Cleland and King (1993) pointed out, prescriptive methodologies are not applicable to MTO products. I would add that prescriptive methodologies in general (including present incarnations of concurrent engineering) do not take into account any of the issues discussed above. Although the use of DFM/DFA does force consideration of production, there is usually no explicit consideration of these design process modifiers in the design process. Cleland and King added that "much more research needs to be undertaken into the field of prescriptive design methodology before the benefits that are claimed to accrue from adoption of such techniques can be fully realized" (p. 67).

The discussion of these design process modifiers reinforces the need for a totally concurrent design methodology. This methodology would automatically include consideration of these effects. Marketing and management would be included in concurrent decision making. As I stated in Chapter III, this methodology will
eventually be utilized in industry, as concurrent design spreads to include more of the design process and more of the organization.
CHAPTER VI

EXPERT SYSTEMS

Expert systems are computer-based engineering assistants that mimic the design process of an expert engineer. They are computer-based versions of standards and codes in that they codify knowledge based on past experiences. The systems contain bodies of factual knowledge combined with "rules of thumb" for applying the knowledge to solve problems (Horn, 1989). The process of producing expert systems is also known as knowledge-based engineering (KBE). Expert systems are used in diagnosis, production scheduling, and airport management, as well as in product design (Bulkeley, 1989).

Presently, there are a handful of practical applications of engineering expert systems, notably in areas requiring multiple numbers of closely related decisions like building customized proposals for a family of similar parts (Bulkeley, 1989) or as controllers in complicated manufacturing processes (Horn, 1989). However, KBE is a relatively new technology. With computers becoming increasingly powerful, more complicated expert systems will become feasible, and the CAD/CAM industry can concentrate on expert systems (which are computationally intensive) as its next big technological thrust (Saxena & Irani, 1993). Intelligent CAD systems are covered more completely in Chapter VIII.

Expert systems, besides being useful for proposals and manufacturing processes, can be used throughout the design process. In particular, the design of part tooling is complex and esoteric enough to warrant the application of an expert system (Cinquegrana, 1990; Haque et al., 1991). Experts can also be programmed to help
with design for manufacturing (Y.-M. Chen, Miller & Vemuri, 1991), and can potentially be used to handle nearly every function of the design process, from the design and analysis to costing, product support, manufacturing, and purchasing (Teague, 1993).

Researchers have done an extensive amount of investigation in the field of expert systems. Because the process being modeled (the thought process of the designer) is so complex, there is room for different schemes of doing so. Wang (1991) has presented a comprehensive survey of research in KBE. He has identified expert system research in three areas: (1) innovative design (introducing novel combinations of features within a design), (2) creative design (analogizing over domains outside the current design domain), and (3) routine design. Expert systems have been created that incorporate optimization rules into the expert (Ellsworth, Parkinson & Cain, 1989), that incorporate finite element analysis (Haque, Dabke, Rowe & Jackson, 1991; Prabhakar and Sheppard, 1992), that use solid modeling (Wang, 1991) and that learn and develop their databases as they are operated (Yang, Datseris, Datta & Kowalski, 1990).

Catalog Selection

Another area of design relating to expert systems is catalog selection design. Although not expert systems per se, catalog selection systems are similar in that they store design rules and use them to determine the optimum point in the design space. Catalog parts are often preferable to special parts because they are cheaper and of proven quality (S. R. Bradley & Agogino, 1993). Computerized selection of parts accelerates what is often a labor intensive search.
The principle behind catalog design is using a computerized knowledge base to assemble a system by selecting individual parts from a catalog of standard components. Catalog selection can range from a simple search for components in a database to finding the best fit for specified parameters (with perhaps some weighted merit function, S. R. Bradley & Agogino, 1993) to more complex schemes evaluating performance of multiple parts.

In a computer search of catalog parts, information is necessarily vague, as the intent of the search is to find a "best" match, optimizing the performance characteristics in a design space that is made up of irregularly spaced points (the characteristics of specific parts). To accommodate this imprecision, catalog selection programs must specifically account for it. Set theory is a popular way to mathematically model the design space. Vadde, Allen, and Mistree (1992) used fuzzy logic to optimize their designs. Ward and Seering (1993) used sets of artifacts to model not only the design space of various parts but also the changing performance of these parts under different operating conditions. More general research into dealing with imprecision has also been conducted (Wood & Antonsson, 1989).

Advantages and Disadvantages

Although the academically-generated expert systems have been slow to penetrate the market, they have many obvious advantages: (a) Knowledge is captured in a permanent form and it cannot be lost if the human expert leaves or dies, (b) the systems are available any time, (c) experts can contain knowledge derived from many human engineers, (d) experts provide a consistent answer to a problem and can be updated at any time, and (e) expert systems for design can potentially free engineers...
from the monotonous aspects of design and free them to concentrate on creative solutions to design problems (Horn, 1989; Teague, 1993).

However, expert systems also have disadvantages: (a) They are useful as a design aid, but cannot engineer on their own; (b) potential for problems arises when unskilled people operate expert systems with no oversight from a skilled designer; (c) expert systems require a large up-front investment in time to get them ready for use; (d) maintenance of the systems can be difficult; (e) they may be a hindrance to innovation because of the large amount of time needed to create and maintain them, and simply because designers prefer to use the system rather than create new designs; and (f) after making investments in expert systems, companies are naturally reluctant to move in new design directions that would require extensively updating the expert, or move to new systems as the old ones become obsolete (Bulkeley, 1989).

Future of Expert Systems

Future expert systems for design will be linked with CAD systems. In order to realistically support the design cycle, expert systems will need to be able to interface both input and output in a CAD format. Expert systems will become more integrated with other design software as more analysis packages come with expert add-ons. With increased interest in knowledge-based engineering, this is already beginning (Teague, 1993).

