AN INVESTIGATION OF THE DEVELOPMENT OF PRODUCT DESIGN SPECIFICATIONS: A CONCEPTUAL DEVELOPMENT AND A CASE STUDY

by

CORINNA S. FU

B.S. Mech. Eng., Massachusetts Institute of Technology
(1988)

Submitted to the Department of Mechanical Engineering
in Partial Fulfillment of the Requirements for the
Degrees of

MASTER OF SCIENCE IN MECHANICAL ENGINEERING

and

MASTER OF SCIENCE IN MANAGEMENT

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
June, 1990

Signature of Author________________________
Department of Mechanical Engineering
June, 1990

Certified by________________________
Don P. Clausing
Thesis Co-advisor

Certified by________________________
Stephen C. Graves
Thesis Co-advisor

Accepted by________________________
Ain A. Sonin
Chairman, Graduate Committee
Department of Mechanical Engineering

An Investigation of the Development of Product Design Specifications:
A Conceptual Development and A Case Study

by

Corinna S. Fu

Submitted to
the Department of Mechanical Engineering on May 18, 1990
in partial fulfillment of the requirements for the degrees of
Master of Science in Mechanical Engineering
and
Master of Science in Management

ABSTRACT

This thesis presents an investigation of the development of product design specifications. The research project was prompted by the desire to enrich the knowledge in product development. The lack of comprehensive studies in the area of product design specifications led to the conception of this research project.

The objective of the study was to better understand product design specifications and their relation to the overall product development. The study focused on four areas: 1. the structure of design and contents of design specifications; 2. the sources of design specifications; 3. the development process of design specifications; and 4. the development methods for design specifications.

Two modes of research were used: a conceptual development and a case study. The conceptual development, based on existing literature and personal experience in engineering design, provided a framework and analytic tools for the case study. The case study, based on a retrospective examination of a recent product development program in an imaging equipment company, verified and supplemented the conceptualization. These two activities were carried out in parallel to leverage the learnings from one to the other.

An examination of a variety of products suggested that any engineering design could be decomposed into Systems, Sub-systems, Modules, and Components. This four-level structural model was verified and used to provide a conceptualization for understanding the structure of design specifications in the case study. In trying to verify the structure of the product

design, I found that there were primary and secondary functions which tended to associate with function specific and field specific hardware systems, respectively. A function specific system was a group of hardware physically located together to perform one high level machine function. A field specific system was a group of hardware functionally assembled for engineering analyses that depended on one particular engineering field. The selection of the type of system could affect the decomposition of a design and thus the nature of the design specifications.

Furthermore, I compiled an extensive checklist of ninety design specification elements and organized them into seventeen categories. To provide a better conceptualization of the contents of design specifications, I developed a two by two Specification Characterization Matrix which characterized these categories into four characteristic groups. The characteristics of the four groups were: Group I, *explicit and functional*; Group II, *implicit and functional*; Group III, *explicit and non-functional*; and Group IV, *implicit and non-functional*. The Specification Characterization Matrix provided a management tool for task assignments and coordination, and created new dimensions for future research.

In terms of the sources of design specifications, I identified a total of eight internal and external sources. They were Customers, Marketing, Research/Development, Design/Engineering, Manufacturing, Quality Control, Field Services, and Standardization Organizations/Regulatory Agencies. The first seven came from the conceptual development and the last one from the case study.

In addition, I found a set of nine systematic and unsystematic development methods for design specifications. The systematic methods were Systems Engineering, Experimental Design, Value Analysis and Value Engineering, Benchmarking, and Quality Function Deployment. The unsystematic methods were Local Optimization, Trial and Error, Spontaneous Solutions, and Gut Feelings. Results showed that the unsystematic methods were more prevalent in industry than the systematic methods, mostly because they require less discipline and time.

Thesis Co-Advisor: Don P. Clausing
Title: Bernard M. Gordon Adjunct Professor of Electrical Engineering

Thesis Co-Advisor: Stephen C. Graves
Title: Leaders for Manufacturing Professor of Management Science

ACKNOWLEDGEMENTS

This project would not have been possible without the generous help and thoughtful support of many people. First of all, Professor Clausing and Professor Graves deserve the most credit for providing insightful guidance and sharing their knowledge with me. Professor Clausing should also be acknowledged for his teaching and his network, which helped to form the basis of my research and provide a large source of information.

I wish to thank all the people at the sponsoring company who had shared with me valuable information and given me generous support, especially the following individuals:

Glenn Tersteeg, Dave Schwardt, Kent Shurtleff, Gene Lachut, Rory Barzee, Bob Meyer, Mark Henshaw, Sam Montello, Bob Deisinger, Cindy Miller, and Paul Ludington.

I wish to give my special thanks to Frank Zaffino, Rohn Harmer, Jack Rittler, and John Luke for making my research project possible.

My appreciation also goes to Jan Betteridge and Terri Ashton for providing outstanding administrative support. Without them, I would have been forever lost in the company.

The following people at the company also deserve to be acknowledged for providing stimulating discussions and keeping my life in perspective:

Alan Lulla, Bob Mills, Mike Poccia, Ken Price, Jeff Mills, Bruce Shaw, Al Moore, and Dave Tinner.

I especially want to express my deep gratitude to my colleague, Rebecca Munroe, for her morale support and friendship. She provided many insightful discussions on my research and helped to keep me on track throughout my project.

Harry Rosenfeld of Xerox Corporation also deserves a special acknowledgement for his timely advice and generous information.

The MIT Leaders for Manufacturing Program should be acknowledged for its funding and support. My special thanks goes to Rosalie Ryan and the administrative staff for providing excellent administrative services from the program.

This thesis is dedicated to my mother who, above all people, gave me the unparalleled support and encouragement.

CONTENTS

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background of Study

During the last two decades, the gradual decline of the American manufacturing industry has resulted in the loss of our ability to compete in the global market. To revitalize the U.S manufacturing base, many U.S. companies are beginning to take drastic measures to improve the way that they are doing business and meeting competition.

One of the areas that have been identified as crucial to this revitalization effort is product development. Although some people still believe that the manufacturing floor is the only battle field, evidence has shown that it is equally important to supply the battle fiel: with good ammunition. What good is it to have a top grade factory that is making poor products?

Some companies have begun to realize the power and benefits of having their product development under control. Since product development has been neglected in the U.S. for a long time, to turn the situation around will require tremendous effort and may take a long time.

One way to improve product development is to focus on the product development process. This suggests a more systematic and disciplined approach to design and engineering, including developing good product design specifications prior to the actual design of the product. As the saying goes, "If you don't know what you are doing, you are not going to do it well." This is very true in product development, especially when the product is a complex one which requires coordination among many different design functions. Without a clearly written Product Design Specification (see definition in section 1.2) up front, the design organizations would not be able to communicate effectively with each other on the same ground. It is, therefore, crucially important to start with good design specifications in any development program.

Currently there is very limited understanding of how design specifications are developed, what the contents of the design specifications are, and how they are related to the product development process. This study will attempt to contribute to the better understanding in these areas.

1.2 Overview of Study

The general topic of investigation in this thesis is product development. However, given that product development by nature consists of a very complex set of activities and processes, this study will not attempt to investigate every aspect of product development. Rather, emphasis will be placed on the development of product design specifications.

Since the term "design specs" is often loosely used, there is a need to define what it means here. For this study, there are two definitions:

1. Product Design Specification (PDS) means a central document that is used to guide all subsequent product design activities;
2. product design specifications (not capitalized or abbreviated) means specific design requirements that govern the detail design of the product.

Typically, item #2 gets compiled into item #1, but for the discussion in this thesis, PDS will be used whenever referring to the first definition and design specifications for the second definition.

The main objective of this investigation is to better understand the development of product design specifications and its relation to the overall product development process. Specifically, this study will attempt to gain knowledge in four areas relating to product design specifications:

1) the structure and contents of specifications;

2) the sources of specifications;

3) the development and evolution process of specifications; and

4) the development methods for specifications.

To tie together and put in perspective these four areas of investigation, the relationship between design specifications development and the overall product development will be investigated as well.

The hypothesis that I am putting forth is that design specifications can be grouped into categories and organized into a generic checklist which can be used as a reference. Furthermore, the design specifications can be cast onto a 4-level structural model: systems, sub-systems, modules, and components. I believe that, by realizing and adhering to such a structure, the design planning and the development of the product can be accomplished more systematically.

This study was originally prompted by three questions: 1) How do designers and engineers know what to accomplish? 2) How do they go about accomplishing it? 3) How do they measure progress and accomplishment? As my research went on, these questions evolved in more specific terms. The questions that ultimately guided the research were basically the restatements of the four areas above:

1) What is the structure of design and its implication for the structure of design specifications?
2) What are the characteristic elements of design specifications? And how are they organized?
3) Where did design specifications come from?
4) What is the process by which design specifications are developed and evolved? And how does this process fit in with the overall product development process?
5) What are the methods used to develop or obtain these design specifications?

To answer these questions, I decided to use two modes of research. One is a conceptual development which was based mostly on existing literature and my personal knowledge of the topic. The other is a case study which was largely based on field data and analysis. These two modes of research were carried out almost in parallel to leverage the learning from one to the other.

While the conceptual development provides a framework and basis for the subsequent field research, the case study provides the actual field data to verify and supplement the conceptualization. For both the conceptual development and the case study, an attempt has been made to generalize some of the observations whenever possible. Comparisons between the conceptual development and the field data are made and discussed throughout the case study.

At the end of this study, some of the findings pertaining to the five questions that guided this study will be summarized. Additional comments that were not made during the case study will be added as well.

1.3 Overview of Structure

This thesis is organized into five chapters. A review of existing literature that is relevant to the discussion in this thesis is presented in Chapter 2. To feed the subsequent study, the focus will be on the contents and development methods of the design specifications.

Chapter 3 and Chapter 4 form the core of this investigation. The conceptualization that is used to frame the case study is developed in Chapter 3 and the case study itself is discussed in Chapter 4.

In both Chapter 3 and Chapter 4, a similar analytical structure and organization are used to present the research. Consistent with the probing questions that guided this research, the topics of investigation in both chapters are arranged in the following sections: 1. Product Development Process; 2. Structure of Design and Contents of Design Specifications; 3. Sources and Development Process of Design Specifications; 4. Links to Product Development; and 5. Development Methods for Design Specifications. In Chapter 4, an extra section is inserted at the beginning to provide some background information for the case. This section is divided into: program history, product, market & competition, and organization.

This thesis will conclude with Chapter 5, in which the major findings and observations specific to the development of design specifications will be summarized. The intent here is to briefly compare field data with the conceptualized answers to the probing questions. Appropriate modifications and refinement to the conceptual development are discussed, and areas for future investigation are suggested. This chapter attempts to achieve some degree of integration between the two modes of research so as to provide a coherent study.

1.4 Research Methods

The overall approach to this investigation was to have a conceptual development and a case study going in parallel, and then integrate the two with a comparison and consolidation of learnings.

For the conceptual development, twenty six journal articles, textbooks, and conference proceedings were consulted. In addition, a large amount of information had come from my advisors, their academic colleagues, other experts in the field, and my previous experience in product design.

For the case study, the information mainly came from interviews and company documents. A total of thirty seven interviews were conducted. Most of the interviews were one on one, ranging from half an hour to over two hours long. Twenty six of the interviews were structured, sit-down meetings and eleven were unstructured conversations. In some of the structured interviews, a list of questions specific to the function of the interviewee was pre-determined.

The people interviewed include five managers and supervisors; nine designers, engineers and technicians; one marketing specialist and one industrial engineer. The functions represented are marketing, design/engineering, field services, and management.

1.5 Summary of Findings

In this section, I will briefly summarize the findings from this investigation. The results will be organized by the topical areas that guided this study: 1. The Structure and Contents of Design Specifications; 2. The Sources of Design Specifications; 3. The Development and Evolution Process of Design Specifications; 4. The Development Methods for Design Specifications; 5. The Relationship between Design Specifications Development and Product Development.

1. The Structure and Contents of Design Specifications

The field data in general supports the hypothesis that there is a hierarchical structure of systems, sub-systems, modules, and components (see Fig. 4-7 and Fig. 4-8). However, there are two types of systems (or sub-systems). One is function specific, which focuses on a high level system function, and the other one is field specific, which depends on a common engineering characteristic of the parts that make up the system (see Fig. 4-12). An example of each, respectively, is a complete camera and the optics inside a camera. Function specific systems tend to draw from more than one kind of engineering expertise, and field specific systems tend to depend on only one engineering field. Furthermore, function specific systems are closely associated with primary design function, and field specific systems are more tied to the secondary functions.

In terms of the contents of design specifications, ninety (90) design specification elements have been identified (see Table 3-3). They are organized into seventeen (17) categories which are further arranged into four (4) major groups. Group I contains design specifications that are *explicitly* related to the *functional* aspects of the design. Group II consists of those that are *implicitly* related to the *functional* aspects. Group III includes the elements that are *explicitly* related to the *non-functional* aspects. Lastly, Group IV encompasses the ones that are *implicitly* related to the *non-functional* aspects of the design or of the overall development program. A large number of elements in Group IV are not typical items that appear in a Product Design Specification, because they tend to be requirements that are more business or management related such as the economics and market conditions. However, from my field data, they are necessary pieces of information that affect many design decisions.

2. *The Sources of Design Specifications*

Various sources of design specifications have been identified. There are two types of sources: external and internal. The information from the external sources are typically generated from the outside of a company and the information from the internal sources are from the inside. The external sources found during this investigation are Customers, Marketing Representatives, Field Engineers or Technicians, and International Regulatory Agencies (i.e. Standards Organizations). The internal sources are Designers, Product Engineers, Manufacturing Engineers, Engineering Supervisors, Quality Personnel, and Research Engineers. (See section 4.4)

The relationship between the various sources and the seventeen design specification categories has also been investigated. Due to the lack of field data, the investigation in this area has been primarily based on my own conceptual development. (See Fig. 3-5) The preliminary results tend to suggest that, for the Group I design specifications, the Customers, Design Engineers, and Field Engineers contribute to more categories than the rest; Manufacturing Engineers actually do not directly contribute to any of the categories in this group. For Group II, the Design Engineers, Field Engineers, Manufacturing Engineers and Quality Controllers seem to contribute equally in terms of number of categories. For Group III, Customers, Marketing Representatives, and Design Engineers are the only three contributors; the other sources do not directly link to the design specification categories in this group. Finally, for Group IV, Marketing Representatives play a dominant role, followed by Customers, Field Engineers, and Manufacturing Engineers. The Field Engineers and Manufacturing Engineers mainly contribute cost information to the Economics category in this group. Research & Development and QA do not directly contribute to this group.

3. *The Development and Evolution Process of Design Specifications*

Based on the case study, the evolution process of design specifications is highly iterative and very complex. Design specifications usually start as general product requirements that are either gathered from the market place or developed as a result of the introduction of a new technology. The general product requirements gradually become more specific as the product concept is more clearly defined. Throughout Concept Development and Product Planning, the different sources of design specifications come together with different information and requirements, which ultimately get compiled into a single document sometimes called the Product Design Specification, or Marketing Requirements Document in my case study. This document serves as a guide to the subsequent design activities. However, even at this point, some of the design specifications are still not clearly defined until more market information can be obtained. In this case, the original Product Design Specification is revised periodically to incorporate the new information.

4. The Development Methods for Design Specifications

A number of development methods for design specifications has been identified. Conceptually, there are nine methods that people tend to use to develop design specifications (see Table 3-4). Five of them are classified as systematic methods while the rest are unsystematic. The systematic methods include Systems Engineering, Experimental Design or Robust Design, Value Analysis and Value Engineering, Benchmarking, and Quality Function Deployment. The first four methods in this list are analytical tools whereas Quality Function Deployment is more of a structured system within which the analytical tools can be applied systematically. The unsystematic list includes Local Optimization, Trial and Error, Spontaneous Solutions, and Gut Feelings. These methods are found to be most commonly used in the product design community because they require less discipline and take less time. It is easy to find design engineers pulling numbers out of the air, based on their gut feelings and engineering instincts. Unreliable as they may seem, however, they can sometimes be effective tools for getting preliminary results, especially when the product technology or the design is new and there is no previous experience to draw from. Furthermore, they help to stimulate creativity in engineering design. However, given the unsystematic nature of these methods and their dependency on the user's experience, a structured system such as QFD is needed to make them more beneficial. My field data shows that both systematic and unsystematic methods must be used to arrive at a good design.

5. *The Relation between Design Specifications Development and Product Development Process*

Two questions are used to organize the findings in this area: 1. How are the design specification elements related to the different development stages? and 2. What implications do the four major groups of design specifications have for the management of product development?

For the first question, there is insufficient field data to draw any conclusion from. Since most of the design specifications were gradually developed over time and were not compiled into a single document until much later, there was no documentation of what kind of design specifications were developed at what development stage.

However, conceptually, there are three classes of specifications: product requirements, design specifications, and manufacturing instructions. The product requirements are usually defined during Market Research and Conceptual Development stages. The design specifications, as defined in section 1.2, must be defined and documented prior to the Product Engineering stage. Thus, they are usually compiled during the Product Planning stage, although some of them may evolve over time as more information is gathered. Manufacturing instructions are the specifications for parts manufacturing or fabrication. They are generated after the detail design is completed, i.e. during or after Product Engineering stage. Therefore, they are not typically product design specifications; rather, manufacturing specifications.

In terms of the implications of the four major design specification groups for the management of product development, the field data provided some useful insights. Interestingly, each of the four groups of design specifications traces to a particular group of people who were responsible for the development of those design specifications. Group I is closely tied to the design and engineering community; Group II the field service engineers; Group III the ergonomic designers and the product designers; and Group IV the financial planners and managers. This implies that the four groups of design specification categories can provide a useful tool for tasks assignments and information management.

In general, the field data strongly indicates that the timely development of design specifications is closely tied to the success of a development program. A good up front development effort on design specifications is an indicator of a well organized management approach, which is essential for any successful design program.

CHAPTER 2: LITERATURE REVIEW

In this chapter, I will briefly review some literature that is related to this research. Most of the literature tends to focus on the general issues of product development. Only a small number of them go in any significant depth on product design specifications.

I will begin with the work done by Stuart Pugh (1988a, b, c; 1984; 1983). He is one of the few authors who offers a comprehensive model that describes the complexity of product development. His model, called the Product Design Activity Model, consists of six stages. If the product is a static[1] design, the six stages are Market, Concept Design, Specification, Detail Design, Manufacturing, and Sell. In his model the Detail Design stage, which is also referred to as the design core, is bounded by product specifications. By "bounding" he means that detailed design must conform to the design specifications developed in the earlier stages and stated in the Product Design Specification document. This model is unique in that it explicitly emphasizes where during the product development process that design specifications should be developed. In his work, Pugh draws special attention to the Specification stage and strongly stresses importance of having a well written Product Design Specification prior to the Detail Design stage.

---

[1] A significant part of Pugh's recent work focuses on the status of the design., i.e. static vs. dynamic. A static design is one whose concept has been around for a long time, such as a differential. A dynamic design is one whose concept is significantly different than the ones that came before it. Pugh suggests that the product development process varies depending on the status of the design. Since it is a research area onto itself, it will not be explored in this study.

To go further, he has compiled a list of 28 design specification elements[2] all of which are necessary to feed the detailed design activities. This list of 28 elements is shown in Table 2-1. As it stands, this list does not seem to have any kind of organization; it is almost a random list. Although it is the most extensive list in the current literature, it needs to be rearranged to serve any useful purpose. Furthermore, some of the elements in the list are not conventional design specification items, such as competition and politics. What role these non-conventional items play in a Product Design Specification remains a research question.

Also shown in Table 2-1 are lists of design specification elements from four other authors: Buhl (1960), Burgess (1982), Cullum (1988), and Leech (1972). The elements in these lists are more traditional design specifications. However, some of them vary significantly across the different lists. For example, "interface requirements" in Burgess' list does not appear in any of the other three lists, and "handling and storage" shows up as "transportability" in Buhl's and "delivery" in Cullum's lists. Although the three terms are similar, they have slightly different meanings for design specifications. "Handling and storage" implies all requirements pertaining to the handling and the storage of the product, including operator handling and field service handling. Whereas, "transportability" and "delivery" imply more the actual transportation of the product, such as warehouse locations and distribution.

