Product design factors focus on the product's function, which is a description of what the object does. The importance of function to the designer is a major topic of this book. Related to the function are the product's form, materials, and manufacturing processes. Form includes the product's architecture, its shape, its color, its texture, and other factors relating to its structure. Of equal importance to form are the materials and manufacturing processes used to produce the product. These four variables—function, form, materials, and manufacturing processes—

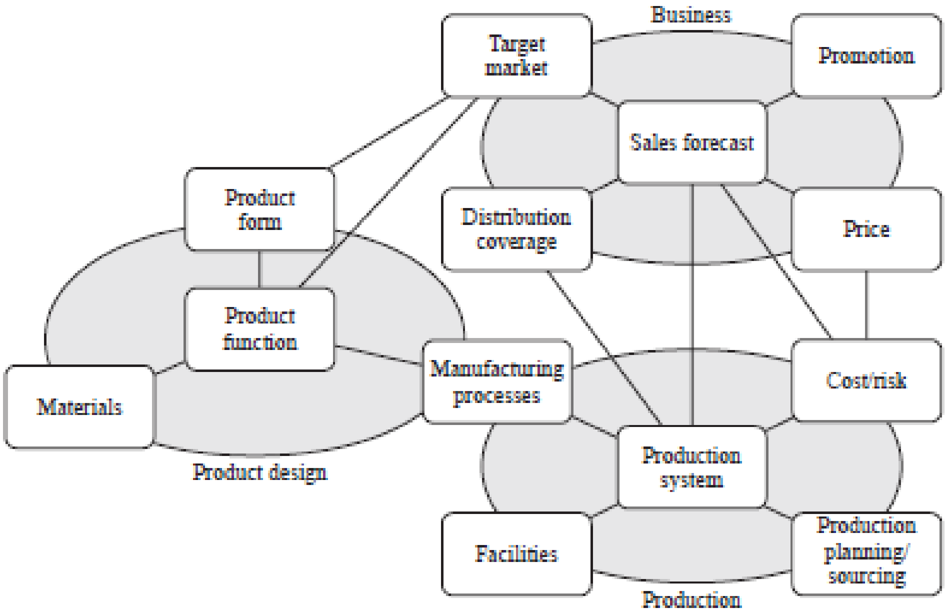


Figure 1.1 Controllable variables in product development.

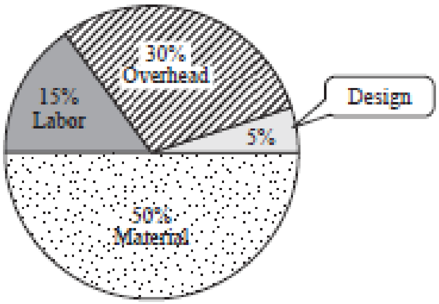


Figure 1.2 Design cost as fraction of manufacturing cost.

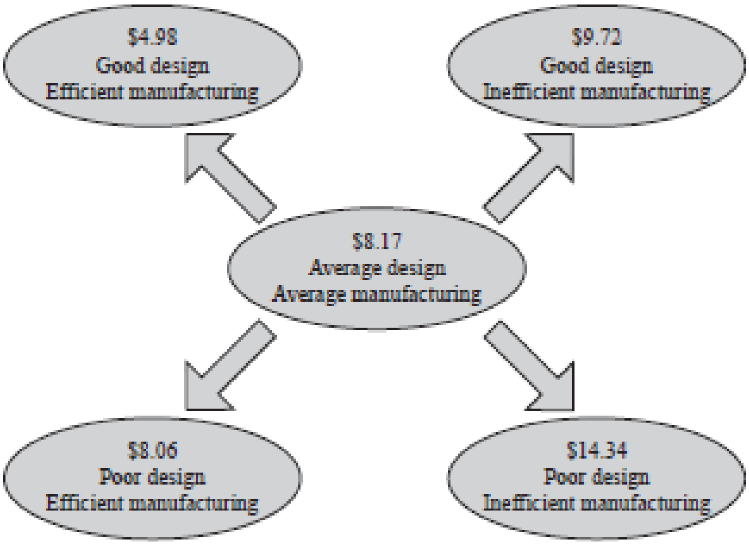


Figure 1.3 The effect of design on manufacturing cost.
(Source: Data reduced from "Assessing the Importance of Design through Product Archaeology," *Management Science*, Vol. 44, No. 3, pp. 352–369, March 1998, by K. Ulrich and S. A. Pearson.)

Designers cost little, their impact on product cost, great.

good design, regardless of manufacturing efficiency, cuts the cost by about 35%. In some industries this effect is as high as 75%.

Thus, comparing Fig. 1.2 to Fig. 1.3, we can conclude that *the decisions made during the design process have a great effect on the cost of a product but cost very little*. Design decisions directly determine the materials used, the goods