Wang (1991) foresaw knowledge-based concurrent engineering becoming more important in the future. He predicted increased use of intelligent assistants to design that automatically consider production, assembly, and other life-cycle considerations. The formation of intelligent assistants seems inevitable if concurrent engineering is to be truly followed. The breadth of life-cycle design goals and the
amount of information processing required in complex products necessitates the adoption of computerized assistants to aid in the CE effort.

In time, expert systems for design will be totally integrated with CAD systems. These intelligent systems will be used in routine areas of design where there is no need for creativity. Eventually, in conjunction with a parametric CAD that stores design intent, the expert systems may be able to automatically update themselves as human engineers create new designs. I will discuss this further in the next chapter.
CHAPTER VII

CAD SYSTEMS

Computer-aided designing has been in use for quite some time. In the 1980s and 1990s computing power became inexpensive enough that it was cost effective for any company to own a CAD system. CAD is quickly becoming indispensable, and is considered by engineers to be the most valuable aid to productivity (Williams, 1989). However, CAD has promised much, but delivered only some. "The benefits delivered by current systems have not met users' expectations" of being truly useful in the design process (Robertson, Ulrich & Filerman, 1991, p. 77). The discrepancy among engineers in their perceptions about CAD may seem puzzling at first, but there are distinct, highly positive features of CAD systems as well as specific areas where improvement is needed.

Advantages and Disadvantages

Using CAD, designers can work 200% to 300% faster than they can work using a drawing board (Kokos, 1992). In addition to increased speed, CAD systems also support 3D visualization, verification of clearances, "what-if" scenarios, and support for DFM/DFA. When an entire family of similar products is designed, CAD can speed up the design process by maintaining a part library for quick access (Rockett, 1990). CAD also encourages modifications to designs because of its quick and easy implementation.

The ease of deleting and moving features is the main improvement of the CAD system over the traditional drafting board. Revision changes that may have required completely reworking a board drawing can be quickly completed in a computer. With
computer networks, these modifications can be sent to all design team members. CAD enhances the visualization of parts, particularly in conjunction with solid modelers.

Computer-aided design can lead to even more productivity enhancements when it is married to computer-aided manufacturing. Linking the two enables quicker communication between designers and their manufacturing counterparts, and often decreases time of manufacture (Stagni & Davies, 1992). Unfortunately, CAD-CAM interfacing is surprisingly rare (NRC, 1991); the manufacturing aspect of CAD is one that is not living up to its potential.

Main and Ward (1992) identified several other problems stemming from the implementation of computer aided design. CAD may stifle design creativity because of its inherent limitations. Because the purchase of CAD and CAM equipment represents a major investment both in money (even at the reduced prices available today) and time (retraining personnel and converting old documents to new formats), companies are often unwilling to change when a system is already in place. This decreases their ability to capitalize on improvements to CAD software or hardware. The problem is exacerbated by the current troubles with integration and communications between systems.

Industry is finding data transmission in general to be increasingly important. Different companies, and often different departments within one company, frequently have incompatible CAD systems. When departments and companies using different systems communicate with one another, all too often designers must reenter data into computers using plots. The Department of Defense has advocated standard file formats for CAD design output (Puttré, 1991a) and the International Standards Organization (ISO) is currently developing a comprehensive set of standards (Curran,
Standard formats should increase productivity through rapid transmittal of data and elimination of double input.

The most serious (and most widely-voiced) complaint about computer-aided design is that it is underutilized (Keirouz, Pabon & Young, 1990; NRC, 1991; Robertson et al., 1991). Keirouz et al. stated that CAD has the power to be more fully utilized in the earlier portions of the design when it can be most valuable; however, CAD is rarely used until much later. In part this is the fault of the companies that utilize CAD; they do not push to use it early in the conceptual design. However, CAD systems that are suitable for use in conceptual design are recent products and have not spread through the industry ("A Healthy Combination," 1993). CAD should support many design activities, including, for example "many types of functional analyses and simulations, manufacturing evaluations at many stages, cost and quality estimates, marketing and sales functions, and tool and process design. Current CAD and solid modeling systems . . . do not serve these requirements" (NRC, 1991, p. 54).

CAD is not living up to its potential as a revolutionary force in design. "Conventional CAD is just an electric pencil," stated Clark (cited in Whitney, 1990, p. 4). Computer aided design is really used primarily as computer aided detailing. While CAD has worked wonderfully to describe, modify, and produce existing designs, it has done little to help in the process of creating designs. Cripps and Smith (1993) fingered the root cause of the underutilization of CAD when they stated that "computer-based systems [are] being developed purely from modeling and manufacturing considerations and not from the underlying base design" (p. 4). Unfortunately, CAD has stressed form over function, losing its promised versatility (Kempfer, 1993).

Computer-aided design is still not used by 70% of the engineers at small and medium-sized companies (Dvorak & Teschler, 1993), and two thirds of the engineers
at some larger firms (NRC, 1991). Although the majority of engineers not using CAD may be affected by CAD in some other way (such as interacting with a drafting department that utilizes CAD), this emphasizes that CAD has not been truly used for design as much as for recording design descriptions.

