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A holistic approach to design from conception through retirement

Mark William Hammond
Lehigh University

A HOLISTIC APPROACH TO DESIGN
FROM CONCEPTION THROUGH RETIREMENT

by

Mark William Hammond

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Date

Dr. Keith M. Gardiner
Professor in Charge

Dr. Keith M. Gardiner
Director, Manufacturing
Systems Engineering Program

Dr. Marlin Thomas
Chairman, Industrial
Engineering Department

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ABSTRACT

The design process and the results of design have recently received increasing attention. This stems from many companies realization that their inability to develop competitive products is like a disease that endangers their existence.

To cure this malaise a number of methods and panaceas are being offered. Unfortunately, they constitute an ambiguous patchwork of often conflicting band-aid solutions. They have improved designs. The improvements, though, are less than what many companies require. To achieve further improvements requires a reinvestigation of the whole design process; a holistic approach.

From a holistic perspective design seeks to develop the "ideal" product for the given system of interdependent factors. Viewing the product design and the entire product life cycle as a system the narrow focus of proposed design methodologies and panaceas is apparent.

Proposed panaceas such as Early Manufacturing Involvement, Simultaneous Engineering, and Total Quality Control by no means address more than a subset of the entire system. The Design For X approaches attempt to optimize an existing detailed design, usually in tightly bound component or process domains.

Although these attempts at panaceas are illfounded, they help develop systems thinking. Meanwhile, those in the forefront of improving design practice should turn from pursuing panaceas to

developing soundly based, enduring strategies to face the design challenge.

A design strategy is presented which has been developed through study of the development process and the methodologies recently proposed to improve the process. The strategy is based on a holistic perspective where the development process is viewed as a vast system of interdependent factors. These factors span the system from identifying the corporate goal and customer need, to the satisfying them. The factors are of varying importances, but none are of supreme importance. All factors in the system impact the success of the product.

Success in the development process utilizing this strategy is characterized by the creation of a balance among the interdependent factors in the system. The balance is achieved through the explicit establishment of a circular chain of relationships spanning the entire development process.

INTRODUCTION

We all design. Common definitions from dictionaries and textbooks for architectural, engineering, and industrial design all describe design as the process or act of making decisions. We do that all the time.

So, why have so many articles been written recently on "Good Design" and methods to improve our product designs? Obviously, we have not been doing something right.

Before rushing off to reinvent the development process it is necessary to clarify the current situation and objectives. We need to answer why it is necessary. The first step toward discovering answers is to ask why there has been strong growth in interest about design.

Why the Interest in Design?

In the past ten to twenty years many American companies have experienced sharply increasing competition in their chosen fields. Many customers ceased buying American products. Industry reviews cite two reasons:

* American products fail to meet customer needs and expectations for function and quality
* American products provide less value than foreign ones

Recognizing this criticism and experiencing reduced sales over entire product lines, many American companies are worried that they may soon be driven out of business.

The companies worry about activities covering the entire product life cycle: identifying customer needs and desires, developing new products, manufacturing the product, selling the product, and finally retiring the product. **Every activity in the process is necessary and equally important. Design, however, is central.** As the design is developed, the identified customer needs become foreseeable reality--a plan. Workers use the plan to make the product, which then competes against other products to fulfill customer needs and desires. Any of these activities may be where the product fails. Not accounting for all issues in the development[1] process is a common cause of failure (Roberts, 1988).

Why Improve the Development Process?

Many companies concede that improving their current products is not enough. They often can not improve a product before the competition introduces its next generation of products. Sometimes their competition even introduces a second generation of products, decreasing product life cycles more. Many companies, experiencing

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[1]To reduce confusion the process of designing products will be referred to throughout this thesis as the development process.

this, decided that they needed to improve their designs by improving the quality[2] and speed of the development process.

An observer might be inclined to ask how these companies propose to improve the development process. A search of the trade and business literature yields numerous references to "smart design," "design for manufacture," "good design" and similar terms. But, a closer examination reveals ridiculous anomalies such as occur in the article entitled, "Smart Design," (Nussbaum, 1988) which features three design consulting companies. The first two produce "innovative" and "creative" looking designs. The third company specializes in redesigning products to lower manufacturing costs. Most of their work is redesigning products developed by companies like the first two; not really "smart"!

Numerous articles appear in professional literature extolling the need for, and benefits of, developing products in less time; satisfying customers; and reducing manufacturing cost. There are few methods proposed for actually improving the development process. One method which is applicable over classes of development is all that is needed as long as it has adequate scope.

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[2] The term "design quality" is avoided to reduce the chance of confusion with the concept of designing quality into the product. That is, designing so the product as manufactured will generate high customer satisfaction.

Current Development Methods are Inadequate

To date, the focus of design improvement methods has been on reducing costs by developing products faster, optimizing component fabrication and assembly, or modifying human involvement. As numerous case studies show, these methods generally result in better products.

The methods seek to improve one factor while assuming other factors will improve, or at least not deteriorate. They do not focus on improving the development process so as to generate near ideal designs consistently. Where an ideal design is the best design for the given system of customers, enterprise, environment, and suppliers--in the broadest sense of all those words. Cost is merely one factor in determining an "ideal" design. By improving designs, the enterprise reduces cost while improving customer satisfaction, sales, manufacturing efficiency, profits, and all the other positive factors in the system.

Maximizing the system is not achieved by maximizing one or two factors in the system. Unfortunately, our current measurements for product performance, as well as individual and organizational performance, place emphasis upon maximizing local factors. This leads to parochialism.

The parochialism of product development, of the other functions in the enterprise, and throughout American society, is reflected in the traditional view of design. "Design" to most engineers is regarded as devising a product to meet some specified functional criteria. The people carrying out this activity are labeled "designers". Their output is a plan which subsequently is used to manufacture the product for sale. Design improvement methods which do not break out of this framework will inherently strive for local optimizations. When these locally optimized products compete against near ideal products--the locally optimized products will always lose.

So What Should be the Basis for Developing Near Ideal Products?

Developing near ideal products requires balancing all factors in the system. Balancing does not imply giving all factors equal weights. Not all factors deserve equal weight and consideration. Rather, it is establishing appropriate relationships between factors. Some factors may deserve an importance rating of zero for that product. More often, however, designers assume a zero value for factors they do not wish to consider, have not considered, or do not value highly. This is how many products arrive in the market with costly or fatal design flaws. Many more products accidentally arrive at a balance due to the designer's intuition. Few products achieve a balance near what could be called ideal.

To achieve an ideal balance in a design requires that the designer consciously recognize the fixed relationships within the given system and then establish the proper relationships between the definable variable elements. This is more than defining which components are part of an assembly, or what power output a component should have. This is the conscious establishment of the web of interrelationships between physical, human, and environmental elements. One major chain of which is the relationships tying together

* corporate goals and strategies;
* customer problems and needs;
* product requirements and constraints; the
* flows, forces, forms, and motions necessary; and the
* appropriate components.

Why a New Model of the Development Process is Necessary

(1) Better product development is needed by companies to ensure their survival. The development process is how ideas become products. Without good designs, good products can not be made.

(2) Computers are becoming increasingly important to product development. The balance between humans and computers in the generation of designs is rapidly changing. To understand where the proper balance lies requires an understanding of the roles necessary in the development process. Since it is unlikely computers will in the near future become capable of designing all products without human aid or evaluation, computers will remain one element of a socio-technical system for design. The humans are and will be essential for creativity and sanity checks on what computers disgorge.

Humans, as another element of the system, also must learn if product designs are to improve. Building more knowledge and capability into the computer system without improving the designer's ability to understand and check the results of computations is a recipe for disasters.

(3) Effective development and improvement of CAD/CAM/CAE[3] systems requires a model of design. CAD/CAM/CAE system improvement has been driven primarily by the application of improved technology and the clamor of users. An understanding of how the development process should be conducted is needed to guide computer system development.

The development process can be different with the aid of computers. The absence of a strategic model for computer system development has been confirmed by the author through discussions with marketing and development personnel of CAD/CAM/CAE vendors. Without more than an intuitive understanding of the development process, a vision of how tasks should be balanced and the interface maintained between the designer and a computer, the development of computer systems can only proceed in an inefficient and random fashion. This creates islands of expertise in a sea of ignorance.

Reducing the ignorance requires a model of design which bridges the gaps between conceptual and detailed levels of development for both individual projects and design theory, and between design theory and practical application. To become a science, design will have to be modelled. The paradigm presented here is intended as a contribution to the development.

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[3]Computer-aided Design, Computer-aided Manufacturing, and Computer-aided Engineering.

The Scope and Plan of this Thesis

As a topic, the size and complexity of the total development process is outside the scope of this thesis. To reduce the subject to a manageable size, the following major topics are discussed in depth:

* The development process
  - Traditional perspectives
  - A spiral analogy
* Recently proposed improvements to the development process
* Organizing for the development process
* Development as a process of establishing relationships
* A product development strategy

The following topics will not be discussed:

* Creative idea generation.
* Corporate policy
* Customer needs analysis
* The role of the computer
* Design aesthetics
* Data requirements throughout development

REVIEW: CURRENT DESIGN THEORY

When discussing the nature of design in technical literature, authors usually present one of two models of the development process. Looking at several different models of the same complex issue often provides insights. This is also true of the development process. Several models of the development process are described and examined. This chapter discusses the traditional models of the development process: design philosophy and design morphology.

Design philosophy and design morphology are usually presented graphically with sets of boxes, or circles, connected by arrows to denote some sequence between them. Although the details of the philosophies and morphologies vary, the basic models are similar.

Design Philosophy

Philosophy may, at first, seem like an imposing term. One meaning could be paraphrased as an outlook or perspective on a subject. A philosophy of design, then, is a perspective (way of looking at) design from the abstract to the most detailed level. There are many design philosophies, since everyone has different opinions on design. In practice, however, most published philosophies vary in detail, but follow a traditional model.

The traditional design philosophy illustrated in Figure 1 regards design as a decision making process to arrive at a plan for a product. The process consists of three parts.

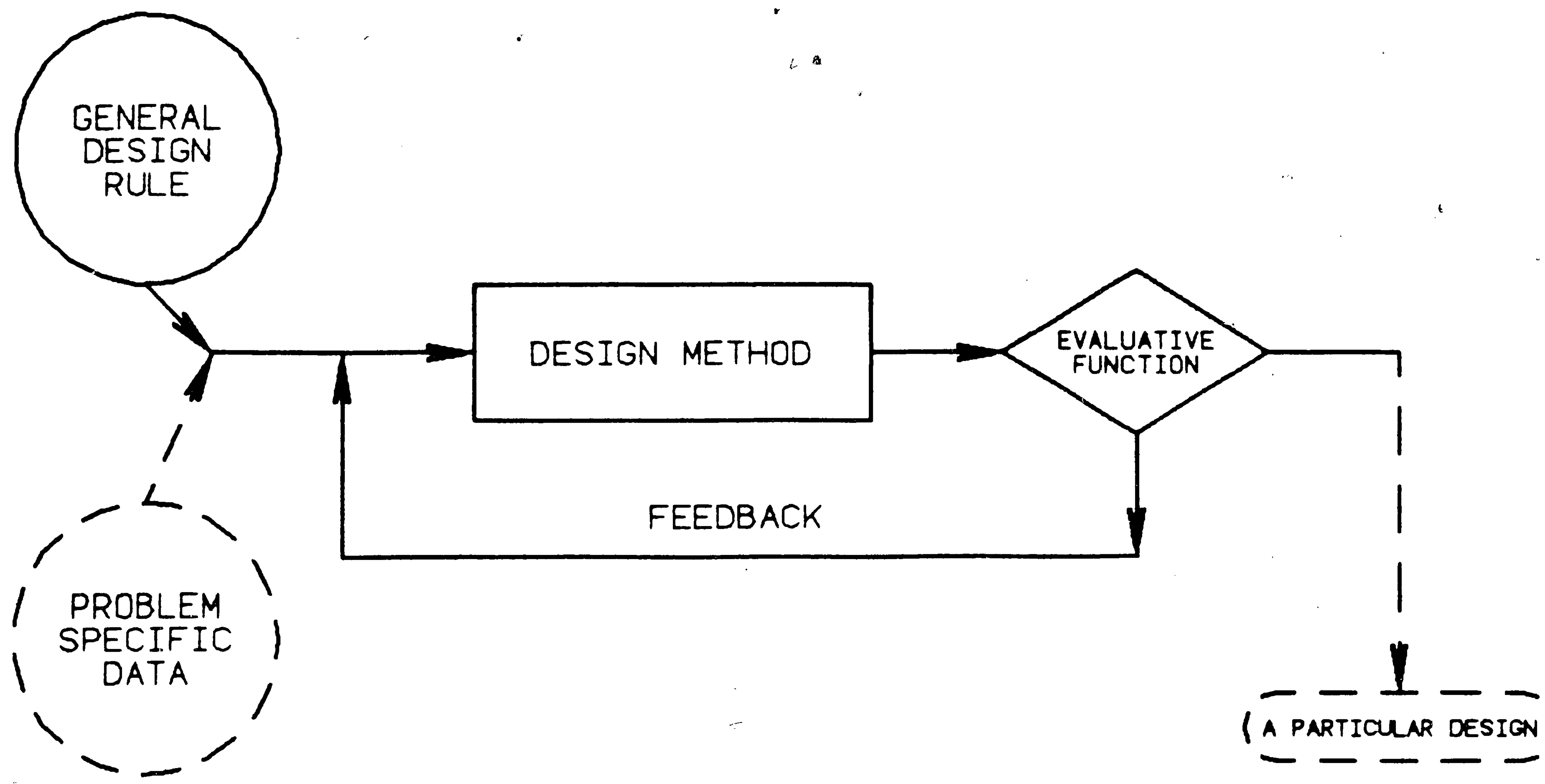

Figure 1. A Design Philosophy

The first part is a set of general principles or rules. This is the primary assumption of the philosophy, that this set of rules does exist. The set needs to be correct both individually and collectively. Conflicting rules could be disastrous. The rules should also be sufficiently general to be applied in all situations.