---

[2] For the following thesis, elements mean fundamental design requirements such as force, torque, speed, length, temperature, humidity, etc.

Table 2-1 Summary of Design Specification Elements by Author

Pugh	Buhl	Burgess	Cullum	Leech
1. performance	1 function & performance	1.basic perform.	1. economics	1. function
2. environment	2 legality & regulations	2. physical characteristics	2. safety	2. functional requirements (numeric)
3. life in service	3 consumer specs	3.standards /specifications	3. mfg. methods	3. operating constraints
4. maintenance	4 safety	4. operating cycle	4. reliability	4 manufacturing constraints
5. product cost	5 ease of operat'n	5. interface requirements	5. aesthetics	5. environment
6. competition	6 life (operation)	6. materials	6. ergonomics	6. cost
7. shipping	7 material	7. packaging & identification	7. packing	
8. packing	8 transportability	8. handling and storage	8. delivery	
9. quantity	9 regidity	9 transportation	9. storage	
10. mfg. facility	10. cost	10 acceptance and testing	10. site	
11. size	11. capacity		11. inspection	
12. weight	12. weight & size			
13. aesthetic	13. producibility			
14. materials	14 maintainability			
15 prod life span	15. appearance			
16. std. specs	16. adaptability			
17. ergonomics	17. environment			
18. customer	18. manufacturing			
19. quality & reliability				
20. shelf life				
21. processes				
22. time scale				
23. testing				
24. safety				
25. company constraints				
26. market constrnts				
27. patents				
28. politics				

This only suggests that none of these lists is complete and consistent enough to provide a sufficient reference source. In addition, some elements seem to be very specific such as life, size and weight, and others need additional clarification such as manufacturing constraints and functional requirements. Perhaps there is an opportunity to incorporate the four lists with Pugh's list to generate a more comprehensive checklist.

Another source of useful information comes from the work done by Don Clausing (1986; 1988; 1989). His research focuses on the application and enhancement of Quality Function Deployment (QFD), which is a technique used to keep track of the customer requirements throughout the different stages of product development. QFD consists of four matrices each of which is used to translate one set of information to the next. The first matrix is called the Product Planning Matrix, also commonly known as the House of Quality. It is used to convert a set of customer attributes into a set of quantifiable engineering characteristics. The second matrix, the Product Design Matrix, is used to translate the output from the first matrix to a set of design parameters with numerical design values. This set of values is then transformed into process design variables through the use of the third matrix, the Process Design Matrix. Finally, the fourth matrix, the Production Design Matrix, is used to relate process design information to a set of production system control factors. This technique has been increasingly recognized as a useful information tracking system and a team building tool for product development. Given the information intensive nature of this technique, it seems highly relevant to the development of design specifications.

In addition, this technique is built on the foundation of value analysis and value engineering. It entails the application of various traditional value engineering methods, two of which seem potentially useful for analyzing the structure of design. The two methods are Function Tree and Hardware Tree. The tree structure can be used to demonstrate the design decomposition from higher levels to lower levels.

Besides the literature discussed so far, there is a wide range of journal articles and textbooks on the general management of product development. Given that this study is more focused on the development of product design specifications, I will not give a detailed review of these references. However, they help me to develop my thinking that sets the stage for the case analysis and discussion.

CHAPTER 3: CONCEPTUAL DEVELOPMENT

This chapter lays the conceptual foundation for the thesis. Its focus is on developing a conceptual basis and framework for the analysis of the field data in Chapter 4. The objective here is to arrive at a set of concepts and principles that can be used to frame the case study. Besides providing a structure for the collection and analysis of field data, it also builds a platform for the comparison and discussion in later chapters as well.

3.1 Product Development

The development of product design specifications cannot be understood without a context. For the purpose of this study, the context is the process of product development, which is sometimes referred to as the product delivery process or the product realization process. Anyone who has studied product development in any shape or form would concur that product development is a very complex process of taking a product concept on paper and translating it into hardware design, and then finally putting it into volume production. This delivery or realization process typically involves many people and a large variety of company functions. Thus the coordination and communication of information are the primary concerns in product development.

In general, the process of product development can be divided into six stages: Market Research, Concept Development, Product Planning, Product Engineering, Process Engineering, and finally, Production Development. These are very generic and descriptive stages. They are sometimes further divided into more specific sub-stages depending on the purpose of the study. For this study, this level of description is sufficient.

Associated with each stage there is a set of design and development activities. Fig. 3-1 is a table showing some of the major activities by each stage. The first stage, Market Research, involves understanding the market needs and relating those needs to the rest of the product development community in a company. This is a fundamental but intrinsically important stage for a market driven product. Unfortunately, it has been a weak link for many U.S. companies in the past. The second stage, Concept Development, is where a product concept gets formulated, developed, tested, and evaluated. Typically, by the end of this stage, a feasible design concept is selected for subsequent detail development.

The third stage, Product Planning, is the most critical one in terms of design management. It is here that most of the critical business and technical activities should be planned and crucial decisions regarding the rest of the development program are made. It is also here that product design specifications, such as product functions and performance targets, should be developed and compiled into a Product Design Specification to guide the succeeding product design stages. Currently, many U.S. companies still fail to recognize the importance of up front planning and thus pay insufficient attention to this stage, which is a common pitfall in product development. The following study will mainly focus on the development of product design specifications during this stage.

The fourth stage is Product Engineering which mainly entails the detail design of the product. Most of the design should be completed by the end of this stage. Engineering models are usually built towards the end of this stage to evaluate and verify the design. This activity often leads to engineering

Fig. 3-1 Major Development Activities by Stage

1. Market Research	2. Concept Development	3. Product Planning	4. Product Engineering	5. Process Engineering	6. Production Development
Market Assessment	Concept Generation & Formulation	Market Forecast	Detail Design	Production System Design	Full Scale Ramp-up
Needs Identification	Clay Model/ Breadboards	Financial Feasibility Assessment	Engineering Analysis	Process Design	Steady State Volumne Production
Focus Group Study	Concept Evaluation	Organization Design	Design Optimization	Tool/Equipment Design	Quality Control
	Technical Feasibility Assessment	Resources Allocation	Documentation	Work Design	
		Product Design Specifications Generation	Quality Engineering	Control Systems Design	
		Facility Planning	Prototyping	Factory layout Design	
			Design Evaluation	Quality Engineering	
				Pilot Run	

changes. Also important in this stage is the documentation of the design decisions and the product design itself, so as to enable other down stream activities such as testing and quality control.

Product Engineering is to be followed by the fifth stage, Process Engineering. In this stage, the manufacturing processes necessary to produce the product in volume of more than one unit are developed. Some of the tasks at this stage include tool and equipment design, control systems design, and factory layout design (the design specifications for these designs do not fit in the scope of product design specifications and therefore will not be explored in this study). Typically, the processes are tested and refined through pilot runs.

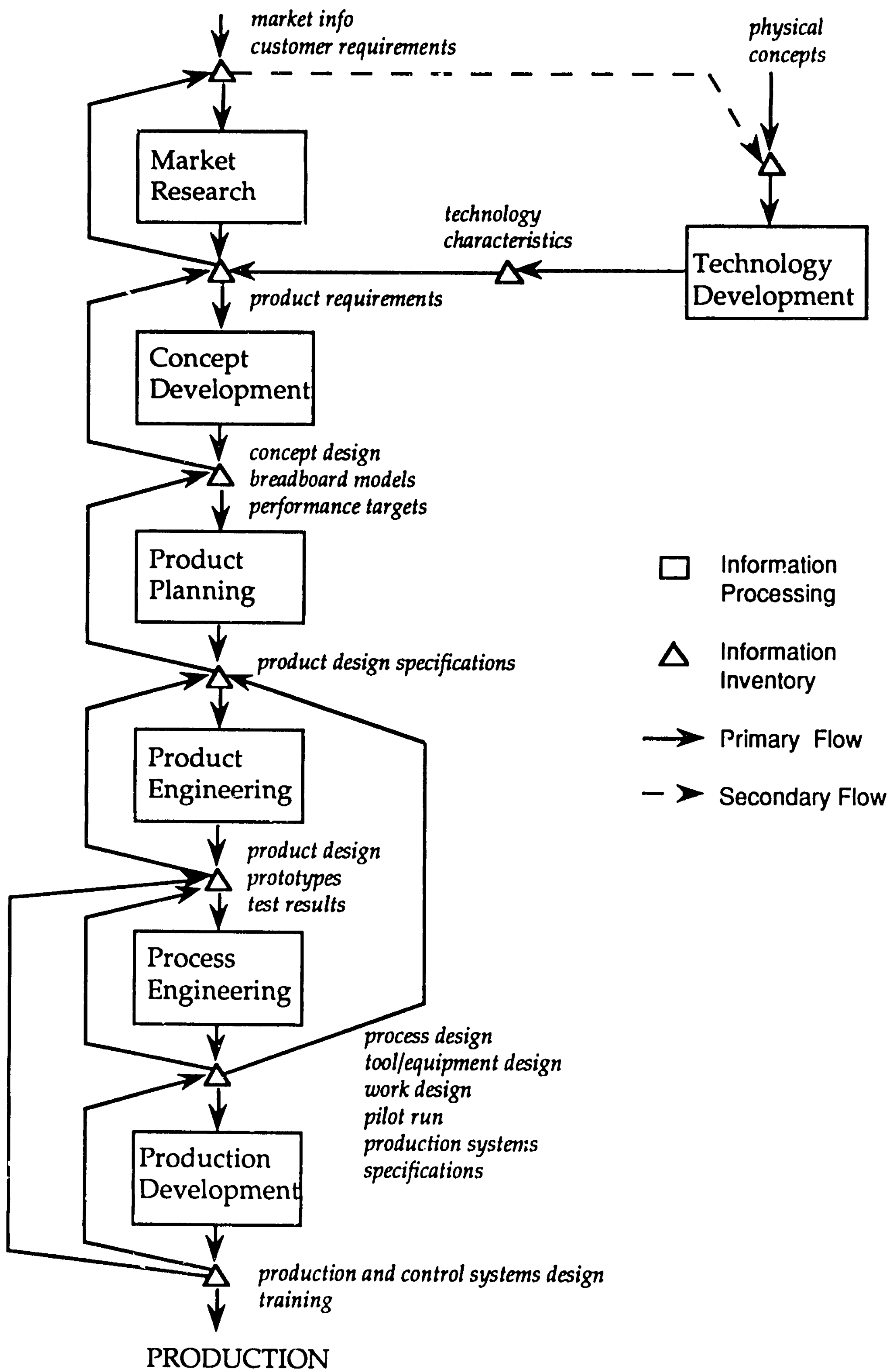
The final stage, Production Development, is where the entire production system, including material handling methods and production controls, comes together for the preparation of a full scale production ramp-up. Such a production system must be designed to handle steady state volume production, with built-in quality control.

With the product development stages now defined, the topic of product design specifications can be discussed. Product design specifications are in essence pieces of information that are generated or gathered in the early product development stages, consolidated during Product Planning, and disseminated throughout the development of the product. They form the backbone of any product development program, providing a reference source of information and guiding the various activities. The output from one stage typically becomes the input to the next or later stages. Thus, in order to frame the development of product design specifications in the context of product development, one must think of product development as an information driven process. Fig. 3-2 shows an information flow model that depicts the information processing through the six development stages and the information transformation from one stage to another. However, it does not necessarily represent a time sequence of activities.

As indicated in Fig. 3-2, information from Market Research, in the form of product requirements, goes through an information storage (which could simply be a marketing document) to arrive at the second stage, Concept Development. During this second stage, marketing specialists and product design engineers transform the product requirements into concept designs, breadboard models, and performance targets. As the information moves through the Product Planning stage, product planners and product design engineers convert it into design specifications which may or may not be quantitative. Some of the requirements at this stage may directly impact the final performance of the product, such as the overall system response time, while some others may still need further definition as the product design evolves, such as the motor speed of a specific mechanism. By the time Product Engineering is completed, the product designers and engineers would have converted the information that started from Market Research into a set of drawings and analyses which fully describes the product functions, performance, and physical parts. The product design is typically tested and demonstrated with prototypes or engineering models. It is here that the development of the product is considered mature and a full scale product evaluation at the systems level is possible.

The last two stages are mainly associated with the manufacturing of the product. During the Process Engineering stage, the manufacturing or process engineers, working closely with the design engineers, translate the product design information into manufacturing process information such as process design, work design, and tooling design. Notice that the type of information

Fig. 3-2 Information Flow Model for Product Design



generated from Process Engineering is quite different than that from the previous stages. Here the information is primarily process related and the previous outputs are mainly product related. However, it is crucial to realize that the process design information directly depends on the product design information. All too often, the information link is broken at this point, as manifested by the "throw-over-the-wall" syndrome. Thus, efforts should be made to ensure constant communications between the product and process development communities. Once the information from Process Engineering gets to the Production Development stage the production planners and industrial engineers, in conjunction with the product engineers and process engineers, incorporate and massage it into the production system design. The output from Production Development is a complete and sound production system that will support the steady state volume production. This completes the information flow at least to the point where the product can be produced and shipped to the market.

3.2 Structure of Design and Contents of Design Specifications

Now that the context for the development of design specifications has been established, the structure and contents of design specifications should be explored.

General observations tend to suggest that any product design can be decomposed roughly into four levels: systems, sub-systems, modules, and components. This ordering is neither unique nor standard. It may vary slightly from study to study although the idea remains the same. For example, in some cases, modules and sub-systems may be switched, or assemblies may be added between modules and components.

In this model, the systems level consists of the highest divisible groups of hardware that typically perform some high level functions. A system is usually loosely defined. It can be the product itself or any major part of the product that does a significant or readily identifiable function. The selection of a system depends on the complexity of the product and the purpose of the analysis. The sub-systems level is a first-tier decomposition of the systems level. It contains smaller groups of hardware that usually carry out the next level functions. Usually, a number of sub-systems makes up a system.

The sub-systems are often further decomposed into modules. The modules level usually contains very small groups of hardware that are not necessarily functionally independent. In fact, they are very often not functional by themselves. They may be created to simplify the design task or enable ease of coordination. Depending on the scope of the design task and the complexity of the product, modules are not always part of the chain of decomposition. When the product is simple, sub-systems (or even systems) can be directly decomposed into components.

This brings us to the components level. Components are the lowest divisible groups or pieces of hardware that comprise the modules, sub-systems, and ultimately the entire system. They are the building blocks of any machine or system. Included in this level are small assemblies and parts that can be either purchased off the shelf or outsourced from a vendor. They often do not require extensive design work by the internal product development people.

To illustrate this 4-level model, let us look at two examples. The first one is a car, which is a very complex product. As shown in Fig. 3-3, in a car, the systems level includes the Drive Train, Body & Chassis, Interior, and Electronics. Within the Drive Train System there are numerous sub-systems such as the Engine, Transmission, Drive Shaft, Differential, and Rear Axle. The Engine itself can be further decomposed into modules such as the Bare Engine, Fuel Injection, Ignition, Cooling, and Exhaust. Finally, the valves, pistons, cylinders, crankshaft, body castings, nuts and bolts make up the components level.

Fig. 3-3 Design Decomposition of A Car vs. A Bike

	Systems	Sub-Systems	Modules	Components
	Drive Train	Engine	Bare Engine	valves
		Transmission	Fuel Injection	pistons
		Drive Shaft	Ignition	cylinders
car		Differential	Cooling	crankshaft
		Rear Axle	Exhaust	body castings
	Body &		.....	nuts & bolts
	*Chassis**		.....	.....
	*Interior**			
	*Electronics**			
	Bike	Transmission		chains
		Brakes		gears
		Frame		brakes & cables
bike		Controls		wheels
				struct.
				members
				handle bar
				foot pedals
				seat

* *The italic items (systems) are not expanded to the lower levels*

In contrast to a complicated car, the second example is a simple bike. In this case (also shown in Fig. 3-3), the Bike itself is the system. The Transmission, Brakes, Frame, and Controls represent the sub-systems. Because of the simplicity of a bike, there are no modules. The components include chains, gears, brakes & cables, wheels, structural members, handle bar, foot pedals, and seat.

Both of the examples show how a complex product such as a car or a simple one such as a bike can be broken down into the four levels. Of course, any of the sub-systems or modules can be referred to as a system if the analysis happens to occur at these levels. For example, Fuel Injection is a module within the Drive Train System of a car and is currently shown in Fig. 3-3 at the modules level. However, it can be thought of as a system by itself. Within Fuel Injection there are further divisions into sub-systems, modules and components as Fuel Intake, Fuel Flow Control, and nozzles, respectively. Since Fuel Injection is elevated from the modules level to the systems level, its sub-divisions along the 4-level structural model are also shifted exactly two levels upward. The decomposition shown in Fig. 3-3 is based on a selection of systems at the vehicle level.

From this theory of structural decomposition, we can see that for each level of the design there must be some design specifications associated with it. Thus, this 4-level structural model can also be applied to design specifications as well.

Having established the structure of the design, we now turn to the contents of the product design specifications. As mentioned in Chapter 1, people tend to loosely use the term "design specs." Sometimes it may mean the specific requirements for the design, and other times it may mean a document that is usually prepared before the full scale design begins. Here, let us review the two definitions for this study:

1. Product Design Specification (PDS) means a central document that is used to guide all subsequent product design activities;
2. product design specifications (not capitalized or abbreviated) means specific design requirements that govern the detail design of the product.

PDS will be used when referring to definition #1 and design specifications for definition #2.

When one looks into any design specifications document, one will find that there are many different kinds of specifications, some very specific to the design and others remotely related. The approach for the following development has three steps: first, identify the elements of design specifications; second, organize them into a generic checklist; and third, categorize them in a way that provides a comprehensive conceptualization of the contents of product design specifications.

To begin, let us examine the elements of product design specifications identified by Stuart Pugh and a number of other sources that were discussed in Chapter 2. As shown in Table 2-1 on page 22, most of the sources emphasize a very limited number of elements and only Pugh gives a more comprehensive list of twenty eight elements. In an attempt to see how the other four lists compare with Pugh's list, Table 2-1 is rearranged into Table 3-1 with Pugh's list as the datum for comparison.

Three observations can be made from Table 3-1. First, although Pugh's list contains most elements, it does not have any apparent structure or organization. The twenty eight elements are somewhat randomly scattered in the list. Second, looking through Pugh's list, one will find that some elements are indeed basic design specification elements but others are more of

Table 3-1 A Comparison of Design Specification Elements

Pugh(datum)	Buhl	Burgess	Cullum	Leech
1 performance	function, capacity perform., adapt'ty	basic performance		function, functional req'mts
2 environment	environment			environment, opr'ting constr'nts
3 life in service	life in operation	operating cycles		
4 maintenance	maintainability			
5 product cost	cost		economics	cost
6 competition*				
7 shipping	transportability	transportation	delivery	
8 packing		packing/ID mark	packing	
9 quantity				mfg. constraints
10 mfg. facility	manufacturing		site	mfg. constraints
11 size		physical charact.		
12 weight	size & weight	physical charact.		
13 aesthetic	rigidity,appearanc		aesthetics	
14 materials	materials	materials		
15 prod life span*				
16 std. specs		std's/specificatns		
17 ergonomics	ease of opt'n		ergonomics	
18 customer	consumer specs			opr'ting constraints
19 quality/reliab			reliability	mfg. constraints
20 shelf life		handling, storage	storage	
21 processes	producibility		mfg. methods	mfg. constraints
22 time scale*				
23 testing		acceptance,	inspection	
24 safety	safety	testing	safety	
25 company constraints*				
26 market constraints*				
27 patents*	legality			
28 politics*				
OTHER	regulations	interface req'mts		

design specification categories under which the basic elements could fall. For example, "size" and "weight" are two very fundamental elements that describe two physical characteristics of the product without additional information. Whereas, "environment" is a category because it requires additional descriptive elements such as temperature, pressure, and humidity to fully state the environmental requirements. Furthermore, some items on the other lists are clearly categories for the elements in Pugh's list. For example, item 5 in Pugh's list, "product cost", is one element under "economics" in Cullum's list because there are other types of cost besides product cost, such as operational cost and field service cost. Therefore, Pugh's list contains both design specification elements and categories. Third, two items from the other lists, "regulations" and "interface requirements," can not be matched with any of the twenty eight elements in Pugh's list. Yet, they are both necessary design specifications items. On the other hand, there are seven elements on Pugh's list that do not appear on the other lists at all. They are indicated on Table 3-1 with an "*."