There is also a negative social effect related to adopting CAD in place of drafting boards. Jakiela and Orlikowski (1990) reported on a comment made to them by a senior manager during a plant tour:

In the past, the large drawing boards had served to record, display, and communicate the current status of the entire project to whoever chose to walk by. The boards had been used as forums for informal face-to-face meetings where designers gathered spontaneously to examine and discuss design problems and to gain a sense of the whole product. Today, designers in this firm tend to work on their own with their CAD workstations, with less interaction and brainstorming around the evolving design. The sense of a public forum, a communal reference point, and continual communication opportunity that had characterized drawing boards in this firm did not translate easily into the CAD environment. Peering at screens over others' shoulders seemed more intrusive and less satisfying as screens are perceived to be private workspaces and only show small subsets of the entire design at a time. (p. 127)

This anecdote highlights an unintended result of adopting computerized design: the isolation of engineers and portions of the design from each other. Engineers who have experienced the transition from board to CAD agreed with the analysis of Jakiela and Orlikowski (J. M. Moskalik, personal communication, January, 1994). Unfortunately, the isolation of individuals from the rest of the team is directly antithetical to one of the basic premises of concurrent engineering. For a team to function at its best, information must be easily available to all members. Correct team management may overcome this problem, however. The team workplace must duplicate the feel of the drawing board offices in that hard copies of parts must be readily available to promote discussion of the current design. Additionally, team
members must be encouraged to informally communicate with each other and discuss changes as they are being made (and have not yet been printed to paper).

**CAD and Concurrent Engineering**

Despite the problems that CAD creates, it also has the potential to solve these problems and others. CAD has shown its worth in supporting concurrent engineering efforts. Early in the design cycle, CAD/CAM can be used to communicate design intent to all people who need to know, in particular among personnel on cross-functional teams that have different backgrounds and points of reference (McCarty, 1991). Throughout the design cycle, current design information and updates can be transmitted at any time. With workstations networked together, this information can be instantaneously transmitted, and any information can easily be obtained by those who wish to know. In order to bring a total concurrent integration to product design, CAD and CAM can be combined in a knowledge-based system to support CE (Wei, Fischer & Santos, 1990).

The true power of CAD, though, is in its ability to be the central point of the concurrent design team. All design information can be contained in CAD files and associated programs. With a recording of design history, the entire design process can be reconstructed at a later date.

**Parametric Design and Design History**

A major potential advantage of CAD systems, particularly useful in concurrent engineering efforts, is the ability to store a design in a parametric form and/or record the steps of the designer in assigning values to characteristics of the part. A. Chen, McGinnis, Ullman, and Dietterich (1990) reported on the development of a system that records the stages of a design and the relationship among design constraints. This
in turn recorded the intent of the designer, which significantly improves design understanding and redesign ability.

Commercial CAD systems are beginning to utilize parametric features. Parametrically based software allows designers to easily change a design by adding or removing an entire aspect of a part rather than alter drawn lines as in traditional two dimensional CAD (Walske, 1993).

Intelligent CAD

Automation of the design process can be accomplished by combining CAD modeling with a type of expert system that will suggest improvements to the design to enhance quality (Jakiela & Papalambros, 1989). "The goal of 'intelligent' computer-aided design (CAD) systems is to provide greater support for the process of design, as distinguished from drafting and analysis" (Nielsen, Dixon & Zinsmeister, 1991, p. 95). CAD supports the detailing process quite well, but has the potential to be an effective tool in design also. However, the current techniques in computer-aided design are insufficient to automate the design process (Chern, 1991).

Development of intelligent CAD is just beginning, in part because the level of computing power required has only recently become available on the desktop. Although there are some intelligent CAD packages obtainable on the market (Cinquegrana, 1990), this area is still primarily a research subject.

Intelligent CAD system can be approached in different ways. A part can be modeled geometrically using features and the knowledge assistant can be utilized to provide suggestions about the manufacturability, strength, geometrical considerations, or other details about the part (Nielsen et al., 1991; J. J. Shah, Sen & Ghosh, 1991). The system can also store information parametrically to make changes more easily to
improve design quality (Chern, 1991). Artificial intelligence principles can also be used to base the intelligent CAD engine on the logical processes of the human designer (Takeda, Tomiyama & Yoshikawa, 1992).

An intelligent CAD system would have the same drawbacks as the expert system, the most serious of which is the high startup cost, in particular in industries with specialized needs.

Future of CAD

To make CAD systems more intuitive and easier to use, some interfacing changes must be made. The command syntax of many CAD systems is nonintuitive and difficult to use (Robertson, et al., 1991). Robertson et al. argued that the primary role of CAD should be to minimize the cognitive complexity facing the engineer. To that end, they stated that CAD systems should: (a) use a production-like metaphor, (b) evaluate designs, (c) automatically assume well-understood geometrical constraints, (d) automate some design tasks, and (e) use controls and displays that are intuitively shaped and arranged (naturally mapped).

To test these assumptions, Robertson et al. (1991) built a system used to design sheet metal parts that used an input device whose movements were naturally mapped into the part shown on the screen. Movement of the input device could cut, bend, or punch the part being designed much like a real part could be manipulated. This system used both a production-like metaphor and natural mapping. Barlow (1993) agreed that natural mapping improves design understanding. He described other input devices (now commercially available) that can interact more naturally with a CAD system than the traditional 2D mouse.
An obvious design task that could be automated in CAD systems is the task of dimensioning parts. Currently, dimensioning is accomplished manually, and it is up to the designer to make certain the part is neither overdimensioned nor underdimensioned. Research into this feature is already in progress (Serrano, 1991), but a completely automated system is still in the future. The major obstacle is that dimensioning schemes are not unique, and interpretation of the correct scheme is apt to be difficult.

The next generation of CAD will contain modes for free-hand sketching (and, in fact, a few already do). Jenkins & Martin (1993) emphasized that sketching is important in the conceptual design phase because it is a quick way to put ideas onto paper. With compressed engineering times and concurrency in the conceptual design phase, support of a sketch mode will be important in a CAD system. Currently, CAD forces its users to think explicitly in terms of rectangles, circles, and so on. Complex shapes can be tedious to input, and CAD is not conducive to quick approximations. CAD systems have the power to clean up hand sketches and store a permanent record of the evolution of a design—an invaluable personal engineering assistant that could change preliminary sketched designs into finished drawings.