The second part of the development process is a discipline or methodology for using the rules along with data specific to the current problem to generate a solution. This methodology is the framework within which specific techniques are used. Possible techniques include brainstorming, finite element analysis and linear programming.

The third part of the development process entails evaluating the results of the designer's application of the design rules through the methodology. A means of evaluating options is necessary since there are usually several concepts of how to solve a problem. For each concept there are also several ways to implement the concept. The designer needs a means of evaluating and choosing the implementation to use. The evaluation also provides feedback, both during the process and after a design is completed, so future decisions can benefit from current experience.

Axiomatic Design

The need for a consistent set of rules for use with a design methodology prompted creation of a new field called axiomatic design. Researchers in this field search for a consistent set of rules--axioms. An axiom is an empirical rule in mathematics which can not be proven, but there are no known violations. Since design involves developing a solution to a specific problem, it would be extremely difficult if not impossible to actually prove any set of design axioms.

Suh's axioms

Nam Suh is the best known author on axiomatic design. He revised his first set of seven axioms (Suh, Bell & Gossard, 1978) into two (Suh & Rinderele, 1982). From these he has derived many theorems and corollaries. His proposed axioms:

(1) Maintain the independence of functional requirements

(2) For the designs meeting (1), the best minimizes the information content

Suh's second axiom suggests the rating of product concepts and their implementations on the basis of information necessary to describe or carryout the design. The implication is that less information necessary to describe a component implies less material used, less components, or less and simpler processing.

Suh's design philosophy-based methodology

Suh has based a development method on his design axioms (1982). In presenting the method, he establishes his axioms and equations for subjectively quantifying measures of the information content and functional independence of proposed designs. For example, he proposes

> The information required to measure [some dimension] is somehow related to the ratio of the range [of the dimension] to [the specified] tolerance, which may be thought of as the inverse probability that the [dimension] will be measured within the tolerance. The most convenient definition to use for the information content is the base two logarithm of the ratio of range to tolerance (1982, p. 334).

The equation provides an easily calculable number of high mathematical precision with, perhaps, tenuous correlation to reality.

Suh continues in his examples of the methodology by picking or calculating numbers for all quantifiable functional requirements and constraints. The prioritized requirements and constraints constitute a set of linear equations, which are solved to obtain an "optimal" solution.

Concerning the solution, Suh notes,

> It is important to note that this result depends on the scaling of the particular design problem. It is of the utmost importance to apply measures of information content and complexity when scaling the design problems so that the results of this type of analysis are significant (1982, p. 336).

It is fair to characterize Suh's approach as:

(1) Quantify all possible factors, ignoring non-quantifiable

(2) Make a leap of faith the model is valid

(3) Apply linear programming to solve the simultaneous equations

(4) See if the results seem reasonable

The axioms and corollaries at this point are too abstract to be used on a daily basis. They have been applied successful as "rules-of-thumb" or mental guidelines.

Yoshikawa's axioms

Yoshikawa has proposed an alternate set of axioms. His objective is also different. Yoshikawa seeks to prove the existence of a theory of design. To do this, he has created three axioms, thirty-four theorems, and four lemmas based on set theory. Yoshikawa's axioms are (Tomiyama & Yoshikawa, 1988):

(1) Axiom of recognition: Any entity can be recognized or described by attributes and/or other abstract concepts

(2) Axiom of correspondence: The entity set S' and the set of entity concept (ideal) S have a one-to-one correspondence

(3) Axiom of operation: The set of abstract concept is a topology of the set of entity concept

Since Yoshikawa defined the axioms and theorems so abstractly, they are neither able to be proven or disproved. This leaves open the question as to whether they describe the real development process accurately.

Design Morphology

Design morphology is another perspective (philosophy) on the development process. It focuses on the chronological sequence of activities, or phases, in the development process. The simple morphology in Figure 2 is adapted from Asimow (1969, p. 12). Morphologies usually start with a customer need and end with either a documented, detailed plan for fabricating and assembling the product, or a series of manufacturing activities. The activities are sometimes split into many detailed activities. There is also a wide variety in the number of activities and the labels authors have assigned to the activities.

The well delineated activities or phases in Figure 2 give the impression they are rigid. Asimow confides that in practice the process sometimes involves the overlapping of phases to complete final details or the returning to a phase for redesign. This separation of the activities in the development process, often with different people involved with each activity has received a great deal of criticism in the renewed interest in design.

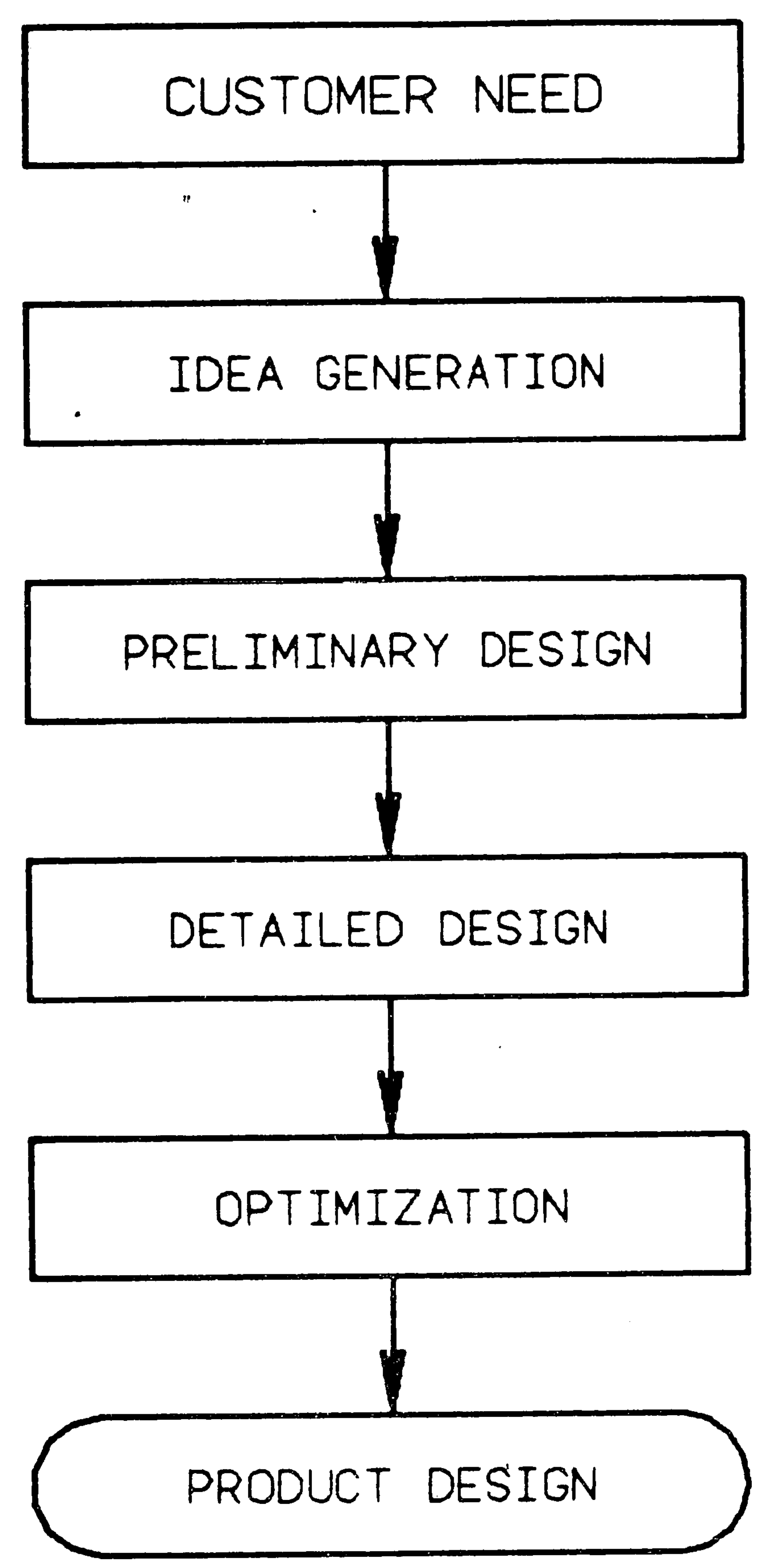

Figure 2. A Design Morphology

Kimura's design morphology

Basing a development method on design morphology requires identifying the different "activities" in the development process and the decisions to be made in each. Kimura has developed a methodology based on design morphology using Artificial Intelligence techniques.

He has had to create an elaborate structure to recognize the level of abstraction the program is addressing at any instant in time. The program seems capable of two fixed levels: preliminary and detailed. It develops products in well-bounded problem areas by accepting preliminary designs and essentially customizing them into detailed designs using known elements (Kimura & Hiromasa, 1986).

REVIEW: CURRENT DESIGN METHODS

A number of concepts for improving the design process have been suggested over the last forty years. These concepts have evolved or been combined into a number of development methodologies since 1970. Many of these methods utilize more than one of the concepts described below. The concepts are explained with a discussion of the methods relying heavily on that concept. Although many of the methods currently proposed utilize more than one of the concepts, each method is discussed under the concept which represents the method's major thrust or means. The advantages, limitations, opportunities, power, and problems with each concept are also explained.

Some of the concepts proposed to improve the development process are inherently computer based. The computer is now and will remain an intimate contributor to product development. As such, the role of computers in facilitating product development can not be ignored. However, issues of computer capabilities and implementation should not drive our vision of design or alter our ability to evaluate the quality of products developed. Since it is the objective of this thesis to explore improvements for the development process, the discussion will remain above the level of specific computer implementation details where possible.

Exploiting Similarities by Reusing or Varying Designs

Group Technology (GT) is a concept for exploiting similarities in products, components, and processes. It involves the creation of families of components with similar design features or fabrication steps. GT does not actively seek to improve designs or the development process.

The principal tactics of GT are reuse of designs and standardization to reduce the number of varieties. Standardization and reuse of designs reduces the time and resources spent on developing products. Standardization also allows a number of manufacturing efficiencies like dedicating groups of machines to producing component families, smoothing material flow, and reducing process planning, inventories and tooling. If the standards applied to the most cost efficient manufacturing activities, then there will be cost savings.

Unfortunately, many companies do not redesign their products while creating the component families. The result is perpetuation of the poor designs of the past. Even worse, unless someone is given the task of constantly updating the standard component and process information, the reuse of previously designed elements causes stagnation. Because the standards and old designs exist, a special and unusual effort is required to do anything new or different. The traditional structures in a mature organization increase the inertia by enforcing standardization to maximize the efficiency of development efforts.

The exception to the stagnation problem with GT is when part families are parametrically defined and a change to the master product definition can update the entire family. Without vigilance and a flexible organization though, most possible improvements will not be made.

GT has spawned two concepts (and methods) that claim to improve development. The concepts are distinct, but the methods are often implemented, at least partially, together. The names of the methods, features-based design and parametric design are commonly used interchangeably. They are discussed in the next two sections.