These observations suggest that there is a need to expand and rearrange Pugh's list before a generic checklist can be developed Building on Pugh's list and drawing from the other four lists as well as my previous design experience, I came up with ninety (90) design specification elements and organized them into seventeen categories as shown in Table 3-2. For example, the element "maintenance" in Pugh's list is now one of the seven elements that fall under the category of "Services;" the "manufacturing facility," "processes," and "materials" are grouped together under "Manufacturing & Production." Furthermore, many basic elements which do not appear on Pugh's list are added, such as the twelve elements under "Environment" and the three elements under "Systems."

Table 3-2 Categories and Elements of Product Design Specifications

CATEGORIES	ELEMENTS
1. Systems	input and output configurations applications
2. General Functions & Performance	design layout basic operations and functions response/processing time quantitative performance measures ie. Mechanical: flow, speed, vibration Electrical: voltage, amp, resistance Optical: resolution, optical length
3. Environment	temperature humidity pressure corrosion abrasion noise acceleration vibration contaminants climate installation limits effects on surrounding
4. Constraints & Operating Points	power supplies and range life in service product design life operating cycles/life (startup, shutdown) quality and reliability
5. Economics	target product cost & price (initial and operational) target manufacturing cost field service costs
6. External Factors	competition customer req'ments/market features company constraints market constraints patents, literatures, product data political and social implications legality, regulatory constraints

CATEGORIES	ELEMENTS
7. Manufacturing/Production	materials quantity demand forecast manufacturing facility processes/manufacturing methods process capabilities quality measurements
8. Handling & Storage	packaging shipping transportability shelf life/storage
9. Physical Characteristics	size weight shape geometric constraints physical strength smell
10. Interfaces	Hardware: physical connections mech/elect/hydraulic/optical contact points and surfaces tolerances Software: control commands type of information Human: type of operator controls type of information communication channels
11. Aesthetics	appearance external finish color
12. Applica Standards and Specifications	international standards U.S. standards (ANSI) military standards safety standards
13. Ergonomics	ease of operations control panel design requirements position of operating surfaces
14. Schedules	design reviews prototype builds shipping approval market introduction

CATEGORIES	ELEMENTS
15. Testing and Acceptance	acceptance criteria/procedure testing facility testing requirements
16. Safety	emergency operations/shutdown failure of parts noise emission hazardous operations
17. Services	failure rate (mean time between failures) failure modes (type, situation) maintenance (times/year) repair (calls/year) field service tooling (types and standards) problem shooting aids (computer software) ease of access and disassembly

For simplification, the seventeen design specification categories are:

1. Systems
2. General Functions & Performance
3. Environment
4. Constraints & Operating Points
5. Economics
6. External Factors
7. Manufacturing/Production
8. Handling & Storage
9. Physical Characteristics
10. Interfaces
11. Aesthetics
12. Applicable Standards and Specs
13. Ergonomics
14. Schedules
15. Testing and Acceptance
16. Safety
17 Services

These are very broad groupings of design specification elements. The name of each category is chosen based on a prominent characteristic shared by the elements in the category. For example, the category "Systems" contains system input and output, system configurations, and system applications. All three elements deal with requirements for the overall system. Another example is the category of "Environment." The twelve elements in this category all have something to do with specifying the environment in which the system or machine may be exposed to during operation or storage. The category "External Factors" contains all the elements that have direct impact on the product design but may not be controlled by the company, such as competition and market constraints. Patents and regulatory constraints fall into this category because they significantly affect the selection of product technologies or design parameters, and are beyond the company's control.

Although the list in Table 3-2 can be used as a generic checklist, it would be more useful if it is organized in some way. This leads to the last step in this development: a comprehensive conceptualization of design specifications.

Since it is very difficult to deal with the ninety elements, the following conceptualization will focus on the categories. An examination of the categories reveals four major characteristic groups which can be organized onto a 2 by 2 matrix, as shown in Fig. 3-4. The column headings are based on the observations that there are two kind of design specifications: explicit and implicit[1]. The explicit kind directly dictates the design, whereas the implicit kind indirectly influences the design. For example, Functions & Performance is an explicit category because it directly specifies the technical performance of the product, whereas Services is an implicit category because it specifies the services requirements that in turn influence the selection of other design parameters.

Within each kind of design specifications, there are two sub-sets as well: functional and non-functional. The functional set is closely associated

---

[1] The original use of these two terms was by Amit Pandey and Professor Don Clausing.

with the functions and technical performance of the product, and the non-functional set is related to the ergonomics and economics of the product. The non-functional aspects could be anything that are not directly tied to the technical performance of the product.

Fig. 3-4 Specifications Characterization Matrix

	explicit	*implicit*
functional	I Systems Functions & Performance Operating Constraints & Operating Points Interfaces Environment Safety	II. Services Maunufacturing/Production Handling & Storage Testing & Acceptance Applicable Standards & Specifications
non-functional	III. Physical Characteristics Aesthetics Ergonomics	IV. Schedules Economics External Factors

The four quadrants of the matrix completely capture the four groups of design specifications. Group I specifications are *explicit* and *functional,* directly dictating the product functionality and performance. This group includes Systems, Functions & Performance, Constraints and Operating Points, Interfaces, Environment, and Safety. All six categories explicitly specify the functionality of the product, such as the road performance of a car.

Group II specifications are *implicit* and *functional,* functionally restraining the design. This group contains Services, Manufacturing/Production, Handling & Storage, Testing & Acceptance, and Standard Specifications. These five categories provide additional requirements besides the functional performance of the product. An example may be that the product is a superior design but the manufacturing facility does not have the process capability to produce it. Therefore, the manufacturing requirements would restrain the product design to ensure that it is producible.

Group III specifications are *explicit* and *non-functional,* non-functionally influencing the design. The categories in this group are Physical Characteristics, Aesthetics, and Ergonomics. All three categories do not directly link to the technical performance of the product. Rather, they provide requirements that govern the non-functional aspects of the design such as operator positions and the outward marketable features. These requirements are explicit because they can alter the selection of technical design parameters. For example, the shape of a product may be dictated by the market or customer's taste, but it can affect the packaging of electronics and the routing of electrical wires.

Lastly, Group IV specifications are *implicit* and *non-functional,* managerially controlling the overall development. Of the four groups, this group is most remotely related to the technical design of the product. However, it controls the overall product development in terms of the economics, the resources, and the business requirements. The three categories in this group are Schedules, Economics, and External Factors. The schedules limit the amount of time available, the economics dictates the amount of funding, and the external factors govern the broader business decisions.

Given that these four groups vary moderately in nature, they have quite different implications for the management of product development. This connection will be explored later in section 3.4.

With the development of the matrix conceptualization of design specifications, Table 3-2 can be rearranged to provide a generic checklist that is based on the four major design specification groups. This generic checklist is shown in Table 3-3. It is organized by rearranging the different categories based on the four major design specification groups. Categories 1 to 6 are in Group I; categories 7 to 11 Group II; categories 12 to 14 Group III; and categories 15 to 17 Group IV. This list is intended only as a generic checklist and it is not industry specific. To use it, one would have to tailor it to one's own needs.

So far there is no obvious, observable relationship between the categories of specification and the structure of the design. It seems that some elements in one category may belong to the systems level while some others may belong to the lower levels. Whether this is true or not will be investigated with the field data in the next chapter.

Table 3-3 A Generic Product Design Specifications Checklist (by Groups)

CATEGORIES	ELEMENTS	
1. Systems	inputs and outputs configurations applications	
2. General Functions & Performance	design layout basic operations and functions response/processing time quantitative performance measures ie. Mechanical: flow, speed, vibration Electrical: voltage, amp, resistance Optical: resolution, optical length	
3. Operating Constraints & Points	power supplies and range life in service product design life operating cycles/life (startup, shutdown) quality and reliability	
4. Interfaces	Hardware:	physical connections mech/elect/hydraulic/optical contact points and surfaces tolerances
	Software:	control commands type of information
	Human:	type of operator controls type of information communication channels
5. Environment	temperature humidity pressure corrosion abrasion noise acceleration vibration contaminants climate installation limits effects on surrounding	
6. Safety	emergency operations/shutdown failure of parts noise emission hazardous operations	

CATEGORIES	ELEMENTS
7. Services	failure rate (mean time between failures) failure modes (type, situation) maintenance (times/year) repair (calls/year) field service tooling (types and standards) problem shooting aids (computer software) ease of access and disassembly
8. Manufacturing/Production	materials quantity demand forecast manufacturing facility processes/manufacturing methods process capabilities quality measurements
9. Handling & Storage	packaging shipping transportability shelf life/storage
10. Testing and Acceptance	acceptance criteria/procedure testing facility testing requirements
11. Applicable Standards and Specifications	international standards U.S. standards (ANSI) military standards safety standards
12. Physical Characteristics	size weight shape geometric constraints physical strength smell
13. Aesthetics	appearance external finish color
14. Ergonomics	ease of operations control panel design requirements position of operating surfaces

CATEGORIES	ELEMENTS
15. Schedules	design reviews prototype builds shipping approval market introduction
16. Economics	target product cost & price (initial and operational) target manufacturing cost field service costs
17. External Factors	competition customer req'ments/market features company constraints market constraints patents, literatures, product data political and social implications legality, regulatory constraints

3.3 Sources and Development Process of Design Specifications

Having now discussed the structure of design and contents, we will explore the sources and the development process of design specifications next. The sources and the development process are very closely tied together. Often, information from one source becomes the input to another, which in turn cascades it further to someone else. It is this process of information cascading that gives rise to the development of design specifications.

Based on studies already done on product development in general, we have identified seven sources. Specifications are often originated from customers, marketing, research & development (R/D), design & engineering (D/E), manufacturing, quality control, and field services. Each one contributes to the final PDS in different capacity and to different extent.

There seem to be two kinds of sources. One is external and one is internal. External here means coming from the outside of the company, and internal means from the inside. The customers, marketing, and field services would be considered external sources, because the information from them is usually from the market place or outside the company. Whereas, R/D, D/E, manufacturing, and quality control would be considered internal sources, because the specifications from them are typically generated within the company and by the internal people. In some instance, R/D may come from external sources such as competitors or collaborators.

Although the internally generated specifications are supposed to be closely linked to the externally generated ones, this does not happen all the time. When the internal sources fail to process and absorb the external information, the specifications from them are bound to be disjointed with the external specifications. This would ultimately lead to a product that does not meet any market needs. Prof. Clausing calls this phenomenon the "Disregard for the Voice of the Customer[2]"

In a market driven situation, the customers are the ones who usually start the information chain. They typically express their needs, desires and requirements to the sales and marketing people, who in turn relate these needs to the various internal sources in terms of more specific marketing requirements. Once the information reaches the different company sources, they each generate a particular set of specific requirements based on the market needs. An attempt to identify the contribution from the sources to the seventeen categories is shown in Fig. 3-5.

The specifications from the different sources are usually consolidated into the PDS prior to the beginning of any full scale design activities. This process sounds very similar to the information flow process for product

---

[2] This is the second of the ten cash drains that Prof. Don Clausing has identified.

design, and it should, because the development of design specifications is very tightly linked to the development of the product. This link will be explored further in the following section and in Chapter 4.

Fig. 3-5 General Sources vs. Specification Categories

		Cust'mr	Mkt.	Eng/ Design	Res/ Develo	Field Service	Mfg.	QA
Group I	Systems	√	√	√				
	Functions& Perf	√	√	√	√	√		√
	Constraints	√		√	√	(?)		√
	Interfaces	√	√					
	Environment	√						
	Safety	√		√		√		
Group II	Service Req'mts					√		
	Mfg/Prod			√			√	√
	Handl'g & Storage	√	√			√		
	Testing Acceptance			√	√		√	√
	Appl. Stds & Specs.			√		√	√	
Group III	Ergonomics	√		√				
	Physical Char	√	√	√				
	Aesthetics	√	√					
Group IV	Schedules		√					
	Economics	√	√			√	√	
	Ext. Factors	√	√					

One last point about the sources of specifications. Intuitively each of these sources should contribute certain elements of specifications to certain categories. However, looking at the categories and the elements alone does not yield a conclusive answer at this point. This will be a topic of investigation in the case study. Perhaps the field data will shed some light in this area.

3.4 Links to Product Development

Now let us return to a point that was brought up in the previous section: the link between the development of specifications and the development of the product. This topic will be explored in two ways. First, how are the elements of specifications related to the different development stages? Second, what implications do the four major specification groups have for the management of product development?

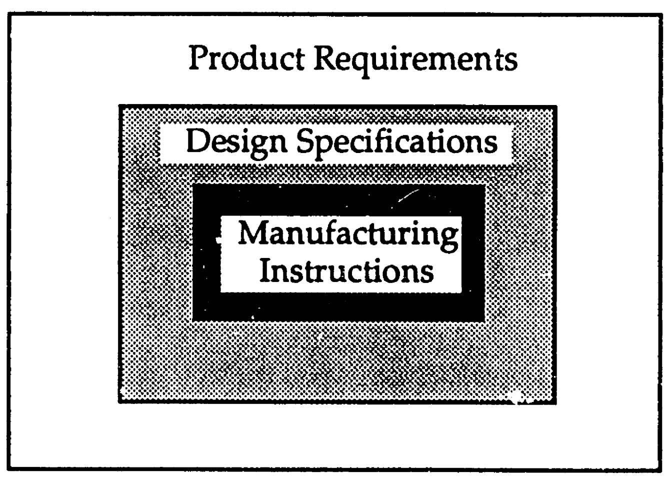
There seems to be a correlation between the elements of specifications and the development stages, but it is not clear how they are correlated. To begin, let us observe a little more of what people usually mean by design specifications. One will find that the term actually means different things to different people, varying from planning to product design to manufacturing. Three types of specifications that are often referred to are as follows:

1. requirements that the product must satisfy; (these tend to stay at the product level and are usually determined very early in the development; marketing personnel, product planners and program managers often refer to this definition;)

2. requirements before the actual design of a product, which falls under definition #2 for this study[3]; (this definition is heavily used by the design engineers;)
3. details of the design, such as parts dimensions and tolerances; these are mostly manufacturing instructions, and are more often referred to by the manufacturing people than by the design people.

Based on this observation, an attempt was made to understand the relationship among them. Fig. 3-6 shows one way of thinking about it.

Fig. 3-6 The Tier Progression of Specifications



In Fig. 3-6, the three types of specifications identified above are given three names respectively: 1. Product Requirements; 2. Design Specifications; and 3. Manufacturing Instructions. Product Requirements lay the overall

[3] Definition #2: product design specifications (not capitalized or abbreviated) means specific design requirements that govern the detail design of the product.

foundation, and Design Specifications give rise to the Manufacturing Instructions. This idea of one type of specifications building on top of another is heavily influenced by the information flow framework of product development.

Fig. 3-7 Linking Specifications to Development Stages

••• Concept Development ••••••> Product Planning ••••••> Product Engineering •••

Product Requirements	Design Specifications	Mfg. Instructions
- product functions	- systems	- part dimensns
- product features	- functions, perform.	- tolerances
- system configurations	- opt. constraints/pts	- materials
- applications	- environment	- processes
- development cost and selling price	- interfaces	- finish/coating
- product constraints	- safety	- UMC
- basic operations	- services	- .....
- system I/O	- mfg./production	
- technology	- handling & storage	
	- testing/acceptance	
	- appl. stds & specs	
	- physical char.	
	- aesthetics	
	- ergonomics	
	- schedules	
	- economics	
	- external factors	

To go further, Fig. 3-7 shows a mapping of certain kinds of specifications to the product development stages. This is only a very crude conceptualization and is certainly subject to criticism and verification.

This mapping suggests that the items listed under each type should be determined prior to the beginning of the next stage. For example, the list under Product Requirements pertains to the product functionality and performance, and it should be defined before the start of the Product Planning stage. Under Design Specifications are all seventeen categories of design specifications that were summarized in Table 3-3. The reason that all seventeen categories are listed here is that they are all necessary and important for the Product Engineering stage. Some of the Product Requirements may appear under the Design Specifications list because they may contain important product information that is necessary for the engineering design. For example, market needs may require that a device be able to transmit information to remote locations. Although the term "remote" may not be defined at the Concept Development stage, this requirement is important to pass onto Product Planning so that an exact distance of transmission can be determined later. Following the Product Engineering stage is a list of manufacturing instructions which enables the parts to be manufactured. Again, some of the manufacturing instructions may come directly from the Design Specifications list. For example, the size of the machine determines the overall dimensions of the body panels, although tolerances must be added to ensure a good fit.

Fig. 3-7 implies a temporal progression of the design specifications development. Although it is intended purely as a descriptive process model to show the connection between the three types of specifications, it may be used as a temporal guide to the development design specifications.

Now let us turn to the second question of what implications the four major groups of specifications have for the management of product development. It would be helpful at this point to review and restate the four groups along with their characteristic roles in the design and development. Fig. 3-8 shows the groups and their individual characteristic roles. Group I dictates the product design in terms of explicit functional and technical requirements, such as quantitative amount of power generation. Group II restrains the design by imposing additional secondary requirements such manufacturing process capability and services tooling availability. Group III influences the design with explicit but non-functional requirements such as appearance, size and weight. Group IV controls the overall development by restricting development resources.

Fig. 3-8 The Characteristic Roles of the Four Specifications Groups

Group I: *explicit, functional* DICTATE DESIGN	Group II: *implicit, functional* RESTRAIN DESIGN
Group III: *explicit, non-functional* INFLUENCE DESIGN	Group IV: *implicit, non-functional* CONTROL OVERALL DEVELOPMENT

In terms of the importance to the final design of the product, Group I seems to play a bigger role than the others. However, all four groups are necessary for any product development program. Given that their characteristic roles vary, these four groups can be used to direct the focus of different people and activities, thus providing a management tool for product development.

None of the four groups of specifications links one to one with a specific function in the company or a particular source of specifications. Each group takes inputs from numerous sources, and each of the sources can contribute to more than one group. For example, the Group I specifications take at least Marketing, R/D, and D/E to collectively develop. However, at the same time, Marketing provides information to the other three groups as well. In specific categories within the four groups (refer to Fig. 3-4), Marketing can contribute to: Group I - systems, functions, operating constraints, and environments; Group II - handling & storage; Group III - physical characteristics, aesthetics, and possibly ergonomics; and Group IV - external factors, economics, and market window (or schedule).

Therefore, by understanding the nature of the specifications within the four groups and the people involved in developing them, the program managers or design supervisors can use this kind of specification groupings to help them coordinate the development efforts and assign people to tasks. Furthermore, given that each group takes multiple functions or sources to develop, this would help to foster a multi-functional team approach to design.

Another useful aspect of this grouping technique is to help make tradeoff decisions. Since Group I is most heavily tied to the functionality of the design, the design specifications in this group should be compromised as little as possible. If tradeoffs are necessary, they should be explored among the other three groups first because these groups tend to play more of a support role to Group I in terms of product design specifications. This is not to say that Group I specifications should never be compromised. In fact, often they are. This matrix grouping technique can help the people involved to keep a big picture of what they are optimizing and compromising so that hopefully the decisions made are truly optimal and the best.

3.5 Development Methods for Design Specifications

The last topic in this chapter is the development methods for design specifications. There really is not a standard set of tools and methods that people can choose from in developing design specifications. Very often design specifications are determined based on gut feelings and guesses. This is no exaggeration. When the product or the technology involved is old and the people are experienced, the design specifications tend to be more structured and well defined. However, when the product or the technology is new and there is no previous experience to draw from, most of the design specifications are usually done by Trial and Error, or by some random approaches.

Although it seems that, in practice, most of the design specifications are chosen or determined without much analysis, there is a number of analytical tools that enable a structured approach to developing design specifications. Some of them include Systems Engineering, Analytical Optimization, Value Engineering, and Experimental Design. In addition, there are numerous methods that allow systematic development of design specifications, such as Quality Function Deployment (QFD). Analytical tools such as Value Engineering and Experimental Design are often used in conjunction with QFD to achieve a more integrative and systematic development.