CAD is now comfortably ensconced in the engineering world. Now that computing power is relatively inexpensive, new CAD systems can be constructed to be more intuitive. The next step in CAD will be to change the look-and-feel of the system to make construction of designs easier, implementing the suggestions detailed above. However, to be a truly indispensable tool, computer-aided design must not only alter its interface, but, more importantly, it must alter its engineering mission.

CAD systems in use today are good for detailing, but are not as effective in the earlier stages of design. CAD systems normally require a complete specification as an
input, and in reality the conceptual design phase is by then complete (Carothers, 1991). CAD must support more of the early design stages, and in doing this the concepts of intelligent CAD and parametric design will become more important.

Computer-aided design will need to support concurrent engineering, with the system becoming the meeting place for the members of the team. The most troubling point is the social aspect of CAD; engineering managers must combat the loss of informal meetings over drafting boards. As engineers use CAD more and more in their work (and that will happen), the ability of CAD to bring the engineering team together through easily shared information must grow faster than the tendency to keep them apart at their own terminals.

CAD will be the foundation around which future design programs will be built. Future CAD will be an intelligent system that utilizes analysis programs, expert systems, design information managers, manufacturing programs, and other software. CAD will support all design activities in one way or another, fulfilling the description of ideal CAD given by the NRC (1991). Some CAD packages already are becoming easier to use in the early design stage and do have the ability to perform complex visualization tasks and interface with analysis programs (Walske, 1993). In the future the number and complexity of these programs will increase.
CHAPTER VIII

OTHER COMPUTER METHODS

Design Integration and Data Management

Managing data has become increasingly important, particularly considering the need for wide-spread, up-to-date information in concurrent projects. CE requires many different people to consider many different effects early in the design cycle. Design software now available is tremendously powerful, particularly analysis and CAD packages. However, the impact of these products is decreased when they are used in a nonintegrated system (Solomon, 1994). Integration can be difficult when different products have different data storage standards, which is why there is a current emphasis on standards for product model data (Curran, 1994).

With engineering data management software (also known as product information managers, or PIMs), design team members can determine the impact of a change on other parts of the design (Cashman, 1992). In addition, all information is accessible to team members immediately. PIMs help design engineers by tracking parts and assemblies, purchasing agents by keeping a stock information database, manufacturing supervisors by aiding tooling and scheduling, and program management by controlling project development (Hunter, 1993).

Solomon (1994) described an integrated design package that is able to combine CAD, solid modeling, analysis (including FEA) and manufacturing. The package supported concurrent engineering by using a master model of all parts. The master may be accessed easily by all team members, and updated as required. Refinements made in analysis can be fed back into the master model. Walske (1993) described a
similar system where feature changes would propagate through assembly drawings, 3D models, and production models.

PIMs are simpler versions of what Cripps and Smith (1993) termed a design information system (DIS). They asserted (like Keirouz et al., 1990) that the computer is underutilized in the design process. They stated that "the tight focus of a majority of past and current research has resulted in islands of computerized processes" (Cripps & Smith, p. 3) which are not linked together. They called for the construction of a system that will support the design process through its entirety. The design information system can (and should) be combined with a CAD system to produce an information system and design assistant that can be utilized throughout the design process.

In the future these product information managers will make up an important part of the intelligent CAD system. Concurrent engineering will be more pervasive throughout the product realization process. The CAD system will be the central point for the dissemination of design information. The heavy flow of information present in a concurrent design environment (particularly in a large project) will require an automatic manager to prevent design changes from being misfiled or ignored.

Virtual Reality

Virtual reality (VR) is a hot concept in the computer world. VR describes software that lets the user experience a computer-based reality by using sensory input devices (like glasses and gloves). These give the user the impression of interacting with a 3D computerized world. Although not yet a technology that is usable in engineering, many are confidently predicting the appearance of a virtual reality CAD, giving the engineer the benefit of true 3D manipulation of parts (Puttré, 1991b).
Recently Autodesk (the makers of AutoCAD) released a suite of VR software development tools (Machlis & Teague, 1993). Demonstration programs using this virtual CAD already exist. Other VR products for engineers are on the horizon (Machlis, 1993).

Most analysts are cautious in their optimism about virtual reality. The technology is not sophisticated enough to be currently used in any commercial product except for a handful of video games. However, VR shows great potential in computer-aided design. To improve CAD, Robertson et al. (1991) argued, the design program needs to (among other things) use a production-like metaphor and use natural mapping in controls and display. The best metaphor and the most natural mapping would be to virtually form parts using the hands as a forming tool. Engineers could potentially use virtual reality to form parts by twisting, squeezing, or stretching them (B. Schmitz, 1993). With more powerful computers, engineers could meet as a group in virtual space and manipulate virtual products, completely overcoming the potential negative social effects of the use of CAD systems.

Analysis Programs

Finite Element Analysis

Engineering analysis programs have been in existence as long as computers have been. The most well-known and widely used type of numerical analysis is finite element analysis. FEA programs mathematically model physical characteristics of parts to determine how the structure will respond to various loads (stress, thermal, etc.) (Gloudeman, 1990). Using finite element analysis early in the design cycle can reduce or eliminate prototyping altogether (Vogt, 1990).
There are a number of commercially available finite element packages, along with programs using similar analysis methods (boundary elements, for example) to solve similar types of problems. Each of these packages may contain many different element types and mesh generation schemes; each of these schemes may work best on a particular type of problem. One area of research in finite element analysis is in the comparison of different methods (J. L. Chen & Ho, 1994). Another area is creating new types of specialized elements (Krawczuk, 1994), or adapting existing elements to new problems (Gibson & Austin, 1993).

The use of finite elements can also be expanded from strictly stress and thermal analysis into other stages of the design. For example, August and Zaretsky (1993) used finite element analysis to predict the reliability of components in a design. Wang (1993) used a scheme based on finite elements to predict the exact path paper will take in a copier.