Adding Blocks of Detailed Data to Designs

The concept of adding blocks of detailed data to designs is commonly referred to as features-based design. In features-based design, blocks of detail constituting logical groups of geometry are added "en masse" to a design.

What are Features?

Three types of grouping are referred as features: (1) a component element, such as a threaded hole, slot, or pocket; (2) a standard geometric shape, such as a cylinder, block, or plate; and (3) a complete (often standardized) component, such as a bolt, washer, or welded on sleeve. The third type is most common in Artificial Intelligence based systems for the development of customized products. The first and second type are used extensively in the parametric design systems described in the next section.

Features are predefined in a computer system and consist of a combination of fixed, selectable from a set, or user definable dimensions. When a designer requests a feature be added to a design the Computer-Aided Design (CAD) system creates geometry in the current database having the logical form and grouping of the requested feature. The dimensions, position, and orientation of the feature are determined by the combination of fixed values and those specified by the designer.

Advantages of Features

The advantages of features are threefold. First, the use of features is an abstraction that saves development time. A designer can specify the creation of a whole block of standard or semi-standard geometric details logically considered one entity. For example, a half inch by one inch threaded hole is a feature. Instead of determining and entering the precise data necessary for the appropriate geometry, the designer saves time by creating or moving a feature with one command. Specifying this entire block of detail in one command also saves the designer from becoming wrapped up in the minute details of creating individual geometric entities in the feature. The designer can spend more time thinking about how to develop the whole product.

The second advantage is automatic or semi-automatic generation of plans and programs for component fabrication and assembly. For instance, to the production planner the features represent the same detail in terms of geometry, but are interpreted differently than by the designer. A threaded hole entails planning for certain processing steps. While to quality control person, the threaded hole represents a location and dimensions to be verified.

The third advantage of features builds on the previous two advantages. Since a feature can be tied directly to one or more means of fabricating that feature, the feature's cost can be determined and supplied to the designer during development. The designer can then quickly and easily make trade-offs between alternative features, or between feature cost and customer satisfaction. Traditionally this might just mean picking the lowest cost alternative, not the "ideal" alternative.

Hazard of Features

There is a hazard to using features. Designers using features tend toward variational design. New designs are based on existing preliminary designs, or developed by combining standard elements. A designer can quickly become accustomed to using these elements to the point of combining them without regard to nonstandard elements, less common elements, alternate combinations, or alternate materials, which may be better for the given product.

Features as a Language

Some CAD system vendors are trying to promote features as a language usable throughout the design and manufacturing process (Drake & Sela, 1989, p. 67). Features are not a language. A feature serves as a symbol with different detailed definitions for people from each functional area within an enterprise. This is possible since a feature is an abstract framework to which details are attached. The details of how people from each functional area view or use the feature is ignored to emphasize the commonality of the abstract symbol. The symbol then serves as a common bridge (or "mental map") between people from all functional areas (McCaskey, 1982). Unfortunately, this kind of "shorthand" can cause miscommunication or parochialism because every person and department has different detailed interpretations.

Easily Manipulating Geometric Elements

The easy manipulation of geometric entities or groups is the basis for the method called parametric design. A parameter is a characteristic that controls an element in a system, but whose value is arbitrary. The value of the parameter need not be numerical. For example, a rectangle is a system. Each line in the rectangle must be parallel and of the same length as the line on the opposite side. But, the actual length to use is arbitrary: a parameter. There are also relationships between the lines. Both ends of each line must be perpendicular to another line, and the intersection must be at their end points. If we vary these relationships we can make squares, parallelograms, or random arrays of lines.

Parametric design takes advantage of the flexibility of parameters. In parametric design the designer specifies features or geometric entities by parameters. The values of the dimensions and characteristics are subject to easy manipulation. The values can even be related to other dimensions or characteristics within the feature, component, or assembly. As the development process proceeds the designer can change values as appropriate for refinement or experimentation. The process has been referred to as design by spreadsheet in reference to electronic spreadsheets like Lotus 123.

Parametric design is especially powerful for:

* customized products,
* part families, and
* products with strong relations between elements.

Parametric design can drastically cut the prototype, feasibility and cost estimation phases on variations of existing products. Gears and gear trains are an excellent application.

Contrast Between Parametric and Features-based

Although conceptually distinct from features-based design the terms are often used interchangeably in marketing and trade literature. Features-based design emphasizes the easy placement of blocks of geometry. In features-based design a designer can specify the placement, orientation, and the values of dimensions or data describing a physical entity or part of an entity. The designer's ability to modify the geometry (and how easily) is not addressed in features-based design. Some currently implemented CAD/CAM systems with a features creation capability allow the designer to modify the feature. The difficulty of modifying the feature varies widely between systems.

This ability to change features is where features-based and parametric design systems overlap. For parametric design, features are one means of creating geometry. Parametric design focuses on the easy manipulation of parameters after the feature or part geometry is created. Parametric design emphasizes the easy specification of values and relationships within and between entities.

Unlike features-based design, parametric design is not inherently a CAD-based improvement. Parametric design can be implemented on non-CAD computer systems or without a computer. An example is gears. For many years gears have been specified by type and the value of a number of parameters.

Capturing the Designer's Intent

Trade and marketing literature mentioning parametric design often cite it's ability to capture the designer's intent. The vendors of parametric computer systems seem to be pushing this notion. The meaning of this claim is unclear. Current systems certainly can not:

* know what the designer wants even if the designer does not know how to express it,
* know to do what the designer does not command,
* know the designer did not command the system correctly, or
* know that what the designer specified is inefficient or ineffective.

Limit of Parametric Design

Although parametric design potentially can be applied on all designs. It can not be applied until the the preliminary design phase when geometry is first specified. The next section discusses the problem of manipulating product concepts.

Computerized Concept Manipulation and Testing

Variational geometry (VG) is similar, but distinct from parametric design. VG is "a technique that can simultaneously solve a set of geometric constraints and equations that establish important engineering relationships within and among the elements of a design" (Deitz, 1989, p.62). Both techniques allow designers to easily iterate through possible designs by changing the values of and relationships between elements in the design.

The difference between parametric design and VG is that VG is applied at the concept and early preliminary design phase of development. VG uses lines and arcs to represent whole components or assemblies, instead of the precise, but variable, geometry of parametric design. The objective of VG is to allow the designer to manipulate, test, and optimize the product's concept and preliminary design. This is a powerful concept and preliminary design visualization tool.

Optimizing Detailed Designs

The basic concept in this large class of methods is to optimize an existing detailed design. Optimization focuses on one area of interest. Typical areas include: assembly, individual fabrication processes, maintenance, and weight reduction. Optimization is a parochial approach to design that will not consistently result in the ideal product for the system. Yet, a large number of optimization methods have been proposed, and claim to improve the development process. All of them can and have improved individual products.

These optimization methods are not inherently computer driven. Most methods have been computerized though.

Detailed Design Optimization Categories

The detailed design optimization methods fall into two categories according to their means of optimizing: (1) review, and (2) generation suggestion or constraint. The review category is much larger. It is divided into three types according to the review media the methods used: numerical, coded, and intuitive. The following sections describe each category and type along with a typical method.

Optimizing by Numerical Review: Methods of this type optimize products through Finite Element Analysis (FEA) or the Finite Element Method (FEM). FEA and FEM are techniques by which a complex shape is divided into many standard shaped units or elements. The properties of these elements are known. The effects of applying conditions to the elements can then be calculated. The overall effect on the complex shape is then calculable by simultaneously solving for all the elements. Commonly applied conditions include electrical differences, forces, and thermal differences.

FEA, also called MFEA (Mechanical FEA) is very popular in the aerospace industry. Their prime objective is to minimize the weight necessary for the required performance, usually strength. FEA is used to determine component strength. Based on the results, the component is modified and reevaluated. The cycle stops when changes yield small or negative benefits.

Optimizing by Coded Review: Coded review methods for design detail optimization use different means of rating product components. The common means is a subjective scale. With some methods the scale is then translated into costs.

The best known method of this type is Boothroyd and Dewhurst's Design for Assembly (DFA) methodology (1987). The review consists of two phases. In the first phase, the reviewer seeks to eliminate unnecessary components. Potential components for elimination are identified using three questions (Boothroyd & Dewhurst, 1984, p. 89):

(1) Does the part move with respect to all other parts?

(2) Must the part be made of a different material?

(3) Must part be separate for assembly or disassembly?

If the answer to all three questions is "No". Then the component is a candidate for elimination. Eliminating or standardizing fasteners is a prime objective.

In the second phase, the designer (or reviewer) rates the design using the Boothroyd Dewhurst code. The code is supposed to point out those components that are good candidates for redesign. The redesign objective is to optimize components for manual or automatic assembly (Stoll, 1988).

Optimizing by Intuitive Review: Design reviews that are more comprehensive than the traditional design reviews are promoted by a methods like Concurrent Engineering, Early Manufacturing Involvement, and Simultaneous Engineering. These are primarily a change in outlook on what development entails and the creation of a team to shepherd a product through development and manufacturing. Greater discussion on these methods appears in the chapter on organizations for development projects.

Optimizing by Generation Suggestion or Constraint: Suggestion or constraint methods do just that suggest or constrain options in the development process. Although both types are based on the same general ideas for optimizing designs, no methods have been identified that do both. The differences seem to be the outlook of the method developers and the means of implementing the method. Constraint methods are generally implemented on computer design systems to restrict the designer's options. The suggestion methods offer the designer sets of guidelines or rules.

Design Guidelines or Rules: Many authors have proposed sets of design rules or guidelines. Hoekstra (1989) identified over two hundred design rules proposed to optimize products for automated assembly. He evaluated, organized, and condensed them into twenty-three rules in five categories (1987). Twenty-three rules for automated assembly considerations alone implies a set for all considerations in the development process would be extremely large. A smaller set probably would be too general or conflicting.

Having a set of design rules for teaching, writing papers, or programming into computer systems would be convenient. But, the world does not always conform to a concise, nonconflicting list of rules.

Making design guidelines available to designers does not insure improved designs. One large company[1] publishes a twelve volume set of design methods and standards. After distributing the manuals to designers, they discovered their internal telephone hotline was much more popular with designers than looking up the information in the manuals. No additional information was available over the phone. To encourage more use of the manuals, they printed a wall chart with condensed examples and references to sections in the manual. Use of the chart and manuals presumably reduced manufacturing costs. But, how close the products with the improved components are to "ideal" is unknown. The improved components may even be extraneous.

<u>Design constraint</u>: CAD systems have provided companies with an opportunity to make sure their design standards are enforced. A CAD system developed at the University of Manchester allows designers to specify components by using any feature producible on a lathe (Plummer & Hannam, 1983). Cost estimates for producing components is also readily calculated and available to the designer.

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[1]Disclosure of the company's name along with the existence of the manuals in not permitted.

Artificial Intelligence

Artificial Intelligence (AI) is applied toward improving the development process in two ways. The first is to use AI to improve or implement a proposed method. This is an implementation issue, and not within the current discussion. The second way is to apply AI techniques to cause a computer to develop products by imitating human reasoning.

Those AI methods attempting to imitate human designers generally can be characterized as trying to stuff the development process into a framework which is familiar or easily digestible for AI solutions instead of building the method to match the process.

The primary contribution of the AI approaches to date is their study of how humans think and conduct the development process.

Fabrication and Assembly Cost Estimating

Frequently fabrication and assembly cost estimates are used as a means of evaluating alternatives or showing the cost improvement made in a design by an optimization method. Among others, Boothroyd (1987) has produced a series of cost tables for various operations and component features. Whether the actual figures used are obtained by surveying several companies or one, the variations in actual costs, cost accounting methods, production equipment, and technologies probably renders the numbers inaccurate for another company. The reliability of the estimates are made more tenuous by variations in costs due to time and technology evolution.

Hoekstra's Cost Estimating Method

Hoekstra (1989) developed a technique where the difficulty of operations are weighted on a scale of 0-10. After summing the ratings for each component and operation, a "Design Efficiency" is calculated relative to an assembly of the same number of "ideal" parts. If the assembly cost of the original assembly is known, a cost for the redesigned assembly can be estimated as the inverse proportion of the assembly costs to the design efficiencies. Using this method Hoekstra reports a correlation of r = 0.983 with Boothroyd's technique. He does not however question the accuracy of Boothroyd's estimates, and assumes the ratios of costs between original and redesigned assemblies remain constant in time. He does not consider changes in materials, component fabrication, or assembly cost. They are lumped into his (potentially) chance correlation with Boothroyd's examples. It is also not clear that Hoekstra's ratio will holdup for more complicated assemblies.