Table 3-4 summarizes some of the most common systematic and unsystematic methods. Some of the methods on both lists are analytical and some are managerial, while others are neither.

Table 3-4 Summary of Specifications Development Methods

SYSTEMATIC	UNSYSTEMATIC
- Systems Engineering	- Local Optimization
- Experimental Design (Robust Optimz'n)	- Trial and Error
- Value Engineering and Analysis	- Spontaneous Solutions
- Benchmarking	- Gut Feelings
- Quality Function Deployment (QFD)	

Let us examine each of these techniques in more details, starting with the systematic methods. Systems Engineering is based on the black box approach to analysis. It seeks to optimize the design by treating the entire system as a black box. The only known parameters are the inputs and outputs of the system, which are typically dictated by the customer and marketing requirements. This technique allows systems level performance to be determined analytically. It can be used whenever inputs and outputs to a system are known or reasonably well defined. This forces the analysts to clearly identify the inputs and the outputs. System Engineering is one of the most powerful analytical techniques for developing design specifications.

Another powerful systematic technique is Experimental Design. The idea behind this technique is to analytically optimize all the critical design parameters before starting the actual detailed design. This is done by first pre-selecting a number of critical control parameters and the noise range associated with each one, and then running the pre-determined experiments. By examining the results of the experiments, the optimum design parametric values can be determined.

This technique has been around for a long time but, in its original form, it is too complicated and cumbersome for any wide spread application. Recently, a simplified version has been made available to practitioners. The name that is often associated with this simplification is Dr. Taguchi. He has constantly emphasized the quality characteristics of a product such as the primary functional elements in the seventeen design specification categories. The so called Taguchi's methods use a series of orthogonal arrays that permit easier application and interpretation the design experiments. If applied correctly, robust designs can be achieved with the Taguchi's methods.

The next one is Value Analysis and Value Engineering, commonly known as VA/VE. This technique also has been around for quite some time but has traditionally been used for design improvements after the design is complete. It provides tools to examine the design components and the cost associated with them. By attaching a dollar value to certain hardware and functions, it enables the designers to identify opportunities for hardware or function consolidation or design simplification. Even though this technique has previously been applied to designs after the fact, it has tremendous potential for the development of design specifications. It should be noted that VA/VE is actually a foundation for the application of QFD. This will be investigated further with the field data in the case study.

Following VA/VE is Benchmarking. Although it is not as well known or as often used as the previous ones, it is also a very powerful technique for getting design specifications. Benchmarking is a practice by which one evaluates and compares with competitors or product leaders. Through such evaluation and comparison, some of the performance targets can be determined. Benchmarking is a very convenient way of obtaining design specifications.

The last, but not least, one among the systematic methods is Quality Function Deployment, which is often called QFD. This is a relatively new import from Japan. It provides a system of four matrices which enables the translation of the customer's requirements all the way to the operating conditions of the factory floor. The intent of this technique or system is to keep the customer in focus throughout the product development process.

In terms of design specifications, the first matrix, which is often known as the House of Quality, is the most important. It relates the customer's requirements to the engineering characteristics. Usually the customer's requirements tend to be qualitative and sometimes not very specific. The House of Quality turns the vaguely worded customer requirements into more concrete and specific quantitative measures. These measures then become the performance goals of the product.

The remaining three matrices of QFD follow the similar logic of translating from one set of requirements to another. The second matrix, the Product Design Matrix, converts the engineering requirements into design parameters and hardware design values. The third matrix, the Process Design Matrix, takes the hardware design parameters and generates the process requirements necessary to produce the hardware. The last matrix, the Production Design Matrix, transforms the process requirements into production system design parameters. This set of four matrices provides a very efficient system for generating and keeping track of the design specification.

Now let us go through the unsystematic methods. As shown in Table 3-4, the four common methods are Local Optimization, Trial and Error, Spontaneous Solutions, and Gut Feelings. Local Optimization seeks the optimal solution without considering the effect on other sub-systems or the whole system. This is sometimes called sub-optimization. This technique is used frequently throughout the design, because it is more convenient to optimize when there are fewer parameters and less complexity. The values obtained from this technique can become specifications that may not be the best for the system.

Trial and Error is a more common technique than Local Optimization in the day to day product development world. This is especially true with new products and new technologies. Typically design engineers would pick some values and then build some models to test them out. In so doing they hope to find a set of values that works. When there is no other source of information, Trial and Error is about the most efficient way of getting information. As the computer technology becomes more and more sophisticated, there are variety of simulation software packages that attempt to systemize the trial and error process. However, it can get very costly. This approach is only good during advanced development or early product design. It must be followed by optimization.

Spontaneous Solutions and Gut Feelings are in essence very similar. These two are by far the most commonly used techniques in design specifications development. Both techniques depend on the experience of the design individuals. Very often, experienced designers and engineers would come up with performance goals and design targets purely based on their gut feelings. Their solutions thus tend to be somewhat spontaneous. Although it may seem that these spontaneous solutions are quite arbitrary, the experience of the designers and engineers is a valuable source of information. However, to achieve a set of sound and comprehensive design specifications, this source of information should be channeled into a more structured specifications generation process.

This brings us to the end of the conceptual development. The topics discussed and explored here forms a framework for the case study in the next chapter. Some of the questions that were raised in this chapter but not fully answered will be addressed with the field data.

CHAPTER 4: CASE STUDY

IMAGE CORPORATION

Chapter 3 provided a conceptual basis and framework to think about the development of design specifications. It offered some answers to the five guiding questions, and created other new dimensions to think about the issues at hand. This chapter will build on that development with the field data from a study of the IRU[1] development program at Image Corporation. The objective here is to verify and supplement the conceptualization developed in Chapter 3, and provide a more in-depth discussion around the topics of investigation.

This study will focus only on the hardware design, although the software development was a major undertaking in this program. This is mainly due to my background in mechanical engineering and my experience in hardware design. The following case study only represents my personal interpretation of my own observations and thus may be biased. An effort has been made to ensure that the analyses are factual and accurate.

This chapter will be mostly an integrated presentation and discussion of the field data. Comparative analyses between the conceptual development and the field data will be provided as well. Some of the general observations related to the topic of specifications development will be saved for Chapter 5.

---

[1] IRU stands for Image Retrieval Unit.

4.1 Case Background

Program History

At the end of 1985 a product, code named 1001, was introduced to the market, and there was no new development programs in the pipeline. As some of the original development group continued to support the 1001, a few individuals began to search for a new product idea. This effort was assisted by another engineer, Ali, from a different group in the same division. He personally became interested in exploring the incorporation of a new technology into the existing 1001. This technology is actually not completely new to the people involved; it has been used in at least one other product in the division and certainly has been the technology base for a different division located only a mile away.

Around mid 1986, Ali got together with four people from the 1001 program and started to tinker with an old 1001 machine. By the fall of 86, they demonstrated the feasibility of this technology, and showed that the new technology can indeed be incorporated into the existing 1001 hardware design.

At this time, Market Planning became interested in the new idea, and management "bought into it immediately in a panic" because another development program was needed badly to follow the 1001. They realized the potential market advantage that this new technology could bring. Thus market planning activities gradually started toward the end of 1986 and boomed during 1987, leading to a Marketing Requirements Document (MRD) in September, 1987.

Meanwhile, the design community had also started doing some conceptual ground work. During the Spring of 1987, one of the most experienced engineers from the 1001 program built a very crude breadboard model and demonstrated a concept design. This led to a phased approach to the development of a new product, code named 1002. The original intent was to leverage as much as possible from the 1001 and make only minimum changes when necessary.

The development of 1002 was divided into two phases[2]. The first phase was a market trial and the second phase was production hardware design. During Phase I, which went from the Spring of '87 to July of '88, 5 trial models were built to put on selected customer sites. The goal was to get inputs from these customers to feed the Phase II development.

During the Phase I design, some of the hardware and software were modified, but a critical part of the hardware system, the imaging optics, remained the same. This was mainly because optics in general are very expensive to develop and the set that was currently in use had been fine tuned over the years from the other previous products. Some of development in Phase I became part of the final design in Phase II. However, the end product from Phase II was very different than the Phase I models. Due to new market requirements, the optics system and a large amount of software had to be redeveloped, which prolonged the entire development.

The product was introduced to the market at the end of 1989 and the first customer unit shipped during January 1990. The program took about

---

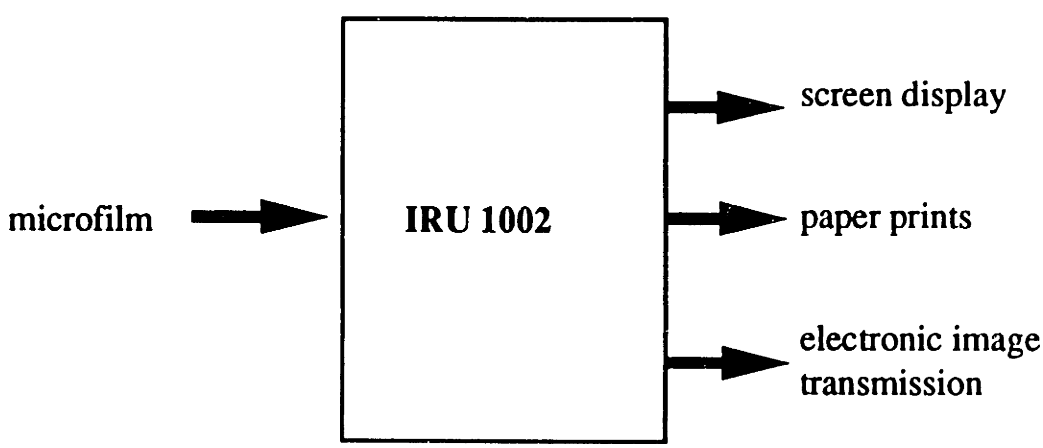
[2] Originally there were three phases but Phase III was cancelled.

three years from concept to final shipping[3], and the product design alone took about two years. A more detailed discussion of the development will be given in section 4.2.

Product

The product is a floor standing microfilm reading device which allows users to view, print, or transmit microfilm images electronically. The machine takes a microfilmed document and reproduces it either on an optical screen or on paper, or transmits it to other electronic data processing equipment. Fig. 4-1 shows an input/output diagram of the IRU 1002.

Fig. 4-1 Input and Output Diagram



To operate the machine, an operator would type in a sequence of commands on the keyboard to instruct the system what document to look for

---

[3] According to a staff person who is responsible for coordinating the implementation of a newly developed Phases and Gates Product Development Management System, a typical product development program in this division takes about 5 years.

and what features are desired for the output, and then insert a roll of microfilm through the film insert slot. The machine would automatically search for the desired document on the film and produces an optical image of the document. This optical image is then either projected onto a viewing screen or onto a device which converts the optical image into digital signals. The digital signals are then processed and sent to the appropriate electronic output equipment such as a printer (these output devices are not part of the base machine).

Market and Competition

This product is targeted for low to moderate volume information searching applications. Some of the most common applications are check processing in large banks; insurance claims in the adjustments offices; automobile industry warranty claims; loan processing in financial institutions; libraries; and accounts payable in small to medium companies. Therefore, there is a wide demand for this type of equipment and the market place is very competitive. Image Corporation is one of the four major players in the market. Each of the major players has very strong presence in certain market segments.

Currently, three factors determined the competitiveness of each player. The overall system productivity, which is the time from film insertion to a finished print, is the most critical customer requirement. This includes the time to scan, time to print to an adjoining printer, and time to print to a remote printer. This requirement dictates the speed of document scan, the speed of signal processing, and the speed of the printer. The second factor is cost per print, which includes the cost of the equipment itself, the cost of labor and the cost of operation such as power consumption and maintenance service. The third factor is the capacity of the machine. Some users have a large microfilm file which would require a system that could automatically locate and insert the film document. These systems are available but they are too costly for the smaller volume users. The IRU family of products is targeted for the smaller volume segment.

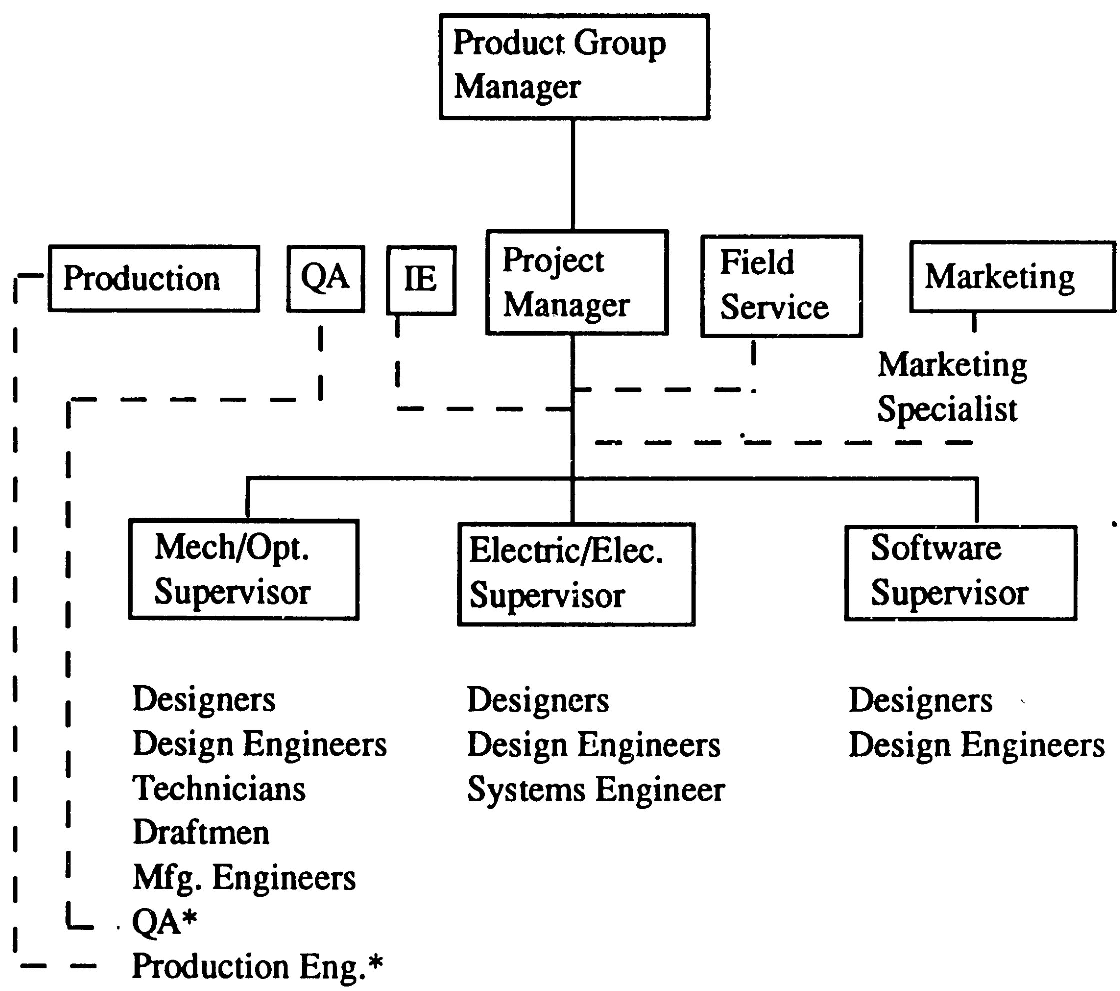
Organization

The 1002 program is in the Commercial Products division of Image Corporation. The division is organized by three product groups. One of them is Retrieval Products, and IRU 1002 is a program within this product group. This division has been making the same type of industrial products for a long time. In this particular family of microfilm readers, the first model dates back to the 70's. They are therefore very experienced with the microfilm reader design and very familiar with the market.

Initially the development group was informally formed. Because of the way the project came about, the people involved at the beginning included an experienced design engineer, a technician, a model maker, and a technologist.

As the project evolved, the organization became more structured. By the time the program was well under way in 1987, there were an electrical supervisor and a mechanical/optical supervisor, both reporting to a program manager, who in turn reported to the product group manager (see Fig. 4-2). Under each of them was a group of engineers, including software engineers and manufacturing engineers. Interestingly, the Program Manager was the one who prepared the MRD at the inception of the program, and the mechanical supervisor was the engineering supervisor for the 1001.

Fig. 4-2 Organization Chart



* added to the team later

In addition, there was a number of other individuals representing planning, marketing, field services, quality assurance, and industrial engineering that were made part of the team. This structure remained almost the same throughout the development, except software design was organized into a third engineering group with a software supervisor. In June of 1988, about one third of the way through the Product Engineering stage, a QA person came on board, and then at the beginning of 1989, about a year before shipping, a production planner was added to the team, both under the mechanical/optical supervisor.

The entire team, including marketing, planning, quality assurance, and field services was located in one place. The interaction among the team members was very strong and constant, which significantly contributed to the success of the program.

4.2 Product Development

The inception of the 1002 program was heavily technology driven, but the actual design of the product was very much market driven. As mentioned earlier, this program took a phased approach to the development (see Fig. 4-3), which was mostly influenced by their marketing strategy. The goal was to first put a number of trial models as quickly as possible at a few selected customer sites for market information collection and then develop a production unit for final market introduction. This way, not only could they obtain market feedback more efficiently, they would also be able to enter the market faster and establish earlier market presence with this new product.

The plan for Phase I was to take an existing 1001 design and quickly convert it to an 1002 with minimum changes. Most of the differences between the 1001 and the 1002 were in performance and features because the new technology enabled easier manipulation of the electronic image and faster system response. However, the primary functionality of the two machines were very similar, at least initially.

The primary intent of quickly converting a 1001 into a 1002 was to gain early market input for later expansion of the system[4]. The original target availability (ie. site installation) date for the trial models was the fourth quarter of 1987. However, by the end of 1987, the Phase I design was completed but the 5 trial models were still being built. They were tested and installed between early February and mid July of 1988. A timeline of the entire development is shown in Fig. 4-3.

The same group of designers and engineers who worked on the Phase I design continued onto Phase II. This was the intention of management to retain the expertise acquired during the Phase I design and was proven to be a very effective management technique. Although the Phase II design turned out to be almost completely different and much more extensive in functionality and product features than the Phase I machine, the experience of the people who came from Phase I was absolutely essential to the successful completion of the Phase II design.