Other Analysis Programs

The availability of the computer enables many specialized analyses to be performed. These include, among others, analysis of multibody mechanical systems (Lankarani, Bahr & Motavalli, 1991) and simulation programs (Machlis, 1991a).

In any analyses, and particularly complex computer analyses, the model necessarily contains some amount of approximation and idealization. In a complicated analysis, the engineer must keep evaluate the effect of any errors introduced by idealizations. Shephard (1990) illustrated this with the simple example of a finite element analysis of a bracket with reentrant corners. A quick approximation was to model these corners with no fillets. In theory, however, perfectly sharp corners would have given an infinite stress concentration, and the model would have reported a stress
level significantly greater than exists in the physical part. This would have posed no problem to the designer if the only data required from the model were overall deformations. However, an unwary engineer may have been led astray by the unrealistically high stress levels indicated by the model. Shephard suggested that using a knowledge-based interface that tracks areas of idealization could alert the engineer to potential problems and provide guidance as to what information may be required to accurately analyze the current model.

Solid Modeling

Solid modeling is an add-on to CAD programs. It is the generation of a three-dimensional image within the computer that is represented by its surfaces and volumes, as opposed to just its edges (like a wireframe). This type of modeling takes more computing power and, often, more human effort than a 2D model. Its big advantage, of course, is in visualization of the product. In a concurrent environment, many team members are not used to visualizing products from 2D or wireframe models. Solid models can be used to overcome this difficulty (Huthwaite & Schneberger, 1992).

Additionally, though, solid modeling can be tied to a shape optimizer or finite element engine to perfect the part design or generate tool paths (Owens, 1990) or to check the manufacturability of a product (Kempfer, 1993; Vogt, 1990). The newest solid modelers can store critical dimensions parametrically, making the design easier to accomplish, quicker to update and modify, and more error-free (Hanratty, 1994). Solid modeling will soon be not just an addition to a CAD package, but a permanent, necessary portion of the package. Solid models can be easily and automatically updated as the design progresses (Walske, 1993).
Other Computer Research

Other computerized research projects are also in process. A popular topic is in support for concurrent engineering. A few examples are research into the maintenance of multiple representations in an integrated concurrent environment (Cutkosky, Tenenbaum & Brown, 1992), group communication in CE (Jakiela & Orlikowski, 1990), and concurrent material selection (Karandikar & Mistree, 1992). Other specialized programs for the designer are also being researched and tested (Ramaswamy & Ulrich, 1993).
CHAPTER IX

PRODUCIBILITY

Research in Producibility

Producibility and ease of manufacturing need to be considered in the concurrent design process. Methods such as design for manufacture are cutting production costs with smart engineering that includes producibility constraints as design goals even in the conceptual design stage. These methodologies usually use simple rules of thumb to describe what makes up a better product. Research has been conducted to expand the capability to analyze products for greater producibility. Some analysis has been done to determine manufacturability directly in the design by creating a CAD-based program that will run through the production steps to determine if a part can be made (Anjanappa, Courtright, Anand & Kirk, 1991). Specifically for stampings, a large body of research is available to determine what features in a design lead to higher costs and what those costs are (Poli, Dastidar & Mahajan, 1991; Poli, Mahajan & Dastidar, 1992; J. Schmitz & Desa, 1992; Wilson & Wang, 1991).

Another system is described in Yannoulakis et al. (1991). The authors built a system that assessed the manufacturability of lathed parts. Their manufacturing aid was intended to be used by design engineers with minimal input from manufacturing. The system indicated which features of the product needed to be redesigned. Yannoulakis et al. used a quantitative approach to the analysis of the design, rather than the usual qualitative approach. The quantitative approach provided a degree of objectivity in producibility assessment. Engineers could then confidently compare alternative designs and pick the best one (Jansson, Shankar & Polisetty, 1990).
Another producibility issue is choosing the method used to produce a part. Often a particular part could be produced in more than one way (machining, sand casting, powder metallurgy, etc.). There are various "rules of thumb" regarding which method may be best and cheapest in particular circumstances, but in reality the choice of a method is often a "guesstimation" by the design engineer (Ishii, Lee & Miller, 1990). Many of the parameters used for deciding the production method cannot be estimated accurately. Ishii et al. have developed a systematic methodology for deciding the process to follow. Major factors affecting selection were (a) mechanical properties, (b) part shape, (c) part size, (d) tolerances and surface finish required, (e) materials, (f) time to market, (g) production quantity, and (h) production rate.

New Manufacturing Capabilities

The design of a product influences its production, but the production of a product can also affect the design. Engineers can take advantage of new production methods in designing their products. Some new production practices are related to new materials, such as fiber composites (Ramani, Cutkosky & Miller, 1990). New materials are covered later in this chapter. Other production practices are related to new ideas of how to manipulate parts in production (Trappey & Liu, 1990).

Automated machinery is another area where production has a big impact. Numerically controlled (NC) machines have been used since the 1950s (ElWakil, 1989), and their impact on manufacturing has gradually increased up to the present as the controlling computers became more sophisticated. NC machines can routinely manufacture shapes that would have been nearly impossible for a human operator to manufacture correctly. When fed with computer-aided machining data received directly from engineering, highly complex parts can be turned out quickly and easily.
NC robots can also be used in assembly. Robots can perform some assembly functions that humans are poorly equipped to do. This includes working in hostile environments (handling toxic, radioactive, or hot parts), performing monotonous jobs, and moving heavy objects (ElWakil, 1989).

These influences, however, do not have the greatest manufacturing impact on the design process. The greatest single impact is from concurrent engineering and the design for manufacture methodologies that enable manufacturing personnel to add ideas to the design process. This methodology creates discussion of manufacturing issues early in the design and lets the production crew contribute to the design and share ownership of the product. The advantages of design for manufacture are well known and were discussed in Chapter III.