DISCUSSION: DEVELOPMENT AS A SPIRAL

As an evolution from the linear, boxes and arrows approach to describing the development process, a small number of authors, like Terry (1988, p. 111) have described the development process as a spiral. In this analogy, the design process starts with an idea in the center. The idea gradually evolves into a product as it passes around the spiral. As the process unwinds the designer often recycles as alternatives are explored or rejected. Yet, the designer never arrives back at the same spot. This is not just a time difference, the designer has always learned a little more about the problem or the options available. Even if the only thing learned is that the last option explored is unacceptable.

Chambered Nautilus Analogy

The chambered nautilus analogy describes the development process better than the traditional, linear design philosophies and morphologies. The bisected nautilus shell in Figure 3 is a very tempting shape. Not only is it natural and pleasing to look at, but the chambers can be labeled with different phases of the design process. The shell combines the perspectives of design philosophy and morphology by showing both the decision making cycle and the phases in the development process.

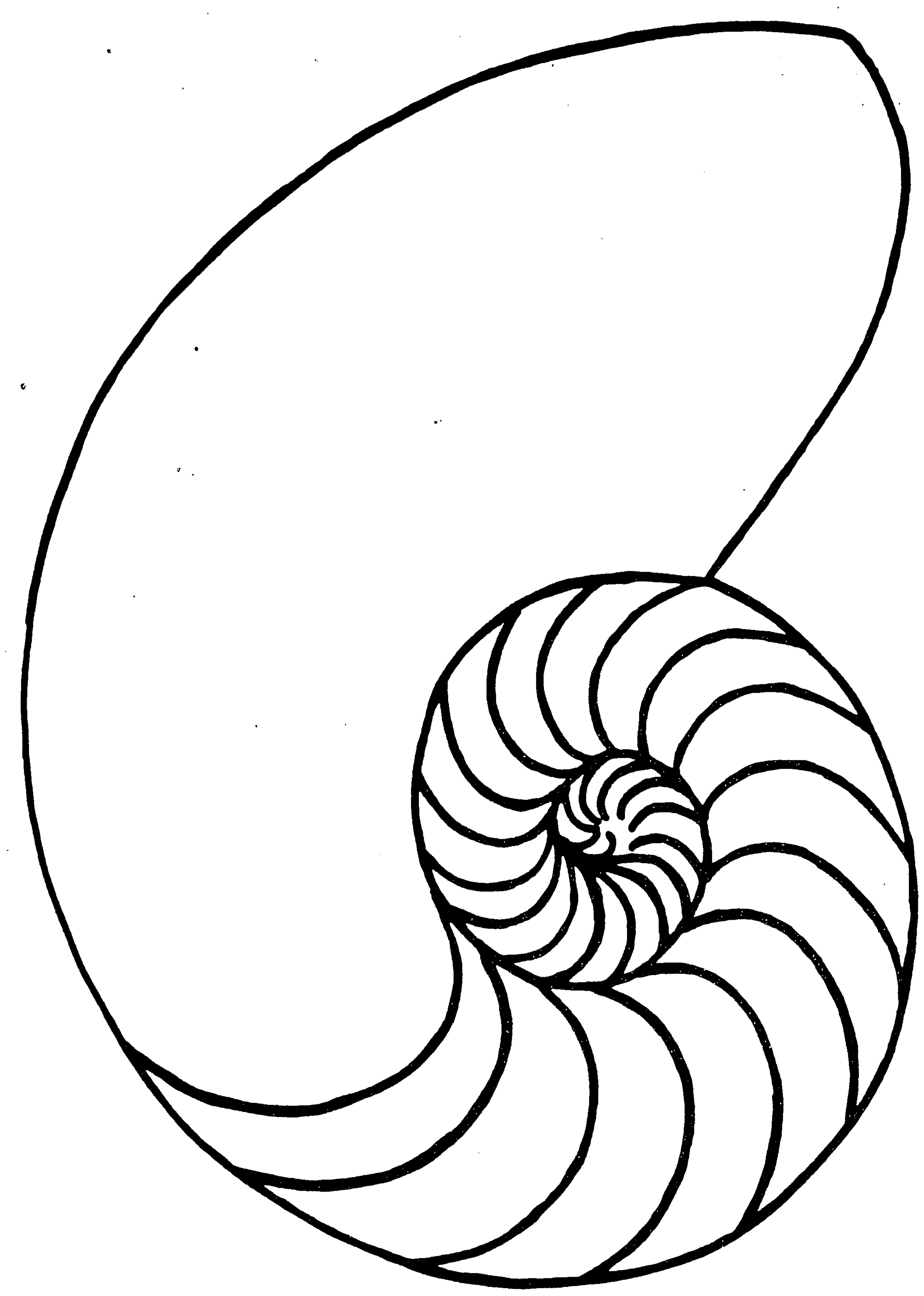

Figure 3. A bisected chambered nautilus.

The Development Cycle is Multilayered

The spiral of the shell suggests the entire development process. The development process though, does not continually wind its way toward the end like the spiral. Designers often, and should, circle back to reconsider, modify, or refine details. The development process consists of many small cycles through the decision making cycle of Figure 1.

Reconsidering Figure 1, it is apparent the cycle is multilayered. The cycle can be the entire development project, or one instant in time when a designer makes a decision. In the nautilus shell the walls between the successively outward growing layers seem to preclude this circling back between layers in the spiral shell.

The large spiral of the development process consists of many small loops through a single decision making cycle as each new layer of detail is added to the emerging design. The development process is not a single pass process.

The Phases are Not Chambers

Carrying the analogy for combining design philosophy and morphology in a nautilus shell further, the different chambers in Figure 4 are labeled as different phases in the development process. This may prompt the reader to question the distinction between the phases many publications list. For instance, what is the difference between concept generation and preliminary design? What is the difference between preliminary design and detailed design. In practice, phases are often separated by reviews. But, when should the reviews be held? At what moment in the development process do designers go from preliminary to detailed design? The decision is often based more on the development schedules and budgets as opposed to the activity actually occurring.

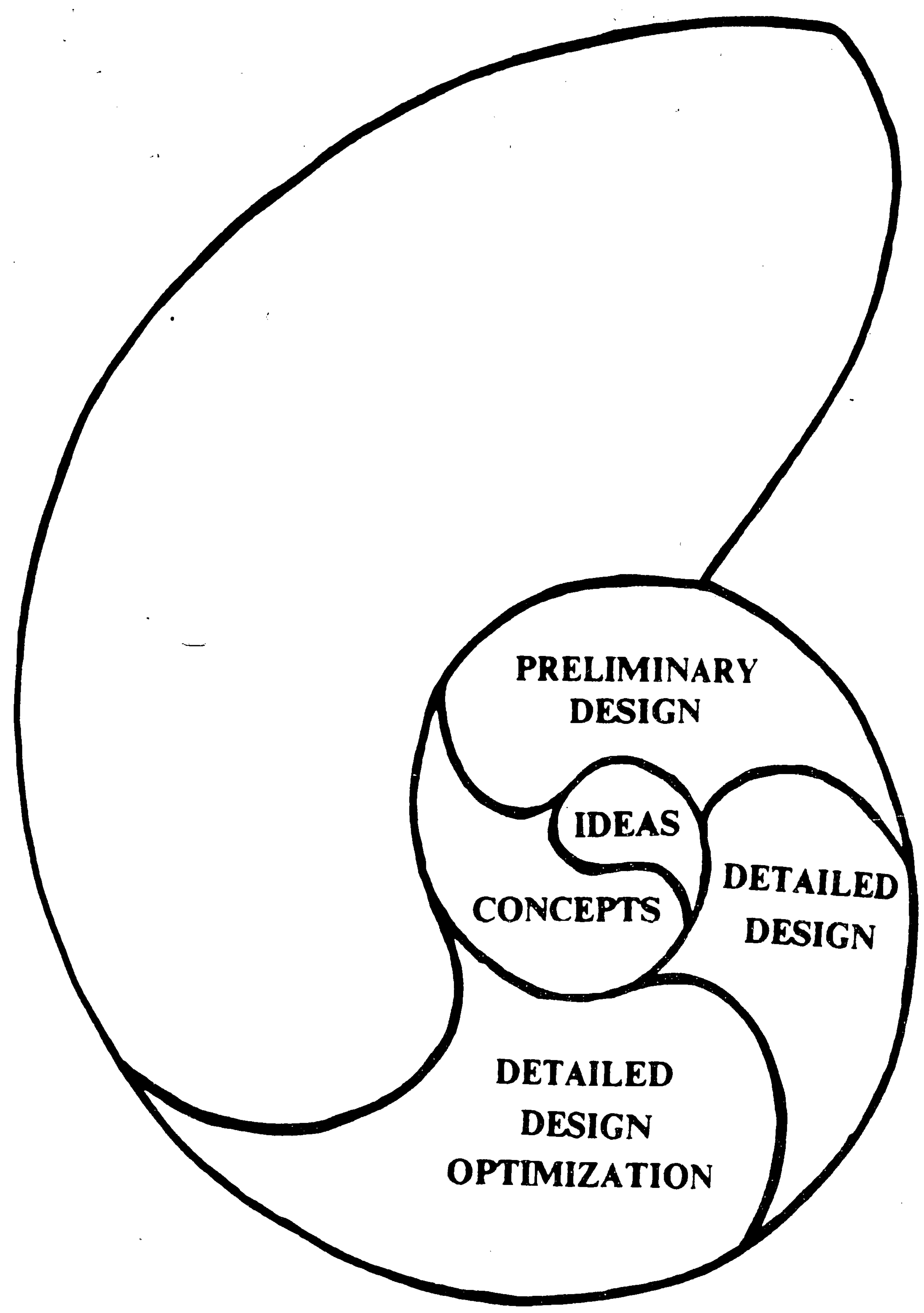

Figure 4. The Development Process as Chambers in a Nautilus

Difference between Concepts and a Preliminary Design: A concept is an abstract idea in a person's mind. There are no details associated with a concept. We can define a preliminary design as a concept to which details have been added. An example may clarify this distinction.

Think of an implement for writing on paper. Chances are a mental image like a pen or pencil appears. This is a preliminary design. "Model" is a word commonly used to describe it. It could be argued that the model pen or pencil imagined had no dimensions. But, what shape was it? Does it have to be that shape? What about using a device attached to the writer's head? How does it make a mark on the paper? There are other ways. What about a typewriter? Does a typewriter qualify?

The number of models we carry in our minds is amazing. They are very powerful. These models and our "learned" behaviors can also be a handicap. They tend to restrict our understanding of what is possible. Understanding the models we carry with us can be powerful. It can be even more powerful to breakout of a model occasionally (Hanks, Belliston & Edwards, 1978).

Difference between Preliminary and Detailed Design: There is no distinct dividing line between the preliminary design and detailed design phases of the development process. Each phase, in all but trivial cases, represents many cycles of adding increasingly fine and definite detail in an emerging product plan. As such, the difference between the last cycle in one phase and the first in another is no more significant than the difference between cycles within a phase.

An example is in developing an electricity generating station. When developing these complex structures the design team starts the task with a common, if somewhat differing, model of the system in their mind. The team generally does not start from scratch and investigate all known models of generating stations, and then try to create alternatives to determine the best model to continue work on. Instead the basic model is prespecified by the customer, formally agreed to, or even tacitly agreed to at the outset. And so, the design team starts with a preliminary design because they already possess a product model derived from some concept (Davidson, 1989, p. 69).

Variational design: A development project which starts with a preliminary design performs variational design. It represents a time savings in the early stages of design, since the designer selects new values only for the dimensions and characteristics requiring changes. Variational development projects are generally low risk since the concept and model have been proven on previous projects (Asimow, 1962).

Variational design does not assure the resulting product will be the best obtainable since there is no reinvestigation of the best concept or model before designers start adding detail. Practicing variational design is seldom innovative. Neither is it generally fatal for products in conservative (not rapidly evolving) industries. When competitors innovates, though, organizations oriented toward variational design may not be able to respond.

A HOLISTIC APPROACH

Many designers view the development process as taking functional requirements and creating a plan. The plan is a specification for a physical entity to perform the functional requirements within the stated constraints, especially, manufacturing cost. Although traditional, this is a very limited perspective of development.

From a holistic perspective the development process is a system. This means the process is a vast web of interdependent factors and activities which collectively determine success or failure. The web covers the circular process of recognizing customer needs that are complementary to the sponsoring organization's goals and then solving the customer's problem to fulfill the sponsoring organization's goals.