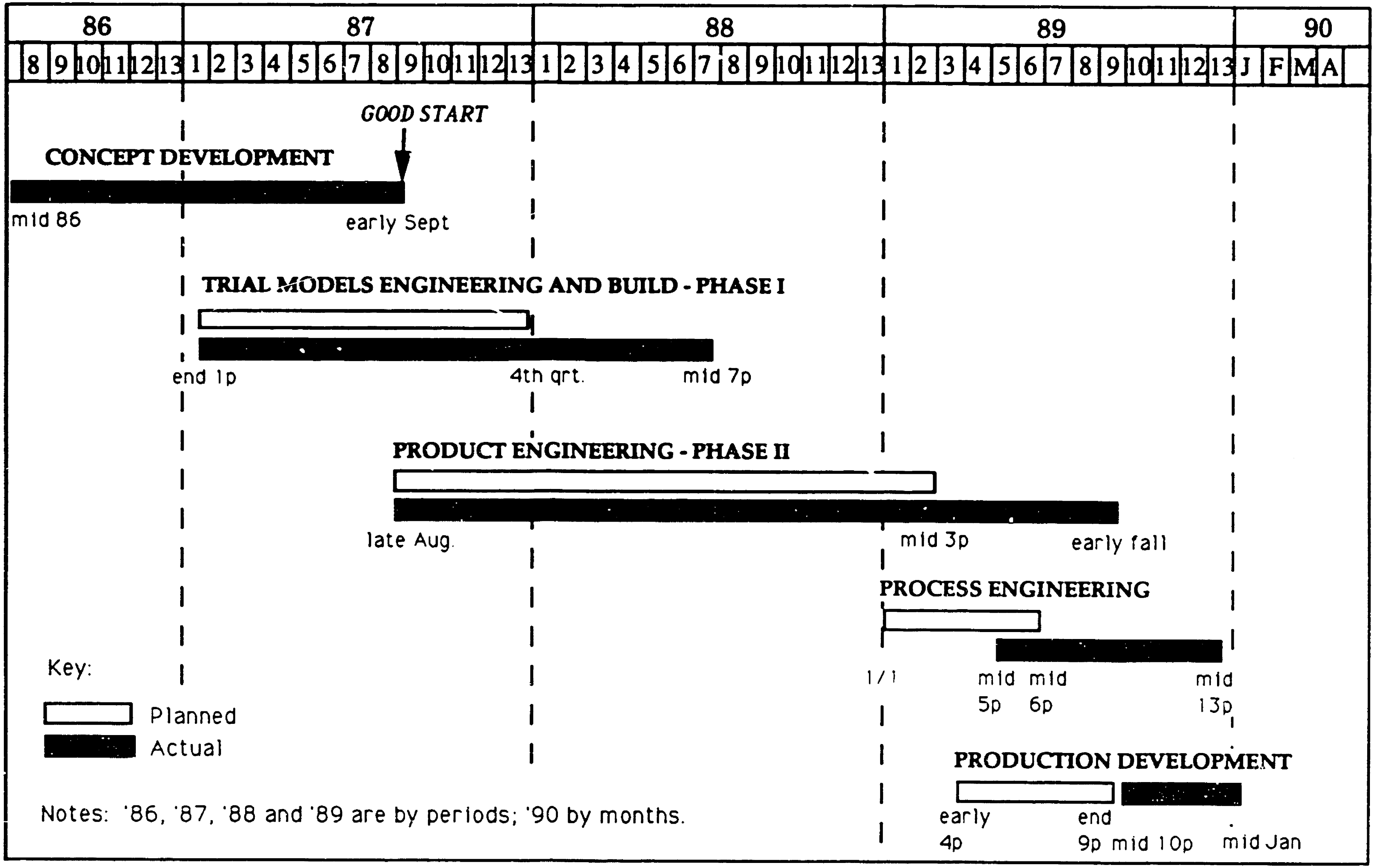
Most of the hardware designers and engineers had worked together on the 1001. This helped to foster a much more cooperative team environment. The fact that they were already familiar with the basic functional requirements of this type of machine helped tremendously with the new development.

According to management, the 1002 development really did not start until the so called "Good Start" in early September of 1987, which was the official start of the Phase II Product Engineering phase. This phase was

---

[4] From a meeting notice dated 12/3/86.

Fig. 4-3 A Development Timeline for IRU 1002



considered completed when 6 engineering models were built and tested. As shown in Fig. 4-3, it took roughly two years.

Because of the original intent to retain as much of the 1001 design as possible, an optimistic customer availability date for Phase II units was set for the first quarter of 1988. Of course, at that point, no one could foresee the challenges ahead of them. However, they very quickly realized the difficult task at hand, and adjusted the schedule accordingly. The revised schedule targeted market introduction for mid 1989 and later moved to late 1989.

Two major development tasks prolonged the Product Engineering phase. One was the redesign of the entire optics system and the other one was the large amount of image processing software that needed to be developed for the first time.

Despite the fact that the 1002 management wanted very much to minimize the amount of redesign, the market place was crying out for zoom capability in this type of products. The fact that their competitors were already offering such a product feature forced the 1002 development plan to be changed. As the market information was fed back to the development team, it was becoming clear that this product could not be competitive unless zoom lenses were offered.

This new requirement almost completely altered the Phase II machine design. One reason was the physics involved in designing zoom lenses. The existing optics system in the 1001 units was completely obsolete and incompatible with zoom lenses. In order to provide zoom capability, a decision to redesign the entire optics system was made. This development was further complicated by the fact that the width of the 1001 design had to be reduced because the current machines would not fit through most of the office doors in Europe. This put a rather severe constraint on the optical length required to develop the zoom lenses within the desired magnification range. It took many iterations and compromises to enable the successful development of the new optics system. The optics alone took over one and a half years, from late 1987 to Fall, 1989.

Image Corporation is organized so that the product development groups are in the product divisions and the specialty design groups such as optics design are centralized in another division. In this case, the optics were designed by a group of optics engineers residing in the centralized division and located in a different building. However, since the previous optics system was developed by the same organization, the cooperation from the optics designers was tremendous. The organizational boundary in this case did not become a major barrier. It was because of the close collaboration between the product designers and the optics engineers that such complicated lens optics were successfully developed in a year and a half.

The software development was the other major hurdle. In this case, because the technology was new for this type of product, software engineers had little experience to draw from. Furthermore, the technology was not yet well understood at that point. Consequently, the software development went much slower than expected. Most of the difficulties were in understanding the image processing needs and print quality requirements. Since this product offered many new features that were not possible with the old technology, many new software packages had to be developed and most of the design specifications were not known before hand. Some of these specifications evolved through the course of design and others remained unknown. It is expected that there will be fewer problems with the next generation design.

The bulk of design was mostly completed by the summer of 1989, and the engineering models were built between April and June of 89. The remaining months of this phase were spent on making and incorporating design changes. Since there was no formal tracking of the design changes, I was unable to obtain a quantitative measure of number of design changes over time.

Most of the 1002 design was done using Computer Aided Design (CAD) tools. The CAD system was linked to the optics design engineers as well, which enabled speedy communication of design changes and new design requirements. In this case, CAD was used mostly as a convenient drawing and analysis tool. One common data base enabled the different designers and engineers to access the same information. The general feelings among the designers and engineers were that CAD was a very useful tool in product design and that they felt comfortable with using this technology.

In terms of supplier management, CAD played an important role as well. Although the CAD system was not linked to any of the outside vendors, some vendors were able to simply take the CAD files on tape and conveniently put them onto their CAD/CAM systems, if the systems were compatible. This enabled very efficient data transfer to and from the vendors. In the case of incompatible systems, some vendors were able to convert the existing CAD files to fit their own CAD/CAM systems. Although this was more cumbersome, the designers felt that it was still quite an efficient way of communicating with the vendors. A vendor in this latter group was willing to keep track of the design changes for the 1002 designers and keep the final design drawings updated. When the design was finally frozen, they would send back the final production drawings for the team's design record. In this capacity, the vendor served as a record keeper or file maintenance agent.

As the use of CAD systems becomes more and more wide spread, a CAD network between the product design organization and its suppliers can potentially be a very powerful tool for supplier management. The use of CAD in the 1002 program demonstrated some of the potentials.

Shortly after half way through the Product Engineering phase, in early 1989, Production Planning joined the development team. Their charter was to come up with efficient production processes to enable quality production of the product. Even though they were involved at the very beginning of 1989, pilot production (also called pre-production in Image Corporation) did not start until mid 1989. This Process Engineering phase gradually merged with Production Development in the later part of 1989.

As mentioned earlier, throughout the development of the 1002, marketing, field services, and industrial engineering were actively involved. A representative from each of the three areas was resident in the development team from the early stages to the end. Marketing was responsible for providing the Marketing Requirements Document (MRD) which was used to guide the subsequent development. The resident marketing specialist played a significant role in terms of continually supplying customer and marketing information. As the program moved into the later phases, he helped prepare a market launch plan and personally trained a sales team. He also demonstrated the new product to the potential customers, on the manufacturing floor.

Similarly, the field service representative actively influenced the design. Prior to the Phase II Product Engineering stage he provided two design specification documents, clearly spelling out the serviceability requirements. Toward the end, he organized and carried out the training of field service engineers. Having had the experience with servicing previous products, he gave substantial input to the general improvement of the design.

The industrial engineer resident started his involvement as a staff assistant to the program manager. He basically facilitated the management of design activities. As the program moved through the engineering phase, his role gradually changed. Especially during the production preparation phases, he assumed a major role in supporting the production planning activities. Being an industrial engineer, he exerted strong influence on the design of the production system.

The management approach in this program was to keep the design target clear and fixed as much as possible. According to the program manager, a big effort was made to adhere to the Marketing Requirements Document. Changes to the MRD were kept to a minimum, and only if they were absolutely necessary such as the addition of zoom lenses. In general, the people involved in the development felt very positive about such an approach and praised the management team for their commitment. As one of the interviewees put it, "It's nice to work on something that doesn't change all the time."

This program in general was very successful. The team, including management, technical personnel, and the support functions, worked very well together. It seems that the people factor was more significant to the success of this development program than the technology itself, although the technology brought about a new product concept. Without the cooperative spirit of the team, the program would have taken much longer time and consumed much more resources. Most of the people felt very good about this program, citing good teamwork as a major success factor.

The other important factors that I observed include:

1) strong leadership and good management commitment;
2) active marketing and field services involvement;
3) superior technical expertise;
4) extraordinary commitment and dedication;
5) excellent services and cooperation from suppliers;
6) outstanding collaboration from optics designers;
7) sufficiently early involvement of production and quality assurance.

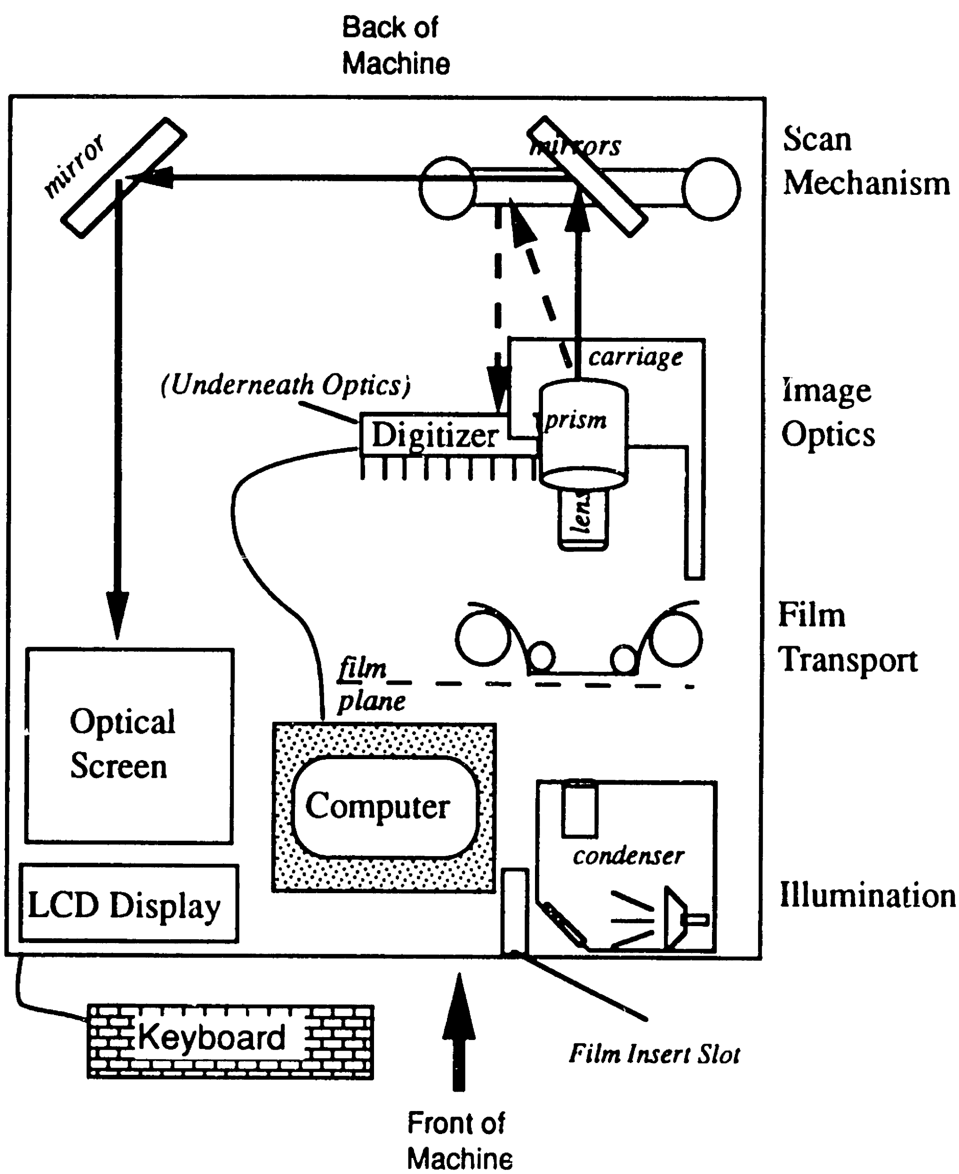
Some of the shortcomings appeared to be:

1) inflexible and cumbersome purchasing procedures;
2) lack of active involvement from purchasing;
3) complicated procedures for formal documentation of design changes;
4) lack of documentation for establishing testing criteria;
5) insufficient specifications preparation;
6) loosely defined design review criteria;
7) inadequate up front planning.

4.3 Structure of Design and Contents of Design Specifications

In order to explore the structure of design and the contents of the design specifications for the 1002, some details about the product design need to be explained first. Fig. 4-4 is a functional diagram of the 1002 machine. It shows the hardware layout and the two optical paths. Basically, the device has four large clusters of hardware that correspond to four hardware sub-systems: Illumination, Film Transport, Image Optics, and Scan Mechanism.

Fig. 4-4 IRU 1002 Functional Diagram (Top View)



Once the film is inserted into the system, the Film Transport would automatically locate the frame and position it for optical magnification. The

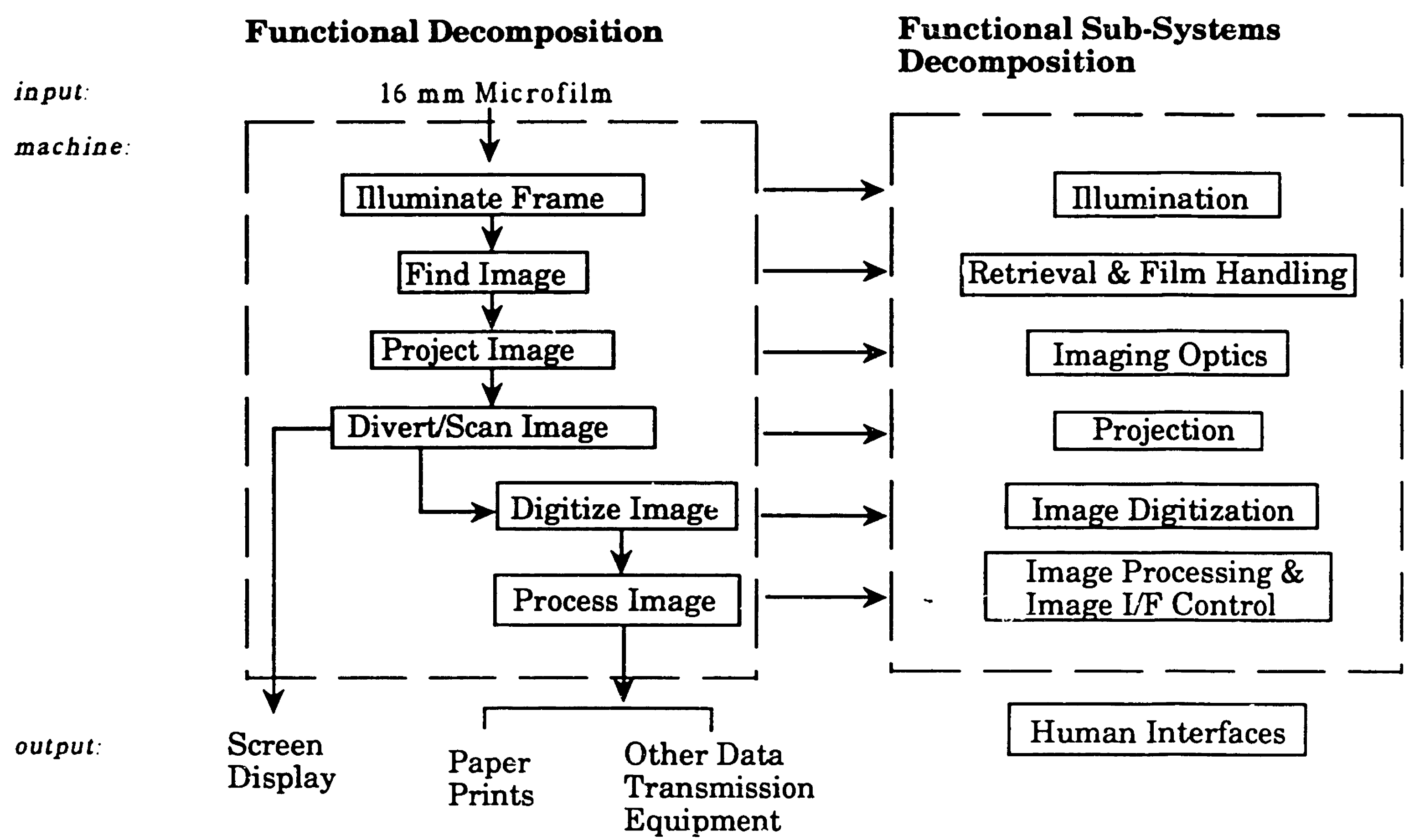
Illumination would illuminate the film frame so that the Image Optics could magnify the film image.

Depending on the operator's instructions, the magnified optical image can be sent to either a viewing screen or a digitizer. A motor drive is mounted on the Scan Mechanism which carries two sets of mirrors for deflecting the optical image to the appropriate destination. If the operator wanted to view the document on an optical screen, the screen path would be selected by the software control system and one set of mirrors would be automatically positioned to deflect the optical image to the screen. If the operator wanted a paper print-out or any other electronic transmission, then the control system would select the digitizer path and position the other set of mirrors to project the image onto a digitizer. The digital signals would be further converted into analog signals through an Analog/Digital converter. The analog signals would then be processed by a computer for the final image transmission to the printer or other electronic output devices.

As a first step towards understanding the structure of design in the 1002, the major machine functions and the corresponding hardware sub-systems are identified in Fig. 4-5. This figure is basically a process diagram of the machine, which shows the sequence of operations (higher level functions) that the machine takes to accomplish the overall task. The higher level functions were obtained by asking "How does the machine turn the inputs into outputs?" The hardware sub-systems were found by identifying the hardware that perform the functions. It so happened that, in this case, there is a one-to-one correspondence between the functions and the hardware sub-systems, which is not typical.

A closer look at Fig. 4-5 led to the realization that there are actually two kinds of functions. Some functions are primary and others are secondary.

Fig. 4-5 FUNCTIONS VS. HARDWARE SUB-SYSTEMS



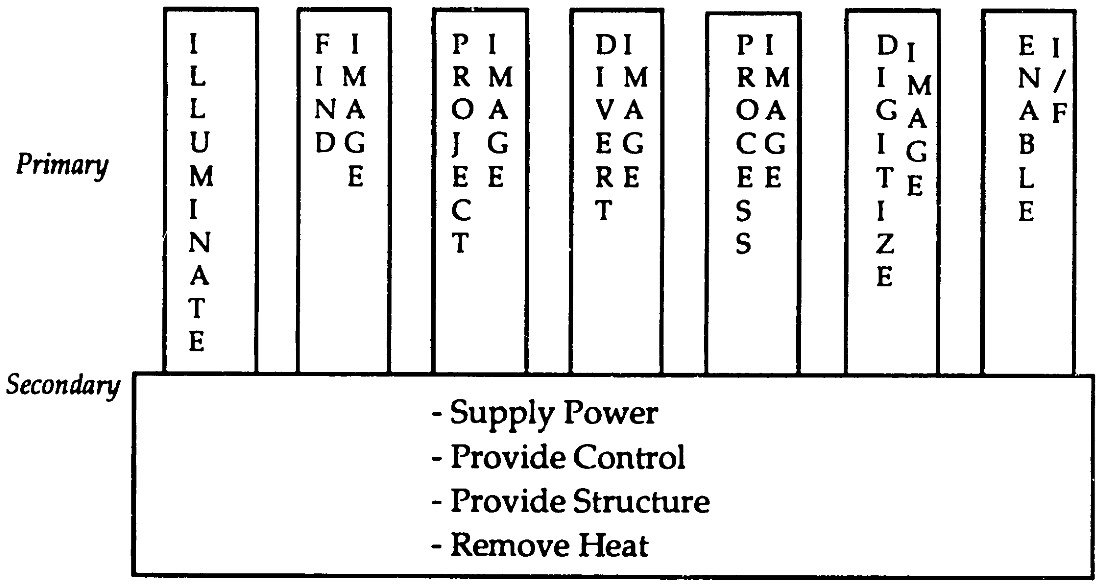
The functions shown in Fig. 4-5 seem to be primary functions of the machine. They directly perform the essential functions. However, there is a whole group of functions that are absolutely necessary to support these primary functions, namely the power supply/distribution, controls, structure and cooling.