Rapid Prototyping

Rapid prototyping (RP), which can be a big aid in the concurrent engineering process, is gaining popularity. RP is a process whereby model parts are produced by slicing a computer-generated solid model and forming each slice in a vat of photosensitive material using laser beams. The stack of slices can create a part in as little as 20 minutes (Deitz, 1990).

The two main techniques in RP are stereolithography, which uses photosensitive resins to form the part, and laser sintering, which uses powdered materials such as nylon, polycarbonate, and casting wax ("Laser Sintering," 1993). Other methods are available (such as fused deposition modeling, Crump, 1991), but their use is extremely limited. The selection of materials at the present time leaves something to be desired, but more powdered materials are being added to the laser sintering line and the mechanical properties of the photosensitive resins are improving.
Advantages and Disadvantages

RP prototype models are generally not prototypes in the classical sense, in that they are built of a different material and are not functionally equivalent to a real part. Although being supplanted with better materials, many materials that are available can cause problems with the part: shrinkage, swelling, warpage, and brittleness (Leventon, 1993). Small and finely detailed parts are also troublesome to make, as rapid prototyping machines cannot duplicate small features that conventional machining and casting can. RP has also been bedeviled with problems in translating data from CAD systems (Ashley, 1991).

On the positive side, rapid prototypes aid the engineer in investigating part properties that cannot be completely simulated by computer, such as the tactile nature, total visual impact, or wind tunnel response of the part (Albert, 1993). Mistakes in part construction can be instantly recognizable in a prototype when they are missed in the computer model.

The big advantage of rapid prototyping, however, is the increase in productivity that it enables. When RP is used in a concurrent engineering environment, everyone benefits. Factory floor personnel can use the part to verify how well assembly will work. Vendors use the part to ascertain the best way to manufacture the real versions. Engineers can count on a reduction in lead time through the instantaneous production of prototypes (Teague & Billings, 1993).

Uses of Rapid Prototyping in Production

Rapid prototyping can also be used by engineers to create tooling in a limited-production environment. Prototypes are being used as patterns for investment, vacuum and sand castings, as well as other methods (Dvorak, 1993; Thomas, 1992).
Thomas added that using RP significantly reduces labor and cycle time. Presently, some RP parts are durable enough to be used in some functioning assemblies (Thomas, 1992), and can be used in low-quantity production where the need for short turnaround time justifies the extra cost.

Materials

New materials also open the door to new ways of designing products. Composite materials, including high-tech metal matrix composites (Zaretsky, 1994), are becoming more popular as the reduction in weight compared to traditional isotropic materials (like steel and aluminum) in certain applications becomes known. Engineering with composites is different than engineering using metals. A composite part, because of its anisotropic behavior, may not look at all like the metal part it replaces (Maloney, 1994).

Plastics are proliferating as manufacturers produce more durable materials. As products are constructed using more and more plastic, plastic manufacturers are turning out lighter, tougher, and less expensive materials (Chamberlain, 1994). Designers are finding that these plastics can more easily form the complex parts that DFM/DFA methodologies specify. Replacing metal parts with plastic can save 50% in material cost, as well as eliminating finishing operations and reducing weight ("Plastic Chain Saw," 1994). Ceramics are being used more, too, as well as parts produced by powder metallurgy (Chamberlain, 1990).

Metals that contract when heated are now taken seriously as solutions to medical, robotics, aerospace, and micromachine design problems (Boggs, 1993). These materials are also used in composite materials; polymers have been produced that will do the same thing (Constance, 1991).
With the proliferation of materials, it is important to keep track of the properties of each available material, in particular when critical analysis depends on the given properties of the material selected. Data bases have been created that will track the material needs of all company engineers (Puttré, 1993b). Databases can eliminate erroneous material specification and the redundancy in labor required to compile material specifications. Additionally, databases can identify preferred materials that the company would like engineers to utilize.

New Directions in Production

As production and design become more intertwined, the distinction between the two will blur. Concurrent engineering already stresses the importance of considering production early in the design. New research in producibility is ensuring that designs are manufacturable when they first come to the production floor, and no redesign need take place. Rapid prototyping, along with other new techniques (CAD, for instance), helps the engineer produce a more manufacturable design and blurs the boundary between manufacture and design further.

New materials will also expand the realm of design possibility. As designers specify more new materials, however, manufacturing workers will be needed to process them. With the increase in the use of NC equipment and robots, the production worker will need to be more versatile and more highly trained.
CHAPTER X

EDUCATION

Because the role of the engineer in the product realization process is changing, engineering education is changing too. In the post-Sputnik era, engineering education had focused more on theory and science than on teaching students design skills. However, due to mounting concerns over the lack of design skills taught during undergraduate education, more emphasis is given to teaching design skills. Engineering schools have endured fairly harsh criticism on the lack of preparation their graduates show for industrial work. Industrial dissatisfaction with the state of engineering education has been growing, in particular because American engineering training suffers in comparison to European and Japanese education (Lyons, Anselmo & Kuller, 1993). "Engineering design education, especially in mechanical engineering, is adrift," stated Dixon (1991a, p. 56).

Criticism of Design Education

The key criticism of engineering education is what industrial leaders see as the lack of understanding new hires have for the job of engineering. Manufacturers have complained that engineering graduates have a narrow view of what the job involves, and cannot work in a team, assume leadership roles, communicate well, or solve real-world problems (Braham, 1991; Katz, 1993; Lumsdaine & Voitle, 1993). Industry seems united in the opinion that engineering schools are turning out engineering graduates who are great scientists, but mediocre engineers (R. J. Damato, personal communication, November, 1993; Nicolai, 1992). Universities are beginning to realize
that teaching just engineering science is not an adequate preparation for an engineering career.