As one of the prime proponents of this approach, Gardiner's (1988, p. 1) eloquent definition says, "Design is not merely the specification of form, equation, mechanisms, numbers and shapes, it is also responsible for the whole implementation of a solution to a problem."

The author offers another description. The development process is a vast system of interdependent entities and factors encompassing all activities and concerns involved in solving a customer's problem while fulfilling the sponsoring organization's goals.

The definitions alone are insufficient to fully convey an understanding of the topic. They mention customer needs and problems, interdependent activities, and systems. These topics deserve some discussion.

What is a holistic perspective?

A holistic perspective encompasses all the issues related to the system under discussion. Why is it worth the extra trouble to consider all conceivable issues? Every imaginable issue should be considered in order to obtain the best possible outcome. In a system there are often many good solutions. There is an "ideal" solution. As the system becomes more complicated it becomes more difficult to reach a good solution. Considering less than all the issues can lead to two unfortunate outcomes:

(1) a solution is reached which is not near the "ideal", or

(2) a solution is not recognized as false because the appropriate issue(s) was not considered.

The Importance and Consequence of Issues

From a holistic perspective all the issues in the development process comprise a system or web of interdependent items. In any nontrivial system there exists a large set of components or issues of various sizes, complexities and importances. The importance of a component or issue to a system can be large, small or zero. Commonly, small and zero are used interchangeably. But, they are not the same.

<u>The importance of a factor and its associated penalty for noncompliance are not necessarily directly related</u>. The importance of

a factor for design trade-off decisions may be low as long as the parameter is kept within a certain range. If the value of the factor goes out of the range, the penalty may be high or low. The penalty can even be fatal to the product.

This implies that in order to keep a relatively unimportant factor within its range other factors may have to be suboptimal compared to consideration of them alone. The system will incur a penalty for this. If the penalty is less than the penalty required if the factor was allowed outside its range, the net advantage is to the suboptimization of the more important factors.

The ability of one issue of seemingly little importance to have a major impact on a system is why a holistic approach is desirable. By addressing as many relevant issues as possible, the likelihood of missing an issue which could spoil the desired solution is significantly reduced. This is a powerful incentive to carefully consider more issues.

Creating a Balance

When considering so many issues it is seldom claimed that one issue is of supreme importance. In a system, if one issue is declared supremely important, then all other issues must suffer, if necessary, to maximize that one. If someone proposes one issue as the most important, then they are probably over emphasizing it to the detriment of the entire system. That is exactly what the optimization methods do. Optimization concentrates on placing one or a small number of factors at the "optimum" value in their range without regard for other factors in the system.

With a holistic perspective the designer attempts to optimize a product for the system in which it will be produced, used and maintained. Optimizing the product for any one or two factors or concerns may result in a product that is unacceptable or unfavorable in other areas. It seldom results in the product ideal for the entire system.

Development is more the establishment of an appropriate balance between all the issues in the system. Issues in the development process include the technical details, customer needs, corporate goals and resources, and the product's future environment.

Determining a "good" design is not necessarily a straight forward process. How "good" a product is depends on many factors. The nonzero factors for any particular product are of varying importance. They can even vary in importance depending on other features of the product.

What is "Good" design?

There are many opinions on what constitutes a "good" design. The differences are primarily ones of perspective. That is, how one looks at the topic and the importance one places on different issues. From a holistic perspective, development is an activity undertaken to fulfill an organization's goal. The product exists as a means of fulfilling that goal. Customer needs are identified that the organization can develop products as solutions for the needs in fulfillment of the goal.

In order to evaluate the product's "goodness" in fulfilling the customer's needs and the organization's goal, measurements are needed. As the reader might imagine, the problem with measurements when utilizing a holistic perspective is determining a complete and concise set. Two are presented.

Design Measurement Criteria: According to Hanks, Belliston and Edwards (1978), a "good" design is "SAFE": Simple, Appropriate, Functional, and Economical. In proposing these design measures the authors show their graphic arts backgrounds. The criteria can be utilized well by a designer evaluating graphics or a designer evaluating the styling of a three dimensional product. Judging an idea's simplicity is often difficult and foreign to product designers, although the simplest alternative is often clearly preferable.

Contrast "SAFE" with Steelcase, Inc's design measurement criteria: suitability for purpose, aesthetics, and manufacturability. These criteria emphasis the factors of strong importance in their markets.

It is not so important the words that are picked, but rather the ideas behind them. The interpretation of the words convey to the designers and everyone else in the enterprise through both official and unofficial communications and actions. For people will behave as judged. Thus, the design measurement system used will profoundly impact the "goodness" of the designs produced in the organization.

If one wanted to pick one word the best would probably be "appropriate". Appropriate is an apt word because it implies the establishment of a relative balance among items. Everything in the system is related and hence dependent on many others. Hanks, Belliston and Edwards (1978) have eloquently expressed these thoughts in their admonition, **"good design depends"**.

"Good" is not enough

In today's and tomorrow's business environment it is often not sufficient to develop just a "good" product. To flourish or even survive, a product must have the enterprise's active support and be near the "ideal" for the corresponding system of customers, product environment, and sponsoring enterprise. A merely "good" product which survives or flourishes indicates a lack of or weakness in the competition. Assuming this condition will last is a strong forecast of trouble ahead for any enterprise foolish enough to make the assumption.

System Structure

The web is not like the cables of a suspension bridge. In a suspension bridge a small number of large cables span the length of the bridge. A mass of smaller cables support the bridge deck from the main cables. Thus, a failure of a small cable puts a greater strain on neighboring cables, but is seldom fatal to the bridge as a system. The failure of a main cable is almost always catastrophic to the bridge system. The product system does not have these small number of supremely important threads.

Instead of a suspension bridge, one might be tempted to use a spider web as an analogy. In a spider web there are many main radial threads. The failure of any one of these threads is unlikely to be catastrophic. However, the threads still clearly and linearly connect two points on opposite sides of the web. The individual relationships in the development process do not span the process.

The web suggested here has many cables of apparently varying importance. No single cable can stretch the length or breadth of the development process. Indeed, the primary cables that at first appear to be large solid masses under closer scrutiny are themselves revealed to be intricate systems (webs).

Development is Specifying Interrelationships

The development process can be viewed as the building or specification of a web. When the process starts there is an ever present web of environmental and physical factors. During the development process consumer, economic, manufacturing, organizational, political, and social factors are added. Each decision in the development process is the addition of strands or an entire web (subsystem) to the existing system. The size, complexity and detail of the system added depends upon the decision made.

Web of Relationships

The web referred to is not a physical web intended to withstand certain forces. Rather, the web is a complex set of relationships. These relationships are the natural interdependences of issues and the decisions made concerning concepts and implementations.

This web is created in every development project. Seldom is more than a small area of the web ever considered by many designers.

Conscious establishment of this web should help insure the pure refinement of an "ideal" concept into an "ideal" product.

EXPLICITLY ESTABLISHING RELATIONSHIPS

The development process is the establishing of relationships. The process relates the sponsoring organization's goals and strategies to a particular customer problem or need. This need is translated into a set of requirements and constraints. The requirements and constraints imply alternate configurations of flows, forces, forms, and motions necessary for the product to meet the customer's needs within the requirements and constraints.[1] The flows, forces, forms, and motions then mature into a detailed plan for realizing the product or service. Finally, the realized product or service produces appropriate customer satisfaction and reward for the sponsoring organization.

Unless the sponsoring organization wants to trust to luck in obtaining a near "ideal" product, the relationships established in the development process must be bidirectionally consistent throughout the process.

In the development process this chain of relationships is not automatic. To reliably arrive at a near ideal product for its given system requires careful attention to the establishment of this chain. Understanding and explicitly establishing the relationship chain should increase its integrity.

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[1] In some cases mathematics accurately represents the relationships between factors and enables easier manipulation.

The relationships in the chain have been discussed independently by the associated traditional fields of interest. The relationships are discussed individually in the following sections. Putting the relationships together during the development process is the subject of the next chapter.

Enterprise Goals and Strategies <-> Customer Needs

The development process is the establishing of relationships. It is undertaken to fulfill the goals and strategies of the sponsoring organization. The organization's goal is probably something like achievement of at least a certain return on its assets. To achieve this the organization decides to sell certain types of products to customers.

Although most companies target specific customers for their products, fewer can be said to examine the problems for which their customers or potential customers need solutions. The idea of relating corporate goals and strategies to customer problems and needs is not new. Levitt (1960), in his landmark article on marketing, expressed the need for companies to know and understand the problems facing their customers and potential customers.

The customers do not have to buy the organization's products. It is not a unilateral relationship. To induce customer's to buy their products there are two approaches:

(1) Convince them to buy the product

(2) Offer a product with the natural appeal that it satisfies a customer's need

The first approach is, unfortunately, closest to the traditional approach. Its objective is to induce sales. In the short term, it can increase sales volume. For the long term, the first approach quickly becomes less effective if the product does not satisfy the customer's need. In practice, most companies use a blend of the two approaches.

The company, then, must not only manufacture the product and offer it for sale, they must have products the customer desires. These products must evolve as the customer's desires change.

The company, then, must develop new or modify existing products to maintain the relationship between the customer's needs and the product's ability to satisfy those needs.

The company sponsors development work to increase, or at least maintain, the relationship between its goals and the problems and needs of its customers.

Customer Needs <--> Requirements and Constraints

The customer's problem or need requires translation into requirements and constraints. These requirements and constraints are used for two purposes. They form the next relationships in the chain by suggesting the flows, forces, forms and motions discussed in the next section. They also serve as a means of measuring the "goodness" of the product concept and the product delivered to the customer.

It is recommended that the designers determine the importance of--and the consequences of not satisfying--each requirement and constraint in the system. Prioritizing the requirements and constraints helps to establish or discern shifts in their relative importance.

A simple prioritizing scheme should never become the basis for automatic development of products. Although this may seem an advance, it is the relinquishing of both the explicit establishment of relationships and the consideration of relationships other than those listed. The supposed advantages are speed of development and reduction in development complexity. Quickly developing a product of tenuous virtue can hardly be called an advantage.

Requirements and Constraints <--> Flows, Forces, Forms, and Motions

The requirements and constraints for the product can be distilled into one or more configurations of flow, forces, forms and motions. Each individual or set of flows, forces, forms and motions is derived from and responsible to a requirement or constraint. If a flow, force, form, or motion is not directly related to a requirement or constraint it is superfluous. Otherwise, the simplest set of flows, forces, forms, and motions to completely satisfy all requirements and constraints is probably at least a near ideal set upon which to build a concept. Optimizing the concept should yield at least a near ideal concept.

Flows, Forces, Forms, and Motions <--> Components

Once the appropriate flows, forces, forms, and motions are identified, they help suggest the "ideal" product concept for the system. Optimizing the flows, forces, forms, motions, and product concept will improve product performance, increase customer satisfaction, reduce development time, and reduce manufacturing cost. Since the optimization should be over the entire system, benefits will appear in other areas also.

The resultant product concept is refined into components and subassemblies. If the refinement is pure the relationship between the flows, forces, forms and motions and each component is straight forward.

If the relationship between a flow, force, form, or motion and a component is not explicit, the concept has not been purely refined. This impurity seldom can be remedied through optimization at the detailed level.

Too much detailed optimization--or any of certain types--means a poor design. An example is eliminating parts. Adding a lot of chamfers to bolt holes is a good detail optimization. Eliminating parts indicates the relationships from requirements and constraints through the flows, forces, forms, and motions do not tie firmly to the need for that component. This results from not explicitly watching the establishment of the relationships in the development process or not maintaining an even detail wavefront.

Conclusion: A Circular Relationship Chain

Every enterprise has a goal (generally to make money, while observing some social and self-imposed constraints). To achieve this goal the enterprise requires new products or services, since all products and services have a finite economic lifetime due to competition and evolving customer needs. To determine new product opportunities within its strategy (if marketing-oriented as opposed to sales oriented) appropriate customer needs are identified. From the customer needs, the requirements and constraints can be generated. Traditionally, only "functional" requirements and constraints like torsion strength, output voltage, and manufacturing cost are considered. There are many more requirements and constraints for most products.

From the requirements, constraints and customer needs a set of product concepts can be generated. Each concept then has associated with it a configuration of flows, forces, forms, motions, and possibly, mathematics (which can be used to express relationships).