Fig. 4-6 provides a schematic for thinking about these two kinds of functions and hardware systems. Fig. 4-6 (A) shows the functions and Fig. 4-6 (B) shows the corresponding hardware sub-systems. Each vertical "pillar" represents a primary function which requires that a group of hardware be physically located together to perform it. These functions have an integrative effect on the hardware because they bring together groups of hardware that form dedicated sub-systems. For example, in Fig. 4-6, the Illumination sub-system is an assembly of hardware components that collectively serve the sole function of Illuminate; it does not contribute to any of the other six primary functions. Another example is the Film Transport. It is another assembly of hardware pieces that collectively carry the function of Find Image; it does not directly serve the Illuminate function or any other primary functions.

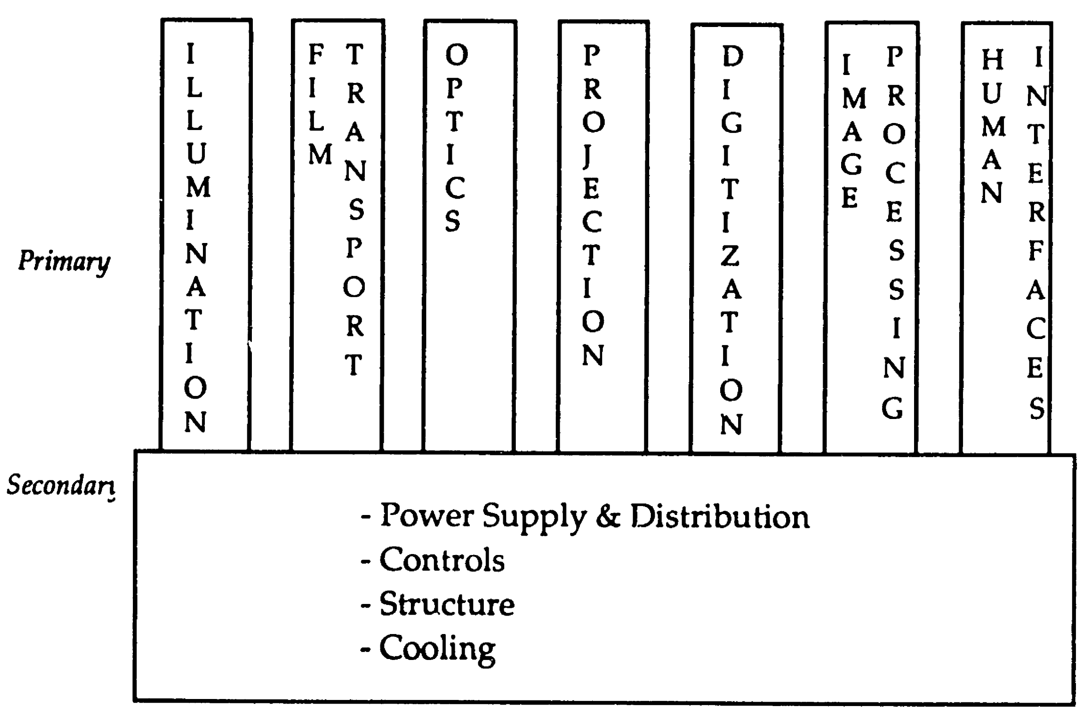
Whereas, the horizontal block on which all the vertical "pillars" rest symbolizes the distributive nature of secondary functions and hardware. The secondary functions provide common services to all the primary sub-systems. For example, the function Supply Power serves any primary sub-system that requires power supply to perform its primary function. In this case, the Power Supply & Distribution sub-system contributes to every primary sub-system in the machine. Therefore, the secondary functions have adistributive effect on the hardware because they disperse groups of hardware to serve the needs of the primary sub-systems.

Fig. 4-6 Primary vs. Secondary Functions and Hardware (Sub-systems Level)

(A) Functions



(B) Hardware



The importance of such differentiation and its implications to the management of design will be discussed in Chapter 5. Here the focus is to understand how such differentiation relates to the structure of design. Clearly, achieving the primary functions are typically the major design tasks for the engineering design. The secondary functions are, however, default requirements that the design must have. In terms of design specifications, both primary and secondary specifications are important and should be clearly defined.

Although a process diagram as that in Fig. 4-5 is helpful in identifying higher level functions and hardware sub-systems, it is insufficient to show the structural levels of the design. A tree structure is a more useful way of decomposing functions or hardware from higher levels down to lower levels. To check whether the 1002 design indeed exhibits a hierarchical structure of systems, sub-systems, modules and components, the 1002 functions are exploded onto a so called *Function Tree* in Fig. 4-7. Correspondingly, a *Hardware Tree* is drawn in Fig. 4-8 for comparison.

As can be seen from Fig. 4-7 and Fig. 4-8, the design and its functions can be mapped onto the 4-level structural model proposed in Chapter 3. Of course, the last branch of the trees, the components level, can potentially be decomposed further. However, as discussed in Chapter 3, the selection of a system is rather arbitrary, depending on the purpose of the analysis. Here, the selection of the systems is at a very high level of the machine. Therefore, it should be no surprise that the components may be broken up even further into very detailed piece parts, which does not give any additional insights into the structure of the design.

At least in this case, there is a general one-to-one correspondence between the functions and the hardware at the sub-systems level. However,

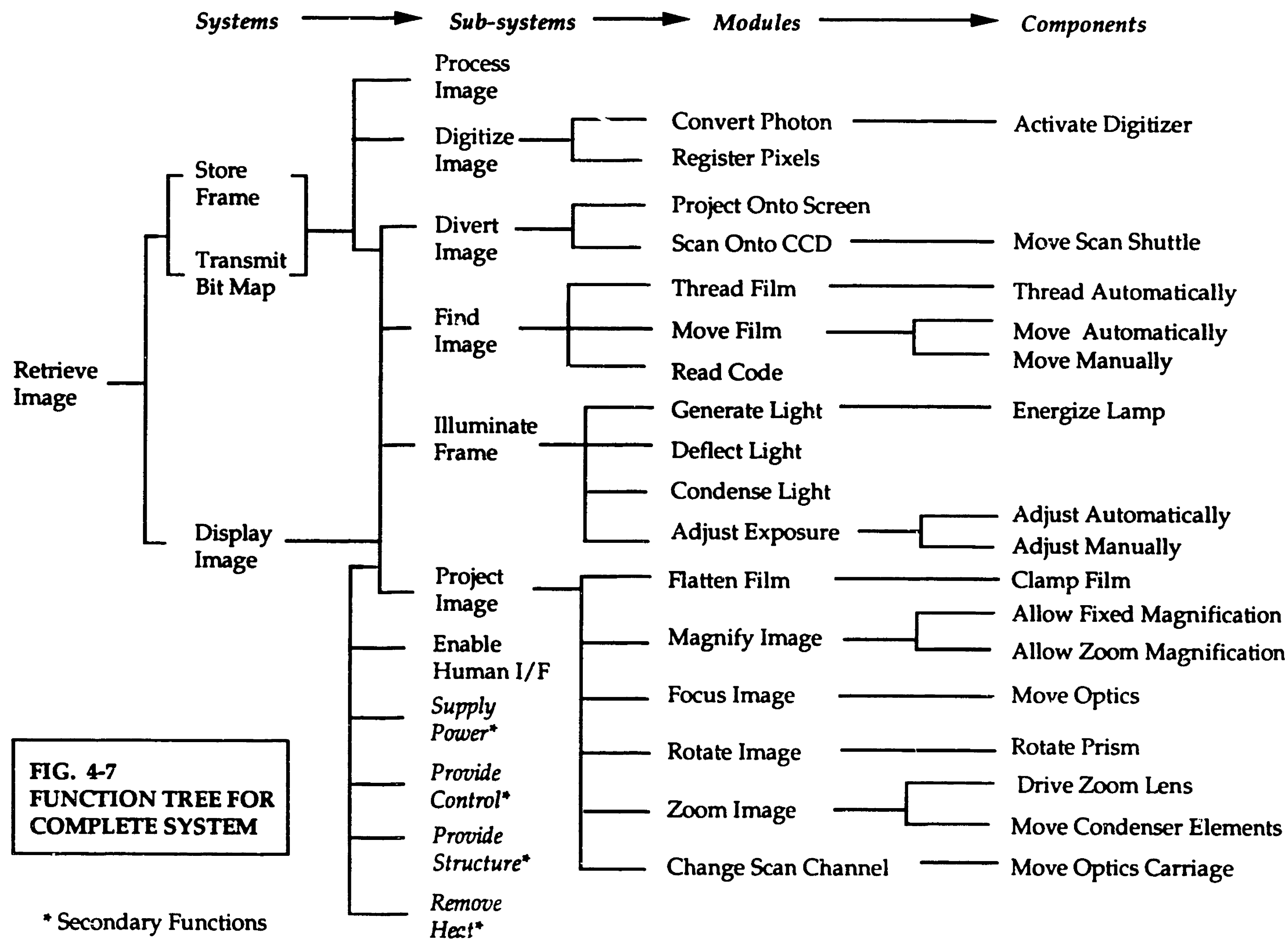


FIG. 4-7
FUNCTION TREE FOR COMPLETE SYSTEM

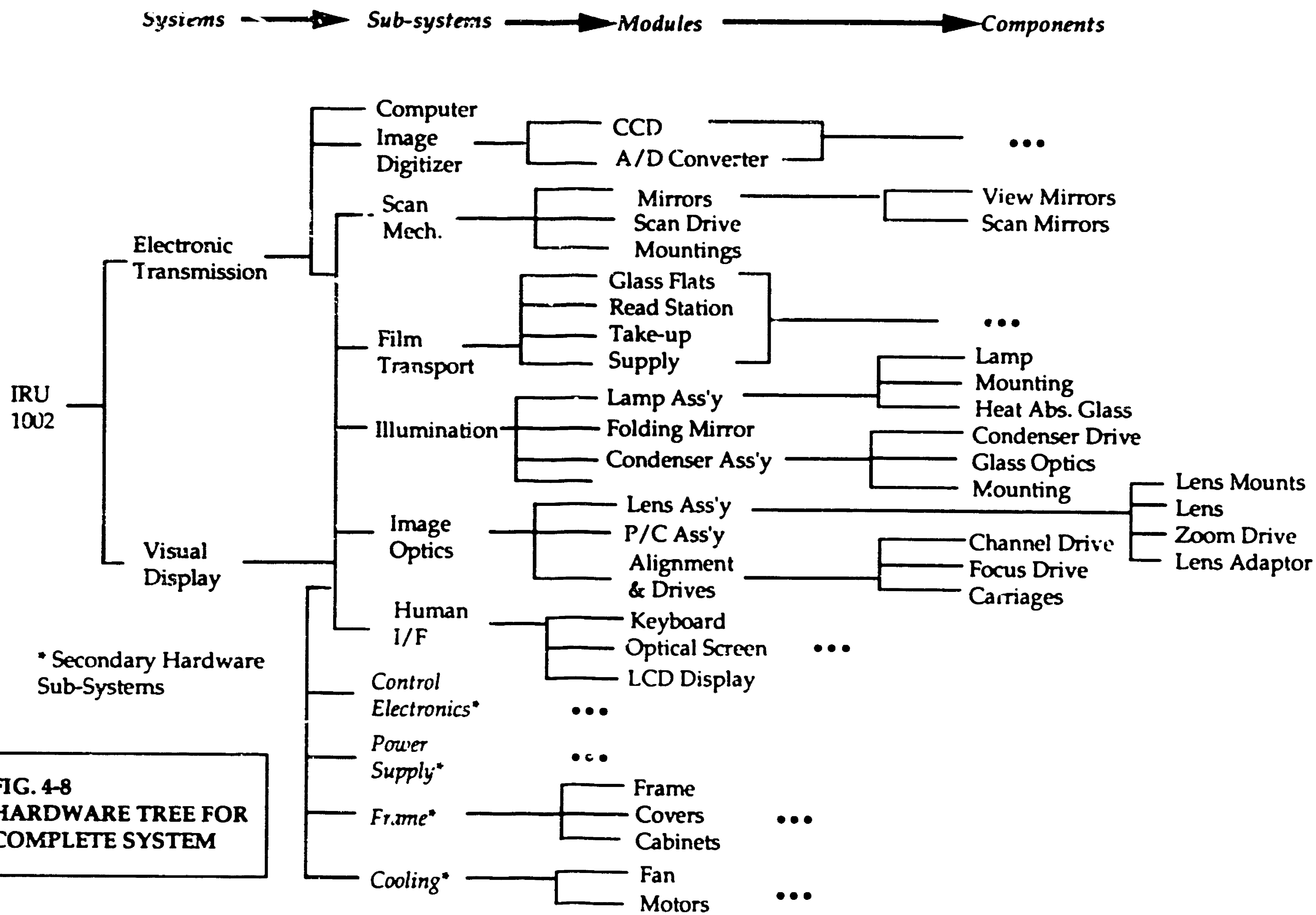


FIG. 4-8
HARDWARE TREE FOR
COMPLETE SYSTEM

this relationship does not hold true once the decomposition goes beyond this level. Fig. 4-9 shows a relation matrix between the primary functions and the primary hardware. The functions are the row headings and the hardware are the column headings. Notice how, at the sub-systems level, there is a nice one-to-one relationship along the diagonal, with only two exceptions which will be discussed later. However, inside each diagonal block, the comparison at the modules level failed to support this one-to-one relationship.

The implication for the design specifications is that the design of certain parts or assemblies below the sub-systems level would require increasing iterations between parts and sub-systems. Therefore, sometimes certain specifications may apply to more than one part design, and thus become the so called interface specifications (specifications at the interfaces of sub-systems or modules).

A relation matrix as the one shown in Fig. 4-9 can be used as a tool in understanding some of the functional interactions and hardware interfaces. For example, one of the exceptions mentioned above is for the module function of Flatten Film. Based on the one-to-one relationship between sub-system functions and hardware, one would expect that this function be carried by a module within the Image Optics sub-system. However, the module hardware that does Flatten Film, the glass flats, resides in the Film Transport sub-system whose primarily sub-system function is Find Image. This "mismatch" creates a functional interaction and a major hardware interface between Film Transport and Image Optics. Another exception is for the function of Adjust Exposure. In this case, there is no matching hardware on the matrix. This implies either the hardware list is not complete or some secondary hardware may perform this function (remember that Fig. 4-9 is

Fig. 4-9 Function and Hardware Matrix at Sub-system and Module Levels

S-systems		Film Transport				Illumination			Image Optics			Scan Mech.		Digitizer		Human I/F		
u b	*Modules*	glass flats	supply ass'y	takeup ass'y	read statn	lamp ass'y	folding mirror	cndnser ass'y	lens ass'y	P/C ass'y	drives, mounts	mirrors	drives, mounts	CCD	A/D convt.	key-board	screen	LCD
Find Img	thrd film		x															
	mv film			x														
	rd code				x													
Illm Frm	gen light					x												
	deflect lgt						x											
	cndnse lgt							x										
	adj exposr																	
Proj Img	flattn film	x																
	magnify								x									
	focus img										x							
	rotate img									x								
	zoom img								x									
	chng chnl										x							
Divt Img	proj -screen											x	x					
	proj - CCD											x	x					
Dgtz Img	cvt photon													x				
	reg pixels														x			
I/F	rec inputs															x		
	give outpt																x	x

only for the primary functions and sub-systems). In the 1002 machine, this function is carried out by the Control Electronics and the software.

This relation matrix has other applications as well. It can show which group of hardware performs what function or functions, and thus yield useful insights for design improvements. By knowing the hardware that is responsible for a particular function, one could use this matrix with cost information to determine or estimate cost per function or cost per module. Therefore, this matrix could be very useful in developing design specifications.

Now, let us turn to the contents of the design specifications. By applying the Specifications Characterization Matrix (developed in Chapter 3) to the specifications in the Marketing Requirements Document (MRD), I obtained the results shown in Fig. 4-10. Basically, I went through all the MRD specifications that were relevant to the design of the base unit (not the accessories), and then grouped them under the seventeen categories which I eventually mapped onto the matrix. Fig. 4-10 shows the categories within the four quadrants of the matrix, as well as some of the important elements under each category. Since I personally developed the Specifications Characterization Matrix, I may be biased in categorizing and grouping the MRD specifications. However, I have made an effort to capture all the requirements in this document as completely and accurately as possible.

One observation is that thirteen of the seventeen specification categories from Chapter 3 were found in the MRD. Some others such as competition and company constraints were found in the business planning documents. Also notice that there is one category in the MRD that did not match any of the seventeen categories, namely *Sub-Systems To Be Borrowed*. This category specified the sub-systems to be leveraged from the previous

Fig. 4-10 Contents of Marketing Requirements Document

	explicit	*implicit*
functional	**I** **Systems:** - Inputs/outputs - configurations **Functions & Performance:** - functional features - software systems - accessories - response time, process time - image quality - warm up time - magnifications - design life - capacity **Opt. Constraints/Opt. Pts:** - power consumption **Environment:** - temperature - humidity - altitude **Interfaces:** - with other equipment - with human ***Sub-Systems To Be Borrowed*** - Film Transport - Image Optics - Control Electronics	**II.** **Services:** - type of tools - type of fasteners - speed of disassembly - computer field analysis tools **Handling & Packaging** **Applicable Standards & Specs:** - UL - CSA - VDE - VDI - Worldwide acceptable EMI limits
non-functional	**III.** **Physical Characteristics:** - size - weight - add'l hardware attanchment **Aesthetics:** color **Ergonomics;** - operator position - control locations	**IV.** **Schedules:** - product availability date **Economics:** - target cost/price

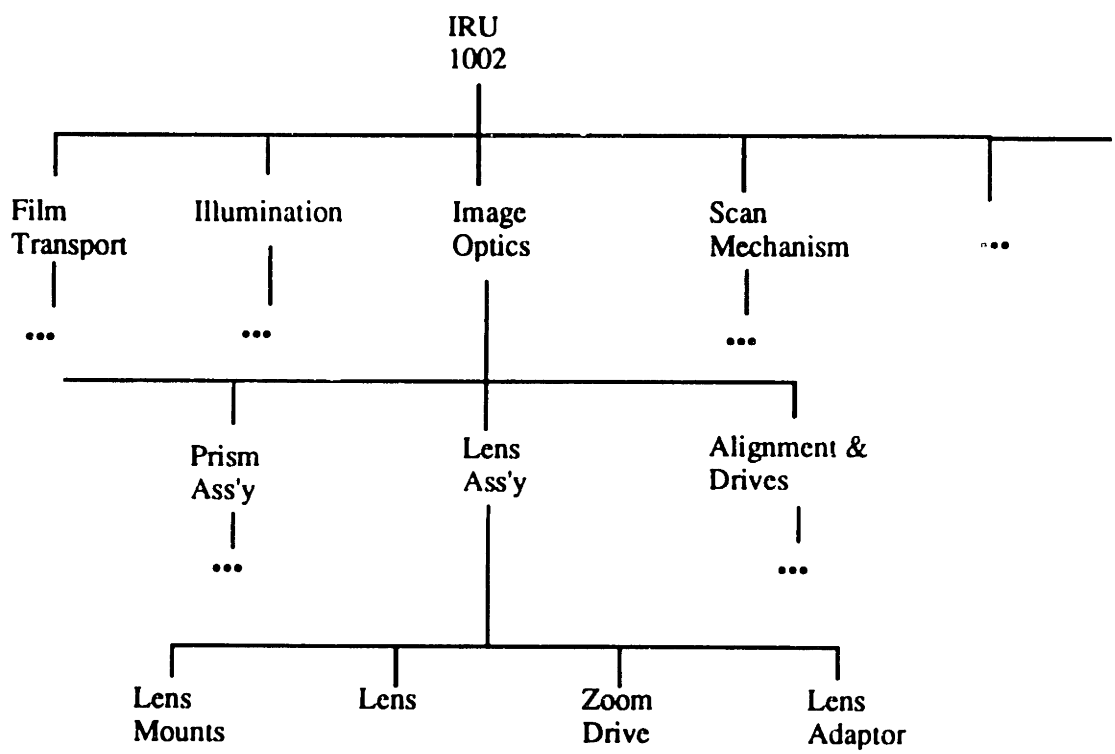
program, such as the Film Transport and the Image Optics. It was a significant one given that the original plan was to convert the existing 1001 to 1002 with minimum changes, at least initially.