The perception of design and design education in the university also needs to improve. Unfortunately, universities do not value design engineering as an intellectual activity (Curry, 1991). Design faculty members are often penalized by the tenure system because the work they do is not recognized as being as legitimate as the work done by engineering science researchers (McMasters & Ford, 1990; NRC, 1991). Part of this perception stems from the thought that design academics are not earning their keep by bringing grant money to the institution. McMasters and Ford suggested creating an alternative reward system to compensate for the limited research being done by design faculty members. Pister (1993) agreed, suggesting that teaching be given at least as much emphasis, if not more, as research in the faculty reward structure.

However, Dixon (1991b) warned against eliminating research as a function of design professors. He argued that design faculty should be doing research to expand the base of design engineering knowledge. The NRC suggested that design be recognized as an item critical to the national security and economy. They further suggested that, in order to establish design as a research priority and stabilize the funding for design-related issues, the National Science Foundation should propose and fund a design theory program.

Adding Design to the Curriculum

In order to improve engineering education, leaders in industry have been calling for more recognition of design education and the reorganization of the curriculum to integrate design throughout (McMasters & Ford, 1990; Nicolai, 1992).
Emphasizing design through assigning open-ended problems and stressing team design techniques would teach students the fundamentals of the industry methods in a controlled classroom environment rather than the first day on the job. Design work included in the day-to-day assignments in engineering science classes would provide immediate evidence of the usefulness of the subject and a bridge to context-dependent design practice (Peterson, 1990). West (1991), a professor at MIT, added the following:

The purpose of undergraduate design education is not just to present the body of knowledge with which we expect the graduating engineer to be familiar, but to lead the student from his or her initial understanding through an educational process that results at the end in the student having acquired and understood the knowledge, strategies and principles appropriate for the graduating engineer. (p. 7)

In response to the previous lack of design in engineering science courses, the Accreditation Board for Engineering and Technology (ABET) has specified that engineering schools should spread design through the curriculum (J. Hamelink, personal communication, November 1993). Previously, design education had been confined to a few courses taken primarily in the senior year and intended specifically to teach design. "Unfortunately," as Demel (1993) pointed out, "asking students to suddenly become creative in the last year or two of their formal education does not provide these emerging professionals with a sense of their profession" (p. 2024).

The problem with the current approach to design education of introducing design in a senior-level capstone course (apart from the overall paucity of design instruction in the curriculum) is that students are not used to solving problems that have more than one answer, and, when dropped into capstone design courses or industrial practice, are extremely discomfited at the prospect of not having a "right" answer to a design problem (Long, Young & Lasher, 1993). Currently, engineering
faculty are not used to dealing with this problem type and many are uncomfortable assigning these problems (Brock, Condoor & Burger, 1993), making the dissemination of design through the curriculum somewhat difficult. However, as faculty get used to the idea and design is slowly spread throughout the undergraduate program, assigning design problems in engineering science courses will become easier.

University professors are aware that they do not have nearly enough time to teach students all they need to know about design (NRC, 1991). However, the way design is taught can be altered and expanded. Design courses in the recent past have tended to focus on analysis rather than design, or are limited in scope (like the traditional capstone design courses). Dixon (1991a) has proposed a list of engineering design fundamentals that are derived from the current best industrial practices that he suggested should be taught in college design courses. He suggested a course organization that could fit into the current ABET-sanctioned structure of engineering education.

Another way of increasing design education would be to simply add more design courses. Realistically, though, adding engineering courses to an already crowded curriculum would be nearly impossible. Although some have suggested expanding the engineering undergraduate degree to five years (Pister, 1993), such a move would be very unpopular. Therefore, adding design courses would necessarily result in the elimination of some design science courses. Graduating engineers are expected to be cognizant of a wide variety of engineering fundamentals; eliminating engineering science courses would be unacceptable.
Team Design

More importance is being attached to team design in education. Nearly all industrial design is a result of teamwork, but throughout their education, students are trained to consider teamwork as somehow "cheating" (Lumsdaine & Voitle, 1993). Typically, engineering students seldom work as teams until their senior design course, except in small lab groups where teamwork is not emphasized. However, teamwork should be emphasized, stressing cooperation (Hamelink, Groper & Olson, 1989) and teaching team design methods (Smith et al., 1992). A truly educational experience would be to create cross-discipline teams to give students a flavor for working in a concurrent engineering environment (Aldridge, 1993).

Students need to realize that teams are the norm in the working world, and the success of a project depends not on the individual designer, but on the performance of the team. While introducing design into the curriculum, engineering educators can also introduce the concept of teamwork, well before the capstone design course. Students can learn the positive aspects of teamwork and what makes a team function well.

Critical and Creative Thinking

Critical thinking, "the ability to attack ill-defined design problems and also how to implement and evaluate solutions" (Hight, Hornberger & Sanchez, 1993, p.90), is an important attribute of a practicing design engineer. A major criticism of engineering graduates is their inability to reason logically, which leads to sloppy communication and poor design habits (Lewis, 1993). The adoption of open-ended problems can be used to reinforce good, critical-thinking design habits.
Often coupled with critical thinking is the concept of creative thinking. While critical thinking stresses methodical problem solving and evaluation of designs, creative thinking emphasizes looking for solutions that may not be readily apparent. Creative design in industry was covered in Chapter II. Creativity and creative thinking cannot be taught, but it can be encouraged; students can learn the methods for enhancing creativity (K. L. Shah, 1990). Some schools have begun programs including teaching of creative thinking methods (Conwell, Catalano & Beard, 1993), but for the most part creative thinking is something left to industry training programs (Braham, 1992).

Personality Types

Another area of research in engineering education is in personality classifications of students. The reasoning behind investigation of personality types is that different people learn in different ways, and in order to help each type of student learn it is best to ascertain his or her preferred mode of learning. Terry and Harb (1993) suggested using a learning cycle where concepts are taught through different activities to reach all types of learners. The classifications can also be used to create balanced design teams where all types of learning and problem-solving personality types are represented (Lumsdaine & Voitle, 1993).