Identifying these elements can help generate and evaluate product concepts. Pure realization of a concept creates specifications for components (or actions in the case of services). If the product is appropriate for the customer needs and the system to manufacture, distribute, and service it, sales to customers fulfil the enterprise's goal. Thus, bringing the process full circle.

A DEVELOPMENT STRATEGY

In this chapter a strategy for developing products is presented. The strategy emphasizes:

(1) the holistic (systems) perspective on design,

(2) the premise that the development of a near "ideal" product requires the pure refinement of a near "ideal" concept, and

(3) the explicit establishment of a circular chain of relationships.

The purpose of the explicit establishment of the relationship chain is to aid in the pure development of products and the evaluation of them throughout the development process.

The strategy presented here is not referred to as a methodology because it is not a strict sequence of steps. Rather, it is a list of important considerations in a sequence well suited to a linear explanation. In practice, the sequence is preferable to not considering these issues, or giving them only token consideration. There is a natural--flexible--order in the list. The objective of the strategy is to create not just a good design, but one near the ideal for the system.

Examine Corporate New Product Strategy

No one can expect to do high quality work in any area of mental endeavor without having a working knowledge of some background material. For engineers, obtaining this background material is one of the purposes of the introductory courses.

A designer needs to know and understand no only the basics of engineering and the technology associated with the product to be designed, but also why the enterprise wishes this product. The objective of the enterprise with regards to new products is usually some strategy to maximize profits over some period. When a product in development is not going to further that strategy, management generally acts to terminate development. The basic tenet being: know who your customers and potential customers are and satisfy their needs by selling the products.

There are many opportunities to develop and sell new products. One company can not successfully identify and exploit every opportunity. It is the venue of one segment of the marketing profession to analyze an enterprise and potential markets to devise a corporate marketing strategy. The methods of formulating this strategy is beyond the interests of this thesis. The reader is encouraged to seek in depth discussions of the basics of market strategy development from Buggie (1981), and Carson and Rickards (1979).

Identify Customer Needs

Unfortunately, even these first two items in this strategy are often performed by companies as a two step process. They designate a market they would like to be in and then search for customers for specific types of products.

Instead, the marketing concept contentions that companies should search for customer problems, the solution of which will follow the companies strategy to fulfill its goals. The preliminary selection of a company strategy will influence the customer problems investigated. The results of the preliminary customer problems investigations will in turn influence the formulation of a company strategy (Levitt, 1960).

Once there is a strong, recognized relationship between the corporate strategy and desired types of customer needs, some product ideas are necessary. There are four sources of ideas for new products or product enhancements: (1) customers, (2) in-house personnel (marketing and other) (3) outside consultants and designers, and (4) an understanding of customer's or potential customer's problems.

Companies often receive ideas for new products and product enhancements from customers and potential customers. Quick responses by a company can generate additional income and product ideas. In many industries though, companies believe they can not afford to react solely to prodding from customers or in-house personnel.

The actual techniques to search for customer needs are the venue of the marketing profession. The reader is urged to seek these out.

State the Design Problem Broadly

It is easy to not devote sufficient effort to the identification and proper statement of the customer's problem. The importance of the task is underscored by Powers and Rudd's (1974, p. 147) statement that in Chemical Engineering there are essentially two steps in the design process: stating the problem and searching for a solution. How the problem is stated has a tremendous bearing on how or whether the problem is solved.

All designers have all run across those little problems that when work is started on a solution, the problem just seems to mushroom. Experienced problem solvers learn to be wary of all problems. Lest the next one is like an iceberg with only its tip showing.

Needs are Seldom Problems

Designer's should be wary when presented with a problem. Even ones similar to many past development projects may be other than they look. True problems are rarely presented to the engineer. Rather, a list of symptoms and irrelevant data often fogs the picture.

To understand and subsequently develop a solution for the problem the engineer must be able to state the problem "to include as much of the total problem as the economics of the situation and organizational boundaries will permit" (Krick, 1969, p. 111).

As differentiated from customer need(s). As Krick (1969, p. 109) points out "the current solution to a problem is not the problem itself." That is to say the need perceived by the customer is often caused by a defect or inadequacy of the current solution to the real problem. A problem may have several solutions that have been used or implemented. These solutions may have errors, have inappropriate aspects, or be incomplete. These defects are commonly referred to as "problems." But, they are not the problem.

A Grainy Example

An example condensed from Krick (1969, pp. 108-112) probably will be helpful. The management of a large livestock feed distributor is concerned over high handling and storage costs. The company's operations include transporting grain to the mill, mixing it, bagging it, storing it, and finally transporting it to customers. To reduce costs an engineer is presented with the problem, floor plans for the mixing area and warehouses, equipment specifications, and process descriptions.

The natural tendency for engineers is to jump right in to the "problem." An engineer could look at bagging techniques, transportation methods for heavy sacks, material flows, or combining operations, among other possible improvements.

Generating possible solutions is exactly what not to do. People can quickly become engulfed in generating solutions. That should come later.

First the problem needs to be stated as broadly as possible. There are many ways of stating the feed distributor's problem. For example:

(1) Filling, weighting, stitching, and stacking sacks of feed.

(2) Transferring feed from the mixing bin (state A) to stacks of sacks in the warehouse (state B).

(3) Transferring feed from the mixing bin to stacks of sacks on the delivery truck.

(4) Transferring feed from the mixing bin to the delivery truck.

(5) Transferring feed from the mixing bin to the delivery medium.

(6) Transferring feed from the mixing bin to the customer's storage bins.

(7) Transferring feed from the ingredient storage bins to the customer's storage bins.

(8) Transferring feed from the producer to the consumer.

All of these statements of the problem are equally valid. They are not equally desirable, however. If each process in the current solution to this problem is treated as a separate problem, they can each be optimized. The result of individual optimization will most likely be far from optimal for the whole system.

Satisfying Needs Instead of Problems

A lot of money can also be made by addressing a customer need instead of the problem. One way is to sell a patch to fix another company's solution. Since the problem is probably still not solved completely and efficiently, the customer will have another need. If however, your company's previous solution is the cause of the need, then selling the customer a need reliever instead of a problem solution may upset them. Customers will be especially upset if they perceive your company makes more money by selling the patch.

Understand Customer Needs

It is not sufficient merely to identify a customer need. In order to effectively and efficiently satisfy the need also requires understanding it. The needs of the customer can seldom be understood fully and accurately by reading a request for product improvement or listening to a marketing presentation. The designer needs to think of the problem facing the customer in-depth, or better yet, talk to actual or potential customers to identify and understand their needs accurately. These needs will often not be what the customer thinks they are. This also can present a marketing problem if it is not obvious to potential customers that the new product is the solution to the underlying problem and the customer perceived need.

Designers Talking To Customers

A company with a long standing policy of having its designers talk to customers is InterMetro Industries, Inc. of Wilkes-Barre, Pa. InterMetro is a medium-sized, privately owned manufacturer of material handling and storage systems holding 126 patents. The company has achieved its worldwide leadership position in commercial shelving systems by aggressively seeking to understanding the needs and problems of its customers. To do this, InterMetro designers often spend more time talking to customers and experimenting with solutions than their marketing counterparts.

Understand Design Problem

As with the customer needs, the designer must understand the problem, not just state it broadly. Otherwise, the designer is hoping a miracle will occur sometime before the solution is implemented.

Design is not Problem Solving

To illustrate more clearly the importance of understanding the problem an interesting point is repeated from Bijl (1987, p. 9, 29). Bijl claims that design is not problem solving. The designer's problem is to find a solution the sponsoring organization can sell. The proceeds of the sale, temporarily at least, help to satisfy the organization's goal. In return the organization is willing to continue paying the designer to work. Meanwhile, the customer is hoping the product or service as designed and implemented will satisfy their need (and solve the problem).

The designer's problem is financial and/or social reward. The organization's problem is to generate revenue. Designing new or improved products is one solution to the organization's problem. If the organization chooses to sell products to solve its problem, then the design of products is an organizational need.

Thus, we can make the following conclusion. **Design is an activity whose successful achievement results in the solution of the customer's problem and need. But, the process of developing the solution for the customer is not the solution to the customer's problem.**

Identify System Factors and their Ranges

Typically at the launch of a product development process there exists a list of prioritize functional requirements and constraints for the product. Unfortunately, this list usually only contains the obvious functional factors.

Also important are the ranges of these factors. The desired ranges of the most important attributes and functions in a new product are usually identified. Unfortunately, there are also often a large number of attributes that are not very critical as long as they are kept within a range. Often these ranges are not identified and the penalty for a factor lying outside the range can be very high or even fatal for a product. All one must do to believe this is remember the Data General computer that did not fit in European elevators (Kidder, 1981). The entire computer had to be redesigned.

Determine Importance and Consequences of Factors

It is good to determine some relative importance between different factors in the product's design. Some methods, particularly AI based ones, suggest the rating of the different factors on a scale or the putting them in priority order. In either case a number is obtained to represent the relative importance of a factor to the others. Since a number now exists to rate the importance of the factor, equations can be created and numerical calculations performed.

The validity of the suggested design results should be examined cautiously. It is not clear to the author that the subjective assignment of numbers can be used as valid input to a rigid mathematical analysis. All the factors are not considered and the factors considered almost always are assumed to be independent, constant, linear functions.

It is also important to determine the consequences of not staying within the require range of the factors. Not only will this shed light on the importance of different factors, it also helps the designer make trade-offs which would send a factor out of its range.

Design the Solution Development Strategy

Much as a problem can be stated and solved in several different ways, there are different ways of developing a solution to the problem. Choosing between the methodologies presented in the detailed design optimization chapter and the strategy being presented is only one issue to be considered. Each problem is different and exists in a different system. The strategy for solving each problem deserves to receive attention sufficient to customize the strategy for attacking this problem.

An opposing (but, nonconflicting) point of view is offered by Schneider (1988). "This should not be allowed to take-up so much time the designing does not get done. If done correctly, designing the development process should save you time."

Design Development Organization

Along the same lines as designing the solution development strategy, the development organization should be designed. The development process is carried out by a socio-technical system. Optimizing this system to its task within the resource constraints applicable is an important task.

The weaknesses of the socio-technical system carrying out the development process can not be expected to be the strength of the product. Therefore, careful design and optimization of the development organization, both social and technical, for the project often has high dividends.

Unfortunately, proving the extent of the dividends is difficult. The degree of improvement is highly dependent on the project, organization, and fluctuations in countless factors. Measuring the benefits however, is not as important as receiving them.

Product (Not Just Functional) Requirements and Constraints

Every product is developed, manufactured and used in an environment with many requirements and constraints. There are many more than those traditionally listed as functional requirements. Many of the requirements will have nothing to do with the function of the product. They may however, have a greater impact on the success of the product than any of the listed functional constraints. Recognizing the requirements, constraints, and their relative importances will help the designer achieve a good balance in the product.

Explicitly Specify the Relationships

Specifying relationships occurs throughout the development process. The consideration of these relationships is most frequently skipped in designing enhanced products and products similar to existing ones. But, all development projects should benefit from the explicit statement of these relationships.

Explicitly specifying the minimum sets of flows, forces, forms, and motions necessary to appropriately solve the customer's problem reduces the likelihood of adding unnecessary components, subassemblies, or features to the product. If the designer feels another feature or function should be added, it is easier to determine the cost of adding it. This is because the associated costs and components are clearly identifiable for assessing costs and benefits. The designer can then make an appropriate trade-off. Measures are needed to determine the appropriateness of different alternatives.

Generate Product Concepts

There are many methods described in a number of publications on the subject. These methods include brainstorming, visual thinking, and lateral thinking (Hanks & Belliston, 1978 & 1980; Adams, 1980; Jones, 1980; Brochmann, 1982). Another useful reference for identifying natural factors that can be utilized is Physical Laws and Effects (Hiz & Riley, 1958).

Optimize Product Concepts

Although no systematic or structured method for doing this is currently available, a little thought and calculation in the concept phase can really pay off. Remember, a near ideal product concept is necessary for refinement into a near ideal product design.

Possibly helpful activities are analyzing the STRATEGY <--> NEED <--> FUNCTION <--> FLOW, FORCE, FORM, MOTION relationships, and applying Suh's axioms. Mathematics and Variational Geometry also might be helpful as a means of expressing relationships between items.

Evaluate Product Concepts

Brochmann (1982) states there are no set, all encompassing and never changing measures of what is a "good" design. Suh's axioms, Hanks and Belliston's SAFE, and Steelcase's criteria can serve as guides. The designer should also remember a correct balance is being sought for all the elements in the system.