Five out of the thirteen categories in the matrix contained more specific requirements than the rest. They are: Systems, Functions & Performance, Interfaces, Field Services, and Safety. Interestingly, they are all in the upper half of the matrix relating to the functional aspects of the design, and four of the five reside in Group I. Whether or not this implies that the functionally related categories take higher priorities than the rest is questionable, because it may vary from program to program. Data from only one case study is insufficient to prove or disprove this hypothesis.

There is another observation on the MRD specifications. Some requirements were very specific and quantitative while others were very vague and qualitative. For example, the optical screen size of 12" by 12" and the screen color were both specified at this point, as well as the size of the overall machine. Yet, the image quality, both on the viewing screen and on paper, was only qualitatively spelled out. It was up to the reader to interpret. One explanation may be that some requirements were leveraged from the previous program and others needed to be developed later as the design evolved.

The last topic of interest in this section is the relationship between the contents of the specifications and the 4-level structure of design. An attempt was made to distill out the specifications to match the function tree and hardware tree in Fig. 4-7 and 4-9. As an example, the image optics were examined. A simplified version of the hardware tree for the image optics is shown in Fig. 4-11.

Fig. 4-11 Simplified Hardware Tree for Image Optics



Since the image optics were designed by a different group of optics designers, as discussed in section 4.2, the optics design specifications mostly came from the optics project engineer. However, I was unable to identify design specifications to match the decomposition structure in Fig. 4-11. In other words, I could not find well stated design specifications that governed the design of the Image Optics at the sub-systems level, the design of the Lens Assembly at the modules level, and the design of the lens and mechanical parts at the components level. Most of the optics design specifications were written around the lens optics based on a different decomposition structure, i.e. grouping together all the optical elements in the optical path and calling it an optical system.

This gave rise to two types of systems definition: function specific and field specific. As it turned out, a system could be defined based on its overall function, *function specific*, or based on the engineering field of the designers, *field specific*. For example, the Image Optics is a function specific system[5] because its definition is based on the function of Project Image. However, it is also a part of a field specific system called the Optical System, whose definition is based on grouping together all the optical elements across the different function specific systems to enable optical engineering analysis.

The function specific and field specific systems cross each other through some common components. Fig. 4-12 shows the cross-sections of these two types of systems for the 1002. Going across the matrix gives the function specific systems and going downward gives the field specific systems. The elements in the matrix are the hardware parts through which the two types of systems cross. For example, the Film Transport (function-specific) system crosses the Optical (field-specific) system through the Glass Flats. Notice that the list of hardware parts that make up the Optical System, as indicated by a heavy border on Fig. 4-12, includes contributions from six function specific systems: Film Transport, Condenser, Image Optics, Scan Mechanism, Digitizer, and Human Interfaces.

This implies that there is a different function tree and a hardware tree for the image optics. Fig. 4-13 shows both trees for the Optical System. The difference between these two trees and the ones shown in Fig. 4-7 and Fig. 4-8 is that the optical trees only contain functions or components that pertain to the Optical System (Remember that Fig. 4-7 and Fig. 4-8 are for the complete

---

[5]The term "system" is loosely used here and does not imply the Systems level in the 4-level structural model.

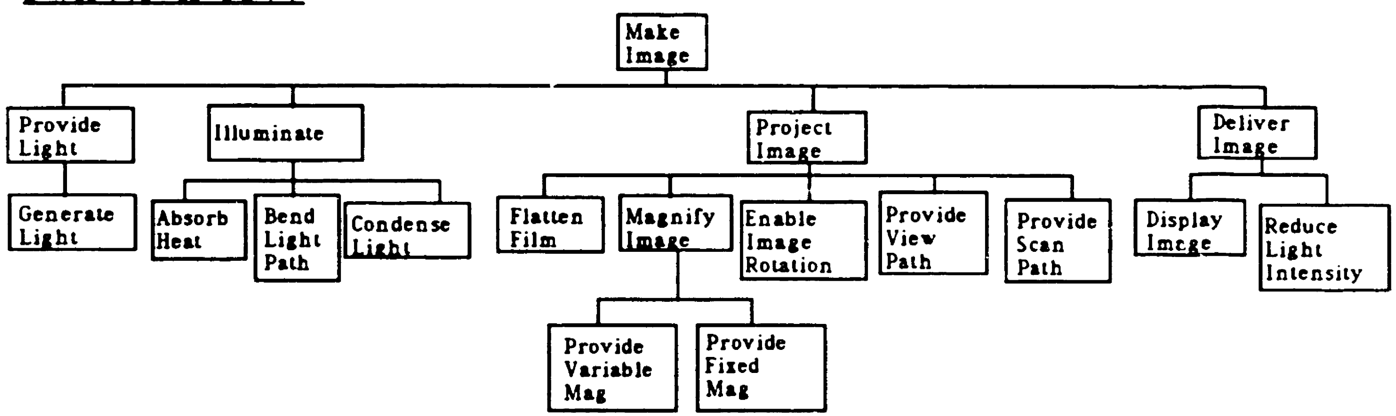
Fig. 4-12 Function Specific vs. Field Specific Systems

Field Specific / *Funct. Specific*	Optical System	Mechanical Syst	Electrical System
Film Transport	*glass flats*	*supply drive* *take-up drive* *thread drive* *structure/body*	
Condenser	*lamp* *condensing optics* *folding mirror* *heat abs. glass*	*condenser drive* *condenser mount* *blower (condenser)*	
Image Optics	*zoom lens* *fixed mag. lens* *prism/collimator*	*focus drive* *AB scan drive* *prism drive* *zoom drive* *lens adaptor* *prism carriage* *AB scan carriage* *support carriage* *focus plate*	
Scan Mechanism	*view mirrors* *scan mirrors*	*XY scan drive* *XY scan carriage* *mirror mounts* *digitizer mounts*	
Digitizer	*CCD glass filter*		
Computer		*computer chassis*	
Human I/F	*optical screen*	*keyboard*	*LCD display*
Frame/ Cover*		*frame, covers, panels*	
Power Supply*		*power chassis* *blower (power)*	*power distribution system*
Cooling*		*blower mounts*	*cooling controls*
Control Electronics*	*optics controls*	*blower (electronics)* *board mountings*	*power controls*

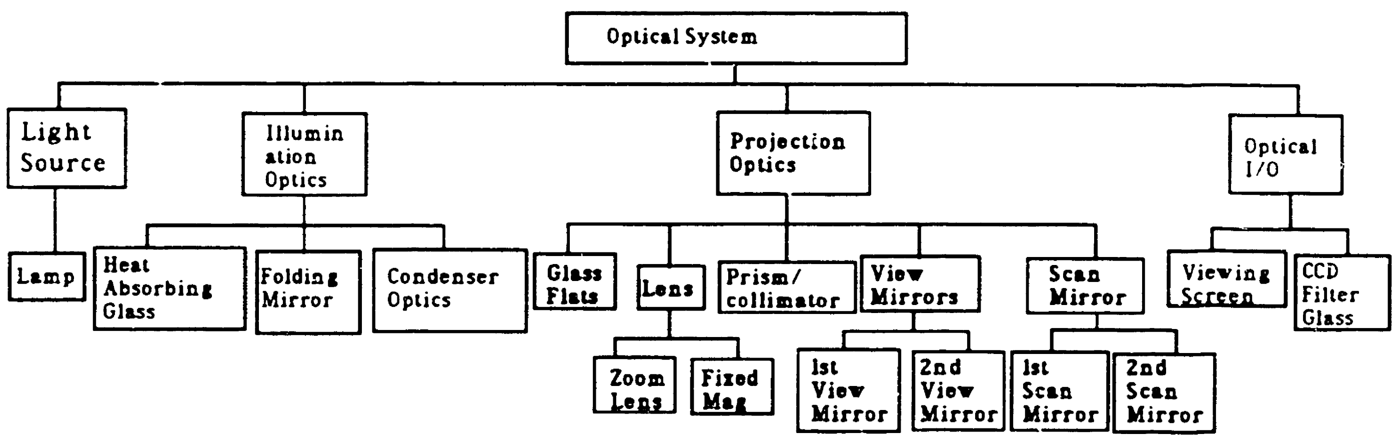
* secondary sub-systems

Fig. 4-13 OPTICAL SYSTEM

Function Tree



Hardware Tree



1002 machine). Therefore, the hardware components on the Optical hardware tree include only the optical elements such as lens, prism, and mirrors but not the mechanical support parts such as mountings and drives; whereas, in the machine hardware tree (Fig. 4-8), both types of elements are included under Image Optics, a function specific sub-system.

With this new design decomposition, I was able to connect the contents of the specifications to the 4-level structure of the Optical System. As shown in Fig. 4-14, there are numerous design specifications for each level of the design. At the Optical System level, there are four design specifications that state the requirements for the design of the optical system. Three of the four are qualitative and one quantitative, specifying the overall size of the machine. The design specifications become more quantitative and better defined as the design moves down to the lower levels. At the components level, a set of twelve quantitative and well defined design specifications is developed to guide the design of the lens elements. The values for the twelve design specifications are not given in Fig. 4-14 because of proprietary reasons.

One observation here is that each design specification does not one-to-one translate from one level to the next. Instead, a set of numerous requirements at one level leads to another set at a lower level. For example, each of the four design requirements at the Optical System level does not directly lead to any particular one at the Projection Optics level. Rather, the set of four requirements at the systems level gives rise to another set of five requirements at the sub-systems level. Also notice that the components level in Fig. 4-14 has many more detailed specifications than the previous levels. This suggests that the number of design specifications increases non-linearly as the design evolves into the lower level.

Fig. 4-14 Structure and Contents of Specifications for A Zoom Lens Design

SYSTEM	SUB-SYSTEM	MODULE	COMPONENT
Optical System	*Projection Optics*	*Zoom Lens Module*	*Lens Elements**
- Must provide zoom capability - Should use same film transport as previous product - Image quality should be at least equivalent to previous product - Must fit into design envelop of ≤ 35" wide ≤ 25" deep ≤ 55" high	- Object to lens distance: 500 mm - Optical path and optics layout - Zoom range: 5x-60x - Image Resolution: 1.0 lines/mm - Space Envelop - Systems MTF: 10%	- Module size, weight - Zoom speed - Zoom control: • manual • automatic - Lens mounting - Mounting to machine	- Conjugate lengths • long: • short: - Magnification range: - Field of view: - Relative aperture: - F#: - Relative illumination: - Transmission: - Achromatism: - Space envelop: - Condenser system must be able to track the zoom range - Materials: - Performance • MTF: • Wavelength: • Distortion:

* Value for the specs at this level are not given here for proprietary reasons.

4.4 Sources and Development Process of Design Specifications

The sources of the design specifications for the 1002 mainly came from Marketing and the 1001 program. The MRD was used in place of a formal PDS. As discussed in the previous section, the MRD did indeed contain a large number of design requirements to allow the designers and engineers to get started with the design.

However, many performance specifications were defined later by the designers or engineers themselves and thus were heavily dependent on their experience. They were the ones who converted some of the general requirements stated in the MRD into concrete and quantitative engineering measures. When one designer was asked who developed the design specifications, he replied in surprise, "It's the designers' job to define the specs. ... No one is supposed to tell you what to do exactly. It's up to the designer or engineer to figure out what to do from the general requirements."

Another source of specifications was from the field services. At almost the same time that the MRD was issued, two serviceability documents specific to the 1002 were circulated to supplement the MRD. They mostly contained field engineering requirements. The three documents collectively served the purpose of a formal PDS, although some very critical design specifications were developed later due to major design changes.

The division research lab also played a significant role in generating design specifications. Since much of the software had to be developed, the research lab was asked to actively participate in this effort. In the process, they helped to develop many of the specifications for the software development.

The last source was the industry and international standards. Many performance requirements, especially relating to safety, are set by national and international organizations. For example, image quality standards are dictated by the International Standards Organization, and EMI (electromagnetic interference) levels are governed by the Federal Communications Commission. Some other major standardization organizations include the Underwriters Laboratory (UL), the Canadian Standardization Association (CSA), the Verband Deutscher Elektrotechniker (VDE), and Verein Deutscher Ingenieure (VDI). The standards set by these organizations became the design specifications and testing criteria.

Compared to the seven sources identified in Chapter 3, most of the sources were the same, except for manufacturing and quality control. In this case, both functions were involved at later stages.

A descriptive model of the sources and the evolution process of the design specifications for the 1002 is shown in Fig. 4-15. Basically, the five sources led to the compilation of the MRD and the Serviceability & Design Specifications in early September, 1987. These documents drove the subsequent engineering design.

During the Product Engineering phase, the various players such as the designers, the engineers and the engineering supervisors interacted closely to solidify the other necessary design requirements. The MRD was first revised in June of 1988 and revised again in February of 1989. Most of the revisions were new marketing information and strategic business decisions. According to the interviewees, the MRD revisions incorporated input mostly from Marketing, Design/Engineering, Research Lab, and Management. Shortly after half way through the Product Engineering phase, in December of 1988, a formal Design/Performance Specification was put out. This document was revised in May, 1989. No other revisions were documented by the end of my field research. Fig. 4-16 shows a history of the revisions along with the development stages.

Fig. 4-15 A Description of The 1002 Specifications Evolution

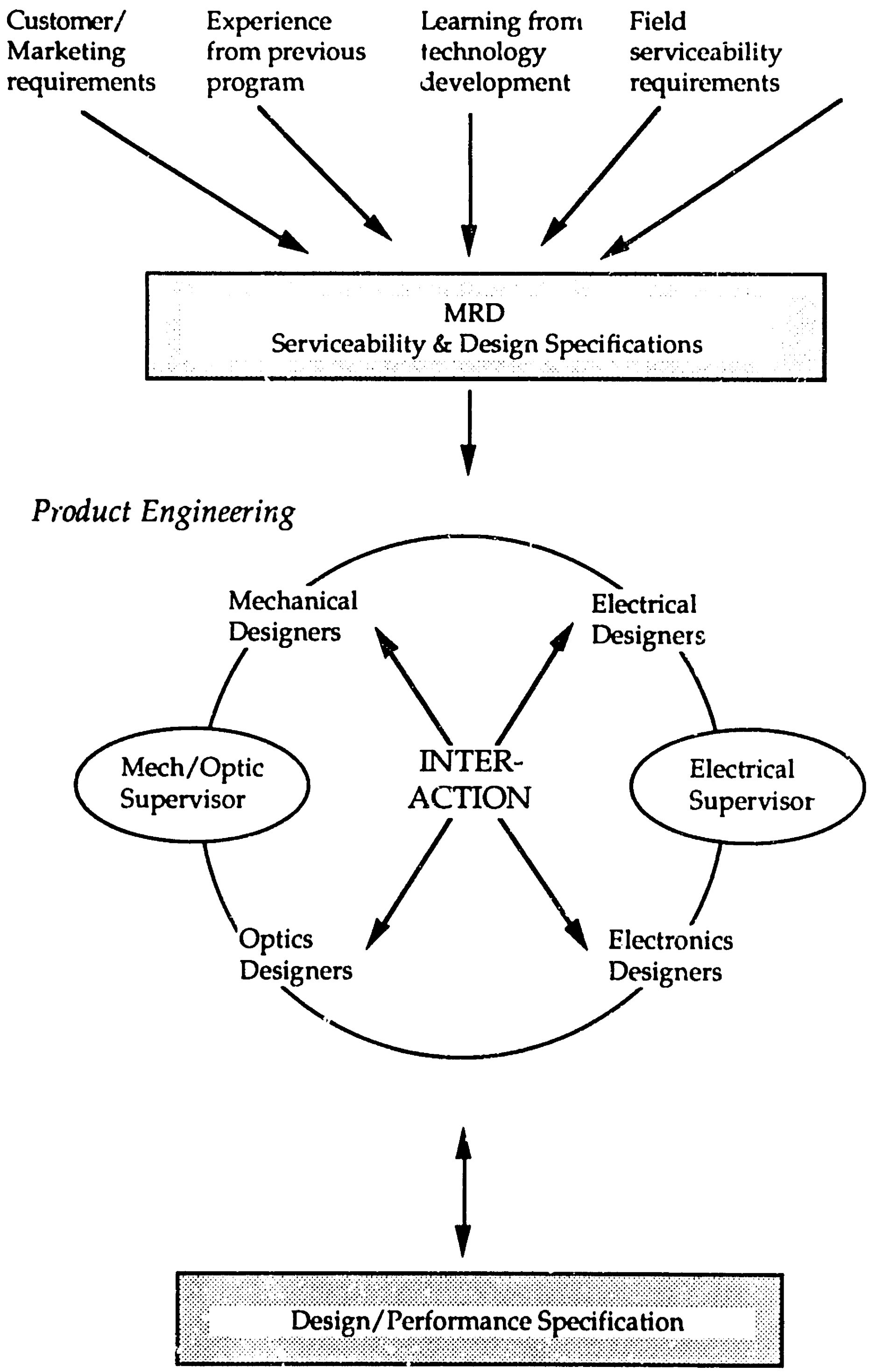
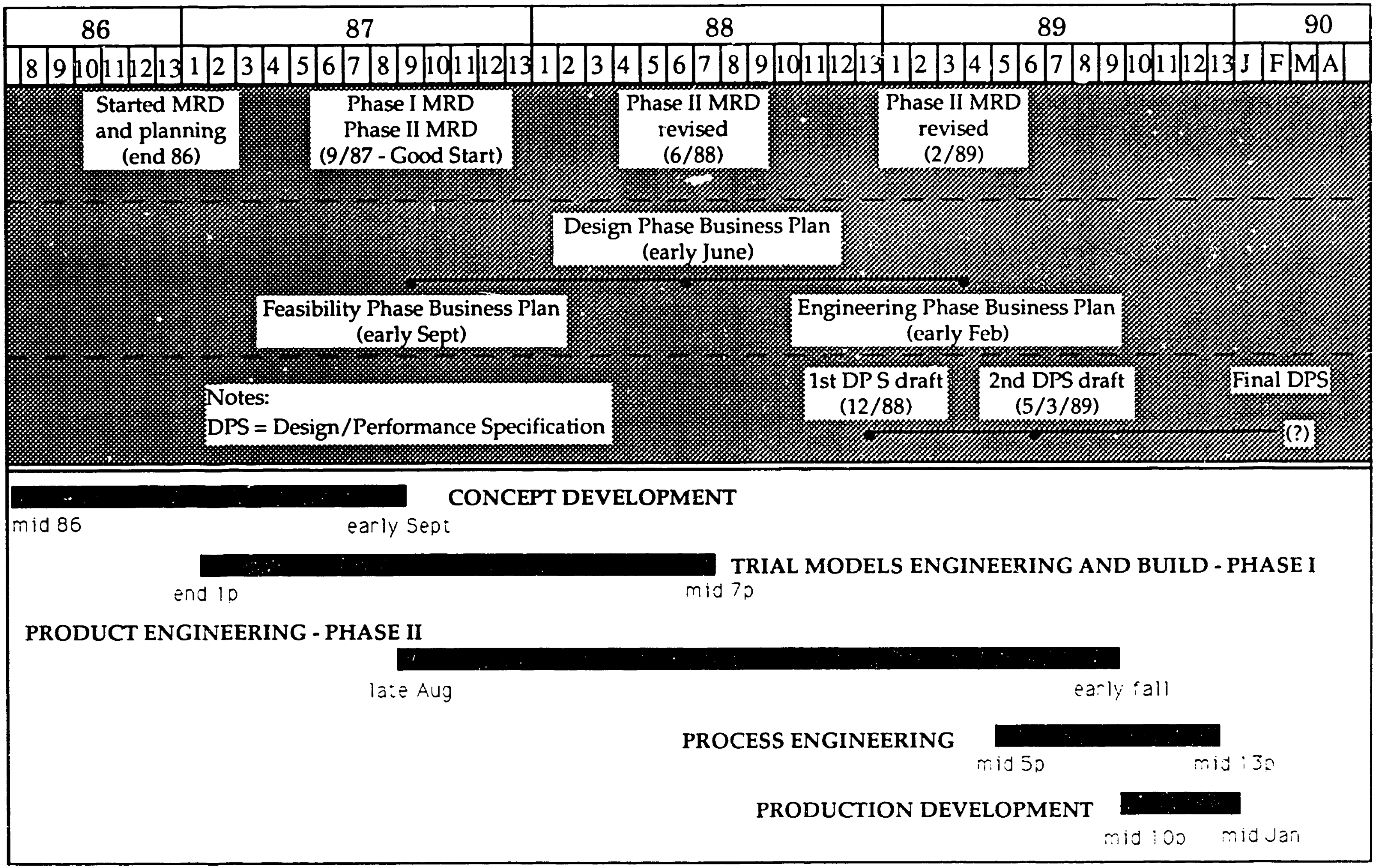


Fig. 4-16 A Revision History of Specification Documents for IRU 1002



4.5 Links to Product Development

Based on the framework developed in Chapter 3, the questions to be asked here are 1) how are the elements of specifications related to the different development stages? and 2) what implications do the four major groups of specifications have for the management of product development?