Future Directions in Education

ABET has now taken a hand in dictating the diffusion of design throughout the curriculum. Using design problems in core engineering science courses will help students learn basics of design and realize the potential applications of the science itself. Engineering faculty must be cautious, however, not to see design problems as
"make-work" for students, but rather to use this opportunity to actually teach the workings of design.

True design education, however, cannot exist as an afterthought contained in engineering science courses. Design must truly be a part of the course. Capstone design courses should continue to be included in the curriculum; however, the basics of engineering design should be taught in a series of dedicated courses (Dixon, 1991a). Using this strategy, the entire engineering curriculum can then be related through the design orientation. The number of dedicated design courses need not be excessive, but they are necessary to promulgate the current best practices of engineering in industry.

In order to prevent the teaching of design from eliminating any other necessary courses from the engineering curriculum, universities and industry must come to a consensus on how to divide the labor of educating engineers. The question is: What constitutes education (that schools should be responsible for) and what constitutes training (that industry should be responsible for) (Dixon, 1991b)? Obviously schools must continue to teach the basics of engineering science. They should also be responsible for the basics of design, to prepare graduates to work in a team environment upon graduation.

Industry, however, must be willing to train incoming engineers in the field in which they are working. Industry must also be willing to identify what skills it wishes engineering graduates to possess—skills that can be taught in a four-year program. Companies could participate in the education of their new employees if they would hire before graduation and provide co-op experience or summer internships for their prospective engineers.

Industry must also be willing to form partnerships with design faculty members. Manufacturers need to actively support design education (McMasters &
Ford, 1990). They also need to actively support design research to make design a viable field in engineering. This does not mean just supplying money to legitimize design, but actively participating in the formation of methodologies and the analysis of other design research. Some faculty could have joint appointments at both a university and a manufacturing company. Both industry and academia would benefit from a closer partnership.

Design education is rapidly changing. It already is quite different from the poor introduction to design I received at the end of my undergraduate career in 1989. In the next few years design education will become even more robust as it is spread through the engineering curriculum. Some manufacturers already actively support design, and more will follow as the utility of new design methods becomes apparent. I suspect, however, that partnerships between industry and academia will be sparser than they should be, in part because of lingering suspicion between industry and academia.
CHAPTER XI

CONCLUSIONS

In this paper I have examined a great number of topics that relate to engineering design. This paper has detailed the current state of design, and ascertained where design should (and hopefully, will) be headed in the next few years. Although I have divided the material into a number of chapters and sections, the division is by necessity somewhat arbitrary, as the subject matter covered here is greatly interrelated. The main influences on design can be grouped into two main headings: computers and methodologies.

The methodologies that are rapidly becoming predominant in industry are DFM/DFA and concurrent engineering. As these methodologies saturate the workplace, other members of the DF"X" family, including quality methods, will be added. Company management will need to realize that managerial functions (as well as engineering and production functions) need to be practiced concurrently. As the traditional sequential string of marketing, management, engineering, production, sales, and service collapses into one concurrent product realization process, industry will be practicing a total concurrent life-cycle design. Different departments within the company, in particular engineering and production, will work more closely with each other.

Eventually, academically created methodologies will become more widely accepted by industry and used as subsets in the concurrent engineering process. Before this can occur, however, researchers will need to consolidate the information already learned in design theory and agree on the next directions to take in
methodological research. Methodologies created will also need to acknowledge the
difference among different design situations—product complexity, lot size,
management factors, new materials and production methods, and the like. The
methodologies produced by academia will need to be field tested, and industry and
academia will need to join together in a closer partnership. Complicated
methodologies (formed of many sections) that cover the entire design process will be
the norm, but these methodologies will be adaptable to any situation. Methodologies
cannot be completely descriptive of the design process because some contextual
information must always be included.

Extensive methodologies can become feasible only with extensive computer
support of the design process. Computer aids to design will grow to support
concurrent engineering and other methodologies. As computing power becomes
cheaper, giant systems for the support of design will be created. These systems will
support the entire design process, from project initiation through customer support.
The ultimate direction of computer-aided engineering is in integrating all functions of
the product realization process into a large design information system. The basis of
this system will be an intelligent CAD system that will be able to control design,
analysis programs, production processes, and all data transferal with an intelligent
assistant.

To accomplish this, CAD must become more intelligent and parametrically
based. It also must become easier and more intuitive to use. Future CAD will be a
design tool capable of extensive what-if scenarios and adaptation of older designs.
Design changes will automatically change part drawings, assembly drawings, solid
models, and production instructions. CAD will also store the intent of the designer.
Virtual reality (should it fulfill its promise) will increase the natural mapping and social utility of CAD.

As the design process in industry changes, so will the teaching of engineering courses. It is widely believed that engineering graduates are well versed in computer skills (Evans, Beakley, Crouch & Yamaguchi, 1993), so the potential future reliance on computers in design should not affect engineering education. However, education in design is perceived to be lacking. Universities (pushed by ABET) are beginning to include more design in engineering science courses, and that trend will continue. Design itself as a topic will receive more attention. Current industry methodologies will be taught, and undergraduate education will serve as a conduit for newer design methodologies, formulated by academia, to be transferred to industry. Industry and academia must reach an agreement on the state of design education.

The change in engineering education has already begun. The future of engineering design in industry and research is rapidly approaching. As new advances are made in design methods and design support, the nature of engineering design will change. The product realization process will become more robust and the production of new products will become easier.
BIBLIOGRAPHY


Reproduced with permission of the copyright owner. Further reproduction prohibited without permission.


Thompson, B. S. (1992). Design creativity: The very essence of engineering, the sciences--and also the arts (3rd ed.). Okemos MI: Infotrans.