Add Detail in Even Waves

To purely refine a near ideal concept into a near ideal product requires the careful addition of detail through a series of decisions. A haphazard approach is almost always fatal to the product. A less than careful approach results in a less than ideal product.

Ideal products result from informed decisions made at the appropriate time. The concept of part envelopes helps the designer determine the issues relative to a decision and whether a decision is currently appropriate. Decisions for which the time is not appropriate should be delayed.

Periodically Review Design and Process Purity

No process can be expected to perform flawlessly without supervision. Periodic design reviews are necessary to evaluate and maintain the project's focus. More often (almost constantly) the evolving product should be examined to ascertain its pure refinement from concept through final detail. Also important is the consistency of the relationship chain from corporate goals and customer problem to customer satisfaction and goal achievement.

A Holistic Development Strategy

Examine Corporate New Product Strategy

Identify Customer Needs

Understand Customer Needs

Understand Design Problem

Identify System Factors and their Ranges

Determine Importance and Consequences of Factors

Design the Solution Development Strategy

Design Development Organization

State Product (Not Just Functional) Requirements and Constraints

Explicitly Specify the Relationships

Generate Product Concepts

Optimize Product Concepts

Evaluate Product Concepts

Add Detail in Even Waves

Periodically Review Design and Process Purity

ORGANIZATIONS FOR PRODUCT DEVELOPMENT

There are two areas concerning organization and the development process. The first concerns the corporate organization. The second concerns the organization for a particular product development project. The primary interest for this thesis is on the project level where the most direct impact on development is felt. Only four corporate organization issues are discussed. The first half of the chapter presents three types of project organizations for product development.

Traditional Design Organization

Traditionally (in the last 40 years) individual designers created designs from a concept and list of functional requirements supplied by marketing specialists. The resulting design was reviewed by people from design, marketing, and possibly manufacturing. The review criteria were primarily form, fulfillment of functional requirements and estimated manufacturing cost. These criteria are now recognized as inadequate.

Due to this inadequacy, several proposals have been made for improving the design process. Although most proposals do not mention organization, I have classified them into three organizational types.

Three Organizational Types for Multiple Perspective Design

An investigation of project organizations for the design process revealed three types. They are: (1) design and review, (2) team design, and (3) a multiple perspective designer. The three types are described below along with their advantages and problems.

(1) Design and review

The design and review organization consists of two functional entities, designers and reviewers. Methods using this organization include: Design for Assembly (DFA), Design for Injection Molding, and Early Manufacturing Involvement (EMI). Particularly in the "Design for" methods, one person performs both functions. The evaluation can be intuitive, like EMI, or can use a special coding system, like DFA. The designer uses the evaluation results to modify and hopefully improve the product (Stoll, 1988).

Eventually, either the available design time runs out or the current design is declared acceptable. Often the review and redesign cycle stops after the easily recognizable improvements have been made. Unfortunately, there is no analytical way to determine whether the cycle should stop or continue.

The cycling between the design and review functions is shown by arrows in Figure 5. Other arrows represent the perspectives and input sources. In this type organization the arrows pointing at design usually represent the marketing and design functions. Those pointing at review represent manufacturing and quality control.

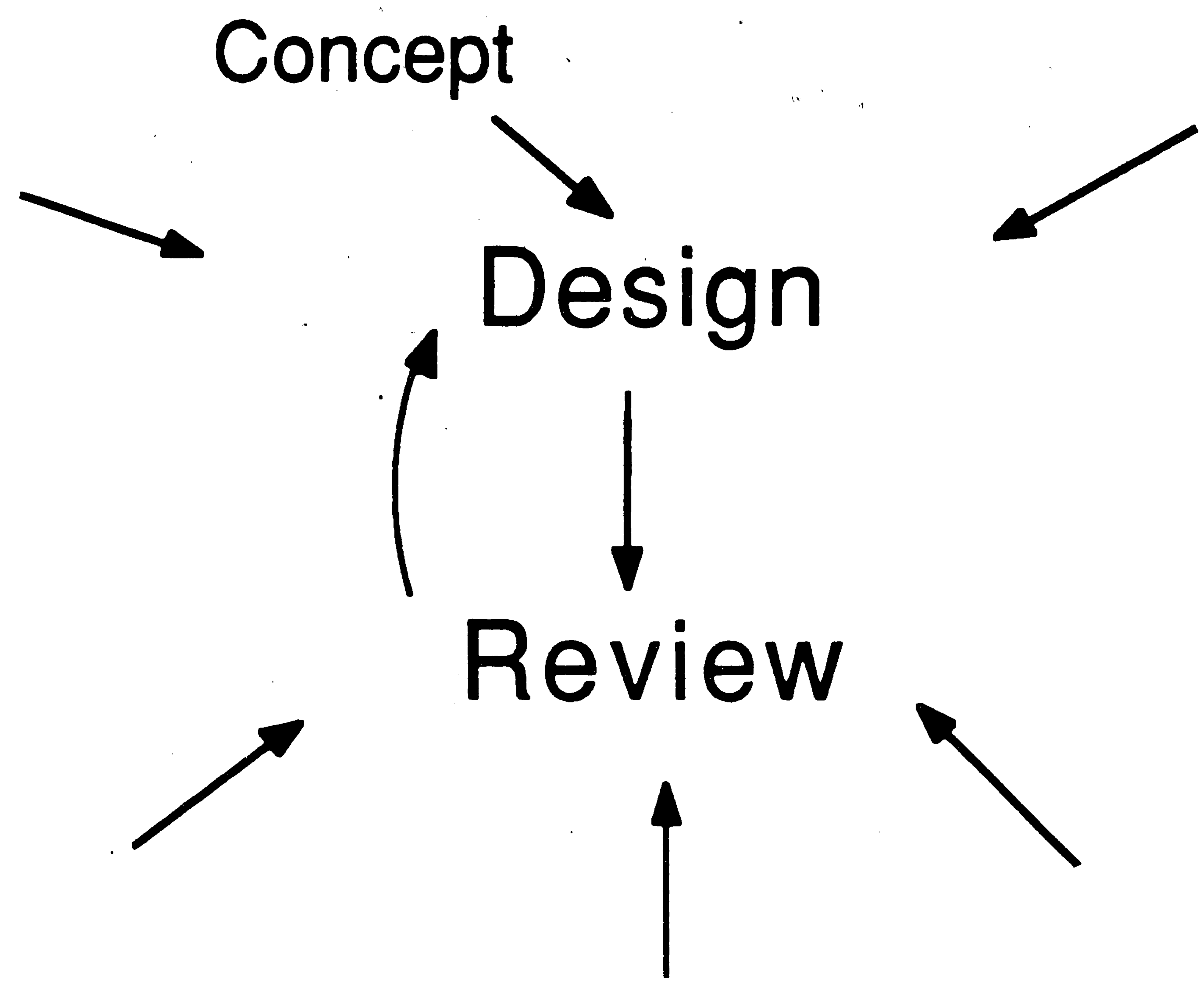

Figure 5. The Design and Review Organization

Proposed Organizational Improvements: The design and review organization is a modification of traditional design organization. Any of three changes have been proposed: (1) strengthening the existing review process by giving departments, particularly manufacturing, the power to reject a design; (2) making design reviews earlier and more often in the design process; or (3) teaching designers a rating method to evaluate designs. By making these organizational changes and performing the design and review cycle, a company can improve their designs.

Uncooperativeness in Design and Review: Unfortunately, design and review can develop quickly into an uncooperative atmosphere between design and other functions. This is particularly a problem between design and manufacturing where the traditional performance measurements conflict. Design is traditionally measured on the elapsed time before design release. Conversely, manufacturing is measured on calculated cost: much of which is determined in design or other functions.

(2) Team design

The team design approach shown in Figure 6 is not as common in the U.S. as the design and review approach. A design team is a group from two or more backgrounds or functions who are collectively responsible for producing a good design. Design team organizations are proposed by Simultaneous Engineering, Concurrent Engineering, and Total Quality Design teams (Evans, 1988). This the team approach that permeates Japanese organizations and society.

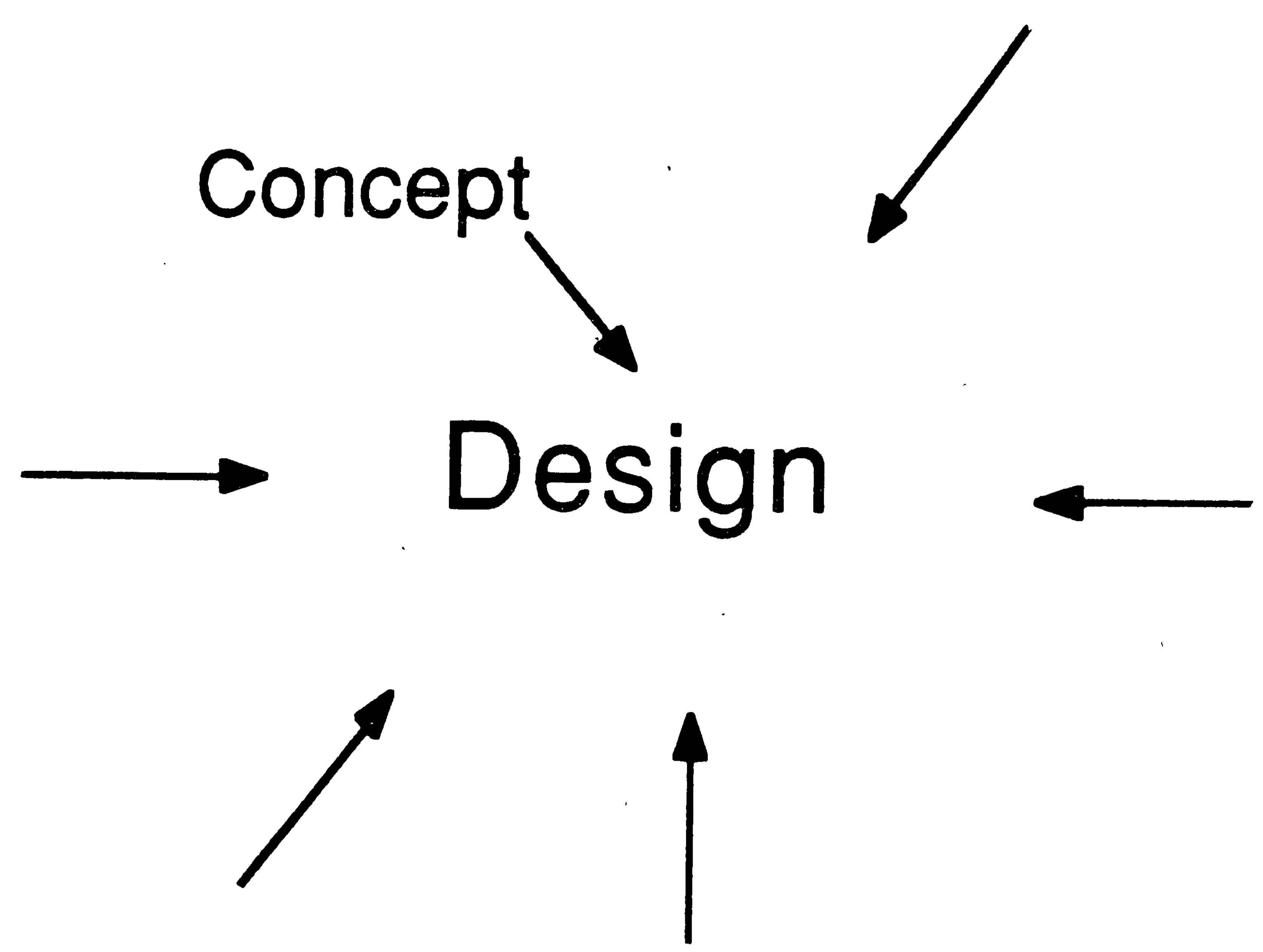

Figure 6. The Team Design Organization

Advantages of Team Design: Team design has three advantages over the design and review organization. The first is the interaction of team members from different functional areas. The diverse knowledge, perspectives and priorities the team members bring to the discussion helps rationalize the design from several perspectives.

The second advantage is interdepartmental cooperation. After contributing to group discussions and influencing the design, team members feel ownership in the design. This is especially true since team member's participation and approval reduces the need for review.

Finally, the third advantage is a reduction in lead time from design initiation to product shipment. The extra time required for a team to complete the design process is quickly repaid in concurrent planning and reduced problems in production.