From the field data, no conclusive statement can be made in regard to the first question. Since most of the 1002 design specifications were generated by various people throughout the development process and were not captured into one single document until a much later stage, there was no way to determine what specifications were defined at what stage of the development. Taking snap shots of the Marketing Requirement Document only confirmed the general characterization matrix shown in Fig. 4-10. There was no other evidence that would allow any mapping of specifications to the development stages.

On a more general ground, there seemed to be a strong link between the development of specifications to the development of the product. Since the 1002 was leveraged from the 1001 program, many of the general requirements were reasonably well defined at the beginning. As a result, Phase I design took a relatively short time to complete, although its functionality and features were much simpler than the Phase II design.

Nonetheless, in Phase II, because some of the hardware and software development was new, the lack of comprehensive design specifications in some cases led to many design changes and iterations. This slowed down the development substantially. Even though the 1002 was a successful program, a more disciplined approach to product development would only help to improve its efficiency.

As for the implications of the four major specification groups (see Fig. 3-7 on page 51 for the definition of the four group), two observations can be made. First, Group I received much more emphasis than the rest. Second, the four groups strongly linked to the activities of the various people on the development team.

As shown in Fig. 4-10 on page 88, the majority of the requirements contained in the MRD fell into Group I. Given that the MRD was compiled prior to the Product Engineering phase, this reflects the development efforts and the focus of management during the concept stage. Furthermore, according to a feature/function matrix developed during the concept stage, most of the technical activities were concentrated in identifying the functions and features of the product. The details of this matrix were completely represented by the 6 Group I categories in Fig. 4-10. The only exception was the frame/cabinetry, which belongs to the Physical Characteristics in Group III. Nonetheless, all the elements in this planning matrix were explicit requirements, functionally or non-functionally related to the product design.

There were four distinct groups of people associated with developing the specifications in the four groups. Group I was primarily the task of the product designers and engineers, with help from Marketing in terms of product features and configurations. Group II was mostly the effort of the field services people, also with Marketing contributing to the Handling & Packaging category. Group III was mainly the responsibility of the ergonomic designers outside of the core development team. Finally, Group IV was principally the focus of the planning and financial community.

Although it may seem that the four groups of people were disjointed, the team environment discussed earlier helped to foster frequent communications between the groups. Most of the people responsible for three of the four groups of design specifications were located in the same office area. The only exception was the ergonomic designers; they were located in a different building. However, since this was a leveraged product from the previous models, most of the ergonomic factors and values had been determined. The fact that the ergonomic designers were located in the same industrial complex helped to prevent communications breakdown.

These two observations stronglv support the conjectural analyses put forth in Chapter 3 in regard to the two questions for this section.

4.6 Development Methods for Design Specifications

Based on my observations, both unsystematic and systematic methods were used to obtain design specifications. As defined in Chapter 3, the systematic methods include: Systems Engineer, Experimental Design, Value Analysis and Value Engineering, Bench Marking, and Quality Function Deployment; and the unsystematic methods are: Local Optimization, Trial and Error, Spontaneous Solutions, and Gut Feelings.

The frequent use of CAD facilitated the use of systematic methods. For example, the overall optical length was determined by using CAD as an analysis tool. The optical length depended on a number of constraints. Once the constraints were identified, the optical length was calculated and the optical path was graphically illustrated on the CAD system. Another example is structural analysis of the machine frame. The FEA (Finite Element Analysis) led to some optimal values for the frame design.

Systems Engineering was another systematic method observed. However, within the 1002 design group, this method was not really used until the first systems engineer was hired almost half way into the Product Engineering phase. At that stage, fire fighting was the main motive for the use of this method.

According to a technician, competitive bench marking was attempted halfheartedly a number of times during the development of the 1002. None of these attempts was planned. In the summer of 1987, this technician got involved with testing a number of competitors' products. Even though some of the machines were tested extensively, not much of the data was used. Again, in the summer of 1988, he was involved in another half hearted bench marking effort. It came about because Quality Assurance had a small amount of money for benchmarking, so they decided to do some testing with it. The technician said that QA actually did some testing unfunded. This round of bench marking ended uneventfully, quoting the technician, "Because ... I couldn't get authorization to do a full evaluation. Joe Blow (not real name) and I demonstrated it (the competitor's machine) but never formally recorded the results or tested it extensively."

Within the Optics design group, there was a more systematic approach to developing design specifications. Extensive analyses and calculations were performed before the actual design could begin. Systems Engineering was used up front to optimize the overall performance of the optical system. This proved to be very effective for the design of the new optics.

While many specifications for the 1002 were leveraged from the 1001, some came from the experience of the designers, which tend to fall into the Gut Feelings and Trial and Error category. These methods, as discussed in Chapter 3, can be valid and effective especially in the case where there is no other source of information to draw from. However, a structure may be needed to control the randomness of both methods.

In general, there was a tendency among the 1002 designers and engineers to jump into the design without thinking about what the optimal specifications were. This is reflected by the methods that they chose to develop certain design specifications.

This concludes the case study. A large amount of data regarding the development of the product and the design specifications were presented and discussed. Some connections between the field data and the conceptual development were discussed, and others will be compared in the next chapter.

CHAPTER 5: CONCLUSION

The following chapter will briefly summarize the research and the results presented in this thesis. Some recommendations in regard to improving the development of design specifications will be made and some areas for future investigation will be suggested.

5.1 Recapitulation

This study was prompted by the need to better understand the nature of design specifications and the process by which they are developed. In addition, there was also the necessity to better comprehend the relationship between the development of design specifications and the development of the product. The general lack of research in this area created an opportunity for this investigation.

Two modes of research were followed: a conceptual development and a case study. The purpose of the conceptual development was to establish a conceptual foundation and basis for the case analysis. The objective of the case study was to verify and supplement the conceptualization with field data. It was the goal of this study to provide new insights on the topic of design specifications development and create new dimensions for further research.

The core of this investigation was governed by five questions:

1) What is the structure of design and its implication for the structure of design specifications?
2) What are the characteristic elements of design specifications? And how are they organized?

3) Where did design specifications come from?
4) What is the process by which design specifications are developed and evolved? And how does this process fit in with the overall product development process?
5) What are the methods used to develop or obtain these design specifications?

These questions were selected in an attempt to gain knowledge in four areas relating to design specifications: the structure and contents; the source; the development and evolution process; and the development methods.

Structure and Contents of Design Specifications

The first two research questions were related to this topic. It was found that there was indeed a hierarchical structure to design. In general, a 4-level structural model of systems, sub-systems, modules, and components could be applied to a variety of complicated and simple designs.

One implication of this structure to the contents of the specifications might be that certain specifications would tend to associate with certain levels of design. However, the field data did not support this hypothesis. Conceptually, the specifications at the systems level should be in general vague and less quantitative, whereas the specifications at the lower levels should be more specific and quantitative. It was found that some systems level specifications such as the overall machine response time was very specific, dictating the speed performance of the entire machine, while some others, such as the image quality, were very vague. Therefore, design specifications at any level could be both quantitative and qualitative.

In terms of the design structure, there were two kinds of system functions and hardware: primary and secondary. The primary systems carried the primary design goals of the design (the primary functions), and the secondary systems provided the necessary supports (the secondary functions). I observed that the primary functions tended to have an integrative effect on the hardware organization, requiring a group of hardware to be centrally located to carry out the function; whereas, the secondary functions tended to have a distributive effect, requiring a group of hardware to be distributed throughout the machine.

Furthermore, I found that there were actually two types of systems: *function specific* and *field specific*. The function specific systems tended to be more integrative, related to the primary functions, and the field specific systems seemed to be more distributive, associated with the secondary systems. In the case study, the design of the Film Transport, which was a completely independent physical module, was designed as a function specific system because it consisted of a group of hardware that collectively served one major function of "Find Image." Whereas, the Image Optics, another functional hardware module doing the task of "Project Image," was developed as a part of the field specific system called the Optical System. This Optical System was comprised of optical elements from various functionally independent modules (i.e. function specific systems) and thus demonstrated a distributive property.

The difference between the two lay in the way the design specifications were developed and the engineering analyses were made. For the function specific systems, the design specifications were based on the engineering analyses that were focused on the major function of a physical module. If the module consisted of mechanical and electrical parts, the analyses would draw from both mechanical and electrical engineering fields. For the field specific systems, the design specifications were highly dependent on the engineering analyses that were dominated by one engineering field. Consider the case of the image optics mentioned above, the design specifications could only be developed if the engineering analyses were performed based on grouping all the optical elements in the optical path together, which formed the optical system. This type of engineering analyses drew only from the optical engineering field.

As for the contents of design specifications, I identified ninety elements and organized them into seventeen categories. To provide a more comprehensive conceptualization of design specifications, I further arranged the categories into four major groups using a two by two matrix.

Although the field data did not verify every one of the ninety elements, thirteen out of the seventeen categories were found in the Marketing Requirements Document that was used to govern the design of the product. All of the other remaining categories were found scattered among a number of business and serviceability documents. Thus, I inferred that the seventeen categories provided a valid categorization of the general product design specifications and could be used as a generic checklist during product development.

The two by two matrix, which I called the Specifications Characterization Matrix, provided a comprehensive presentation of the seventeen categories. The four quadrants of the matrix completely characterized the four groups: Group I, *explicit and functional*; Group II, *implicit and functional*; Group III, *explicit and non-functional*; and Group IV, *implicit and non-functional*. Each of the four groups exhibited a common characteristic which called for a particular type of technical or non-technical expertise for the development of those particular design specifications. With this realization, this matrix could be used as a management tool for task assignments and coordination between different development efforts. Given that each group of experts tended to develop their own design specifications in isolation, this matrix could help to bring them together and facilitate information exchange.

Sources of Design Specifications

Conceptually, I identified seven sources of design specifications. They were: Customer, Marketing, Research/Development, Design/Engineering, Manufacturing, Quality Control, and Field Services. In the case study, however, only Customer, Marketing, Research/Development, Design/Engineering, and Field Services were associated with the design specifications development. The remaining two functions, Manufacturing and Quality Control, did not play an active role until later in the process. In the future, I would strongly suggest that the two late comers be involved much earlier on.

One additional source which I neglected in the conceptual development, Standards Organizations & Regulatory Agencies, came out of the case study. Data showed that many performance specifications were dictated by national and international industry standards. It was indeed a very significant source of design specification and thus was added to the list as the eighth source.

Development Process of Design Specifications

As mentioned in the discussion, the sources of design specifications were closely tied in with the development process. It seemed from the case study that the sources of design specifications typically lead to the compilation of a central Product Design Specification document which would be used to guide the entire development program. In the case, it was called the Marketing Requirements Document.

Based on this document, the designers and engineers would translate the general requirements into specific and quantitative engineering measures. Development programs that take a more systematic approach to design would spend a great deal of effort up front on obtaining and defining more detailed design specifications prior to the actual design. This was not necessarily the case with the development program studied; some of the design requirements remained vague until a much later stage.

Development Methods for Design Specifications

During the conceptual development, I divided nine methods into two categories: systematic and unsystematic. The systematic methods were: Systems Engineering; Experimental Design (Robust Design); Value Analysis and Value Engineering Benchmarking; and Quality Function Deployment. The unsystematic methods were Local Optimization, Trial and Error, Spontaneous Solutions, and Gut Feelings.

The field data showed that a number of these methods were frequently used for various engineering designs. The commonly preferred methods tended to be in the unsystematic group, such as Local Optimization, Trial and

Error and Gut Feelings, which required less discipline and took less time. The three systematic methods that were least familiar to the design engineers were Experimental Design, Value Engineering, and Quality Function Deployment. Benchmarking was attempted but not completely carried out. Of all the systematic methods, Systems Engineering was applied extensively by the optics engineers. Evidence showed that it was not used frequently in other parts of the organization. Insufficient use of systematic methods proved to be a drawback in the case used for the study.

5.2 Areas for Future Investigation

To conclude this study, I would like to suggest three areas for future investigation. I believe that the following areas are potentially rich research topics that will enhance the understanding of the relationship between design specifications development and product development:

1. the relationship between functional requirements and design parameters;
2. the implications for modular or black box design;
3. the connection between this study and the application of QFD.

Let us begin with the first topic. This study, for the most part, remained within the boundaries of product design specifications but did not cross into the territories of the design parameters. The major difference between these two is that one deals with the functional requirements and the other one deals with actual design values. Conceptually, going from the product design specifications to the design parameters is equivalent to jumping from the functional domain to the hardware domain. The transition from one to the other is not as simple as it may seem. Very often, certain design parameters do not lead to designs that render the desired functions.

One might want to ask "How does a designer or engineer go from a set of functional requirements to a set of design parameters?" and "What is the relationship between the functional requirements and design parameters?"

Here, I will offer some of my preliminary thoughts. It seems that there is a three-step translation from functional requirements to design parameters, as follows:

FR's ••••••> DR's ••••••> DP's

The FR stands for functional requirements; DR design requirements; DP design parameters. These terms are borrowed from Nam Suh's Axiomatic Design Theory (1988).

One may ask what the difference is between a functional requirement and a design requirement. I personally think that there is a difference. A functional requirement states what functions the design is to achieve, but a design requirement specifies how the design is to achieve the function. For example, if a system is required to illuminate a certain subject, then the functional requirement is to provide illumination. However, one of the design requirements is to fill the entrance pupil with light. This requirement specifies how the system is to provide illumination. Furthermore, this design requirement directly leads to some very specific design parameters, such as the type of lamp, power consumption, and brightness. Numerical values can be readily attached to all of the design parameters. Whether this three-step translation is valid or not has yet to be tested out.

The second aspect of this topic is the relationship between the functional requirements and the design parameters. Professor Nam Suh has a theory that functional requirements should be linearly related to design parameters. If the design parameters are the lower level of design specifications on my 4-step structural model, then this theory does not seem to hold because Fig. 4-10 shows that functions at the module level do not one-to-one translate to hardware modules. This has been an area of active debate and can benefit more from further research.

The second area that I would like to propose is the implications of the design specifications development for modular design. The question to be asked here is "how does the structure of design specifications enable or hinder modular design?" I claim that the 4-level structural model of design specifications can help design planning teams to identify early on what part of the system may be designed as a black-box. Following from the discussion earlier, if a system is intrinsically integrative, which is typically the primary systems, then a set of design specifications can be developed around this function to enable the design of a group of physically connected hardware. Such a group of hardware is essentially a modular design.

However, it still needs to be proven that the 4-level structural model is valid for every design and whether it is sufficient enough to enable the development of design specifications at any level along the structure. Therefore, I think that further investigation in this area can lead to better understanding of what the implications of the structure of design specification are for modular design.

The last area is the connection between the development in this study and the application of Quality Function Deployment. Quality Function Deployment is essentially a system which allows product development teams to go from the customer or market requirements down to the design parameters a step at a time. This seems to imply that the translation of information from the customer to the designer follows a structural decomposition similar to the 4-level model discussed in this thesis. This connection should be further explored.

Another connection is the categorization of design specifications to the QFD matrices. It seems that each of the QFD matrices leads to a set of functional or design requirements. However, it is not clear where these detailed requirements come from; the matrix only provides a structure for the information, but does not generate the information. It seems that the categorization of design specifications developed in this study can assist the effort of filling in these matrices. Perhaps there is a relationship between the design specification elements and the information needed for the different QFD matrices. I think an examination in this area can lead to very useful insights for the application of QFD.

REFERENCES

Buhl, H. R. (1960) Creative Eng Design. Ames Iowa State University Press.

Burgess, John A. (1982) Assuring the Quality of Design, Machine Design (pp. 65-69). Cleveland, OH: Penton/IPC.

Burgess, John A. (1984) Design Assurance for Engineers and Managers. New York: Marcel Dekker.

Chestnut, H. (1965) Systems Engineering Tools. New York: Wiley.

Chestnut, H. (1967) Systems Engineering Methods. New York: Wiley.

Clark, K. B., Chew, W. B., & Fujimoto, T. Product Development in the World Auto Industry: Strategy, Organization, and Performance. (Working Paper).

Clark, K. B. & Fujimoto, T. Lead Time in Automobile Product Development: Explaining the Japanese Advantage. (Working Paper).

Clausing, Don P. & Hauser, John R. (1988) The House of Quality. Harvard Business Review. Cambridge, MA: Harvard Business School.

Clausing, Don P. (1986) Improved Total Development Process - Changing the Ten Cash Drains into A Cash Flow. (Lecture notes)

Clausing, Don P. (1989) Quality Function Deployment: Applied Systems Engineering. 1989 Quality and Productivity Research Conference, University of Waterloo.

Cooper, Robert G. (1983) A Process Model for Industrial New Product Development. IEEE Transactions on Engineering Management, Vol. EM-30, No. 1, Feb '83

Cullum, R. D. (1988) Handbook of Engineering Design. Boston, MA: Butterworths.

Dixon, J. R (1966) Design Engineering - Inventiveness, Analysis, and Decision Making. New York: McGrow-Hill.

Frank, G. R. (1977) Tolerance Challenge. Presented at the American Society for Quality Control Technical Conference, May, 1977. In R. N. Wright and D. Lucca (Ed.), "Tolerance Challenge" - Product Design Engineering for Quality Improvement. Society of Manufacturing Engineers. Dearborn, MI: SME.

Hayes, R. H., Wheelwright, S. C., and Clark, K. B. (1988) Dynamic Manufacturing. New York: Free Press.

Leech, D. J. (1972) Management of Engineering Design. New York: Wiley.

Pugh, Stuart and Morley, Ian E. (1988) Total Design: Towards A Theory of Total Design. Design Division, University of Strathclyde. (A Monogram).

Pugh, Stuart and Morley, Ian E. (1988) Total Design: Product Design Specifications, Representative Outcomes. Design Division, University of Strathclyde. (A Monogram).

Pugh, Stuart and Morley, Ian E. (1988) Total Design: Some Questions and Some Answers. Design Division, University of Strathclyde. (A Monogram).

Pugh, Stuart (1984) Further Development of the Hypothesis of Static/Dynamic Concepts in Product Design. International Symposium on Design and Synthesis, Tokyo, July 11 - 13, 1984.

Pugh, Stuart (1983) The Application of CAD in Relation to Dynamic/Static Product Concepts. International Conference on Engineering Design (ICED), Copenhagen, August 15 - 18, 1983.

Shigley, J. E. and Mitchell, L. D. (1983) Mechanical Engineering Design (4th Ed.) New York: McGraw-Hill.

Siddall, James N. (1982) Optimal Engineering Design: Principles and Applications. New York: Marcel Dekker.

Suh, Nam P. (1988) Axiomatic Design. MIT. (Working Paper).

Tribus and Myron (1969) Rational Descriptions, Decisions and Designs. New York: Pergamon Press.

VDI 2221: Systematic Approach to the Design of Technical Systems and Products. VDI Society for Product Development, Design and Marketing, Aug. 1987 [VDI: Verein Deutscher Ingenieure]