Problems with Team Design: Unfortunately, a design team's advantages and problems both derive from forming a group. In a diverse team of individuals with conflicting goals, hostility can explode quickly--or simply simmer. A diverse team requires even more time and skill to work effectively than a homogeneous team. A team requires training in effective teamwork, along with a common goal, common performance measurements and responsibility. This also means complex management structures.

Other problems with design teams relate to practicalities and efficiencies. Due to the impracticality, or impossibility, of including at least one person representing every perspective, the design may not receive input from all interests. Other than a purely academic concern for complete design rationalization, the oversight of a seemingly small detail can be expensive. A classic example is the Data General computer which did not fit into European elevators. Not considering this detail involving distribution delayed sales and necessitated redesign (Kidder, 1981).

The design team's inefficiency stems from the increased personnel and resources required. Not only are more people required to design the product, but they also spend a good deal of the time communicating within the group and educating one another enough to allow communication.

(3) A multiple perspective designer

A third organizational type tries to avoid the problems of the previous organizations. With the design team, the problems stem from interaction of team members. This interaction also supplies the desired knowledge and perspectives. If one or two well trained individuals provide the desired perspectives, a specially structured database might supply most knowledge required; eliminating the interaction problem.

Another benefit appears from placing a more skilled designer in place of the group. The single designer, trained to look at all perspectives of a design can blend the concept, design, and review activities so the relationships between customer needs, product concepts and detailed designs can be viewed. The purpose of blending is to create the best product concept and constantly review from all perspectives its pure refinement into a detailed design. The multiple perspective designer organization in Figure 7 amounts to someone looking at everything--the whole system--from all angles. This is the only way of ensuring the design process will produce the best design for all conceivable issues.

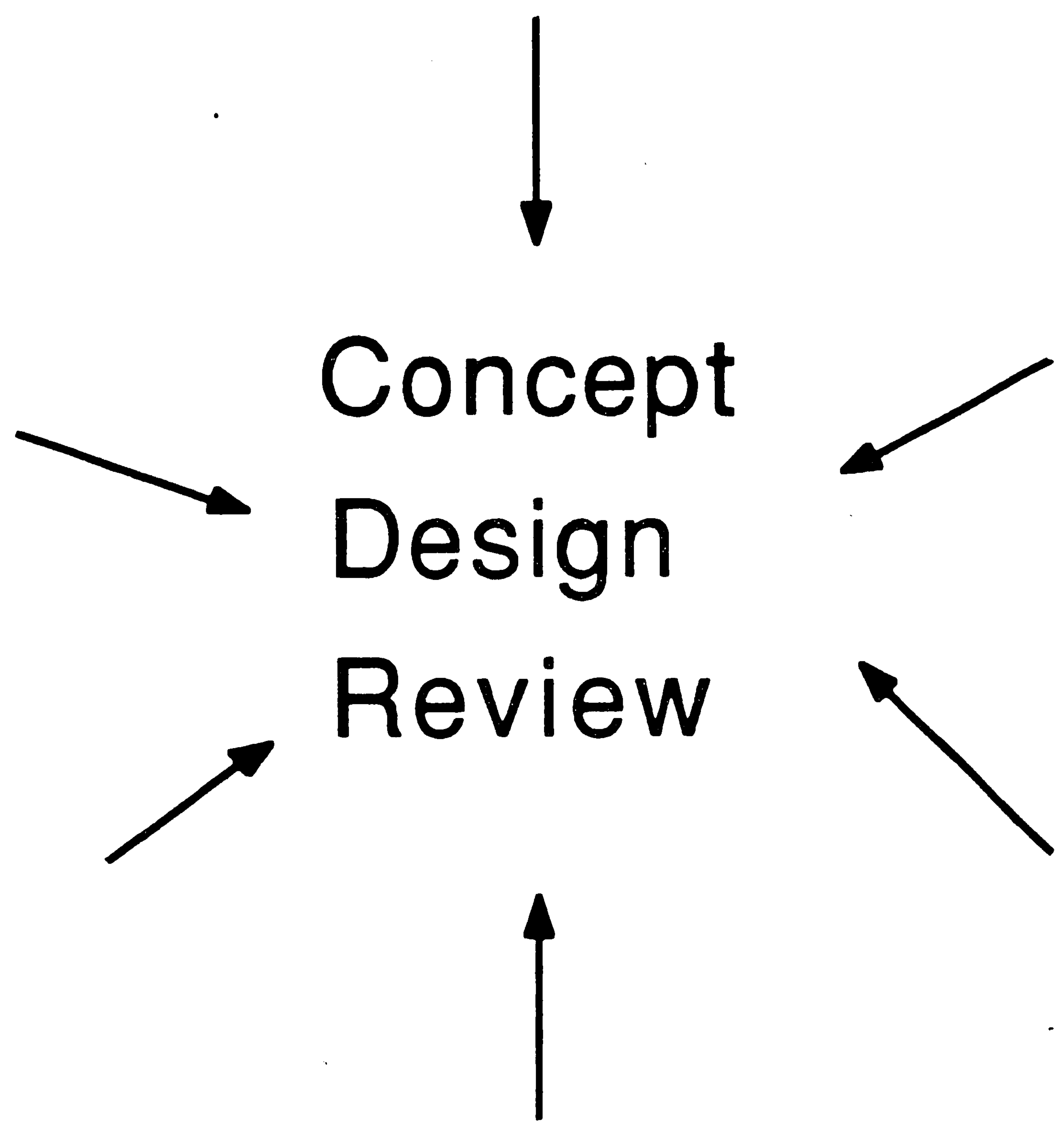

Figure 7. A Multiple Perspective Individual Organization

Why an Individual? Why can't this be done with a team? It can, except there are two drawbacks: (1) the team members interaction can slow or eliminate progress, and (2) having a team do what one or two designers can do with a little help is expensive in both time and money.

Implementation Problems: The problems with the multiple perspective designer organization are implementation.

(1) The required designers with multiple perspectives are in extremely short supply and not rapidly increasing.

(2) Current computer capabilities are inadequate to manage and correctly supply the necessary knowledge.

(3) The necessary knowledge has not been collected or must be put in the appropriate form.

(4) The organization is radically nontraditional and might receive considerable opposition.

Summary of Design Project Organizations

Of the three design organization types presented, design and review, is closest to traditional design organization. Therefore, a company can implement a design and review organization relatively quickly by allowing other functions, or a coding scheme, to reject or comment on designs. This also means the relations between design and other functions may become strained.

The second organizational type, team design, brings representatives from design and other functions together to design and prepare the product for sale jointly. Its major advantages are the multiple perspectives applied to the design process and improvement of interdepartmental relations.

The third organizational type is the multiple perspective designer. Here the multiple perspectives of the design team members are trained into a designer. This allows a unique ability to view the whole product and its environment to achieve a fit. The operating cost is less than a team design, and there is no risk of quarreling design teams. Unfortunately, designers with a systems perspective are in short supply, and the computer systems to help them may not currently be implementable.

Conclusions on Design Project Organizations

Paying attention to a process usually produces better results. This is true for design. By making some small organizational changes a company's designs can improve quickly if the company implements a design and review organization. To produce better results than a design and review organization a design team organization takes a longer time and is harder to implement.

With the increasing capabilities of computers, the relationship between computers and designers is apt to change drastically. The computer might eventually assume an intimate role in helping designers carryout their work. In the meantime, design teams are a good stepping stone.

Corporate-wide Product Development Issues

Four corporate-wide development issues are quickly addressed in the following subsections. Although these are not all the development issues related to corporate organization, they are the primary differences attributable to a holistic or systems perspective.

Team Approach

Even with one or two designers in the multiple perspective designer organization described previously, a team approach should exist throughout the organization. The organization achieves its goal by producing and selling a product or service. Everyone in the organization must trace their responsibly back toward carrying out this activity.

No Title or Department Separation

In attempting to carryout the production and sale of products or services, no individual who is making an effort to carryout the production and sales of products is independent of others in the organization. There must be team work for many individuals to carryout the many tasks efficiently and without conflict. Functional titles and departmental/disciplinary labels tend to segregate and impede individuals and groups from efficiently and effectively carrying out these tasks.

Measurements

Another traditional barrier to individuals and groups acting in the best interest of the sponsoring organization is the performance measurement system. To determine how "good" something is you must measure it against one or more standards. Individuals and organizations almost always act in what they believe is their own best interest. So, if employees know the measures their performance will be measured against, they will act to maximize their personal measures over those of the organization. Goldratt (1989, p. 1) has phrased this as, "Tell me how you'll measure me and I'll tell you what I'll do."

Creativity and Acumen in Mature Organizations

To successfully develop products requires both acumen and creativity. Creativity is the recombination or alteration of elements to produce something new. Acumen on the other hand is the application of sharp thinking to a problem. Acumen is the attribute emphasized in our current educational and business establishments. This creates a business enterprise that matures into doing best what it has always done and considering in the best tradition of bureaucracies, change, innovation, and uncertainty to be antithema (Buggie, 1981, p.1).

Summary

Interest in understanding and improving the development process has increased in the past several years. Increased competition has prompted many companies to realize their traditional development methods are inadequate. A primary reason is the use of parochial methodologies and perspectives.

The traditional perspectives on development, design philosophy and morphology, portray development as creating a plan by completing the phases of a decision cycle. Although these perspectives are true, they have no connection to the decisions designers constantly face. These theoretical perspectives lack the ties to detail necessary to form an inadequate basis for development methodologies.

Lacking a strong theoretical basis, the development methodologies being proposed have not revolutionized development. These proposed methods attempt to optimize small subsets of product details or to rearrange the human organization.

Three types of organizations can be envisioned for development projects. They are design and review, team design, and a multiple perspective individual. Design and review is the most traditional type. A design team has the advantages of:

(1) gaining diverse perspectives from the different members of the team,

(2) increased interdepartmental cooperation, and

(3) reducing lead time.

A multiple perspective individual, although rare, should be able to develop products more cost and time efficiently without the risk of quarreling design teams. Although the organization impacts the development process, an organization is not a method for carrying out a process.

The methods proposed to improve products by operating on the details are of two types. The first type concerns how details are added or manipulated in the development process. These methods are Group Technology, Features-based Design, Parametric Design, and Variational Geometry. These techniques are tools for shortening development time. They do not specifically try to improve products being developed.

The second type tries to optimize the product details for a small number of considerations. Since they attempt to optimize over a few considerations without any conceptual basis, they can not guide designers to consistently develop near ideal products.

To develop the near ideal products competition demands requires the pure refinement of a near ideal concept. To consistently perform this pure refinement requires considering all factors in the system and explicitly establishing the relationships between the factors. The primary, circular chain of relationships is

Enterprise Goals and Strategies <--> Customer Problem or Need

Customer Problem or Need <--> Requirements and Constraints

Requirements and Constraints <--> Flows, Forces, Flows and Motions

Flows, Forces, Flows and Motions <--> Components

This chain of relationships forms the basis for the development strategy presented. It is not a methodology because it is not a step-by-step recipe for development. Rather, the development strategy guides designers in considering the problem and the factors in a system. Then it guides them through the process of expanding and detailing the system. Constantly during this process the relationships used and being established are as explicit as possible.

Use of the strategy offered will not guarantee the development project will result in a successful product. The author offers this strategy though as a paradigm for increasing the consistency of developing successful products.

A Development Strategy

Examine Corporate New Product Strategy

Identify Customer Needs

State the Design Problem Broadly

Understand Customer Needs

Understand Design Problem

Identify System Factors and their Ranges

Determine Importance and Consequences of Factors

Design the Solution Development Strategy

Design Development Organization

State Product Requirements and Constraints

Explicitly Specify the Relationships

Generate Product Concepts

Optimize Product Concepts

Evaluate Product Concepts

Add Detail in Even Waves

Periodically Review Design and Process Purity

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VITA

Mark W. Hammond is the son Mr. and Mrs. Richard C. Hammond of Stroudsburg, PA. Born February 26, 1963, he graduated from Stroudsburg High School. He went on to receive his Bachelor of Science in Computer Engineering from Lehigh University in 1985.

During the next two years Mr. Hammond worked for Lehigh's Computer-Integrated Manufacturing (CIM) Laboratory. While at the CIM Lab he initiated, managed and participated in a wide variety of projects with industrial partners. The objectives involved the improvement of corporate operations through such activities as CAD/CAM system selection, customization and training; design of automated processes; and software development.

In 1988 Mr. Hammond entered Lehigh's Manufacturing Systems Engineering Graduate Program. A program to develop generalists who can guide appropriate change in organizations. The first organization Mr. Hammond joins upon graduation is InterMetro Industries, Inc. of Wilkes-Barre, PA.