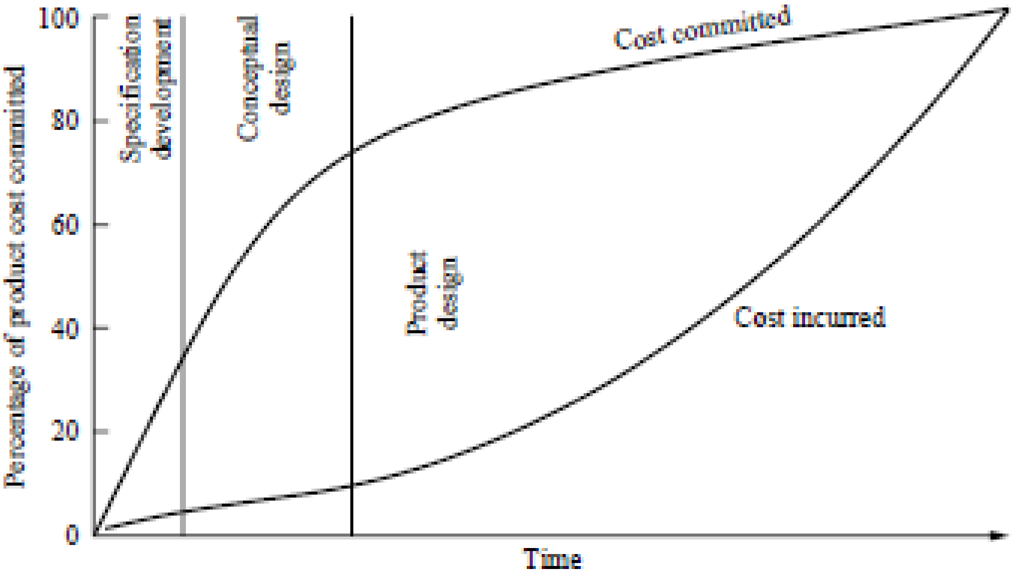


Figure 1.4 Manufacturing cost commitment during design.

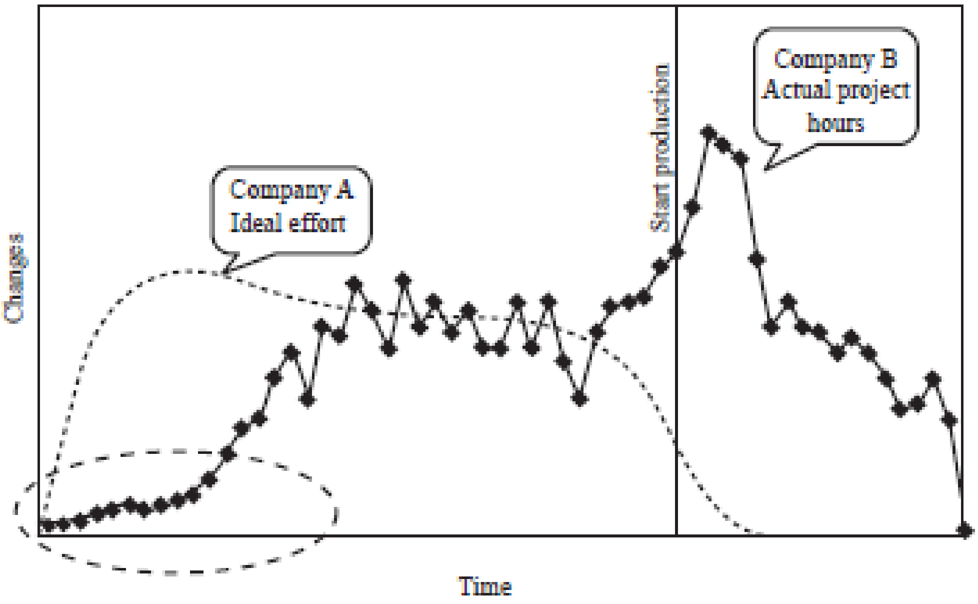


Figure 1.5 Engineering changes during automobile development.
(Source: Data from Tom Judd, Cognition Corp., "Taking DFSS to the Next Level," WCBF, Design for Six Sigma Conference, Las Vegas, June 2005.)

Fail early; fail often.

1.3 THE HISTORY OF THE DESIGN PROCESS

During design activities, ideas are developed into hardware that is usable as a product. Whether this piece of hardware is a bookshelf or a space station, it is the result of a process that combines people and their knowledge, tools, and skills to develop a new creation. This task requires their time and costs money, and if the people are good at what they do and the environment they work in is well structured, they can do it efficiently. Further, if they are skilled, the final product will be well liked by those who use it and work with it—the customers will see it as a quality product. *The design process, then, is the organization and management of people and the information they develop in the evolution of a product.*

In simpler times, one person could design and manufacture an entire product. Even for a large project such as the design of a ship or a bridge, one person had sufficient knowledge of the physics, materials, and manufacturing processes to manage all aspects of the design and construction of the project.

By the middle of the twentieth century, products and manufacturing processes had become so complex that one person no longer had sufficient knowledge or time to focus on all the aspects of the evolving product. Different groups of people became responsible for marketing, design, manufacturing, and overall management. This evolution led to what is commonly known as the "over-the-wall" design process (Fig. 1.6).

In the structure shown in Fig. 1.6, the engineering design process is walled off from the other product development functions. Basically, people in marketing communicate a perceived market need to engineering either as a simple, written request or, in many instances, orally. This is effectively a one-way communication and is thus represented as information that is "thrown over the wall."

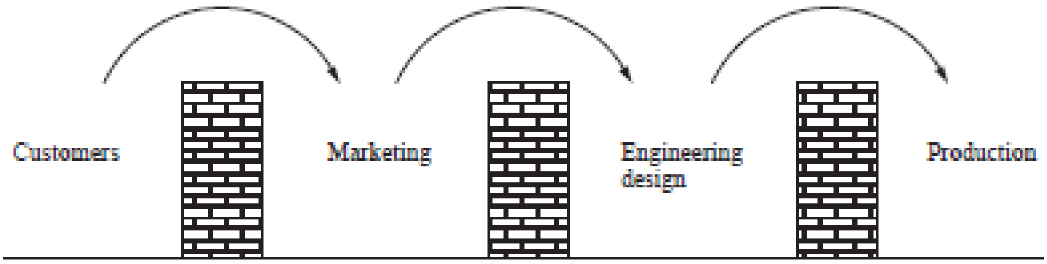


Figure 1.6 The over-the-wall design method.

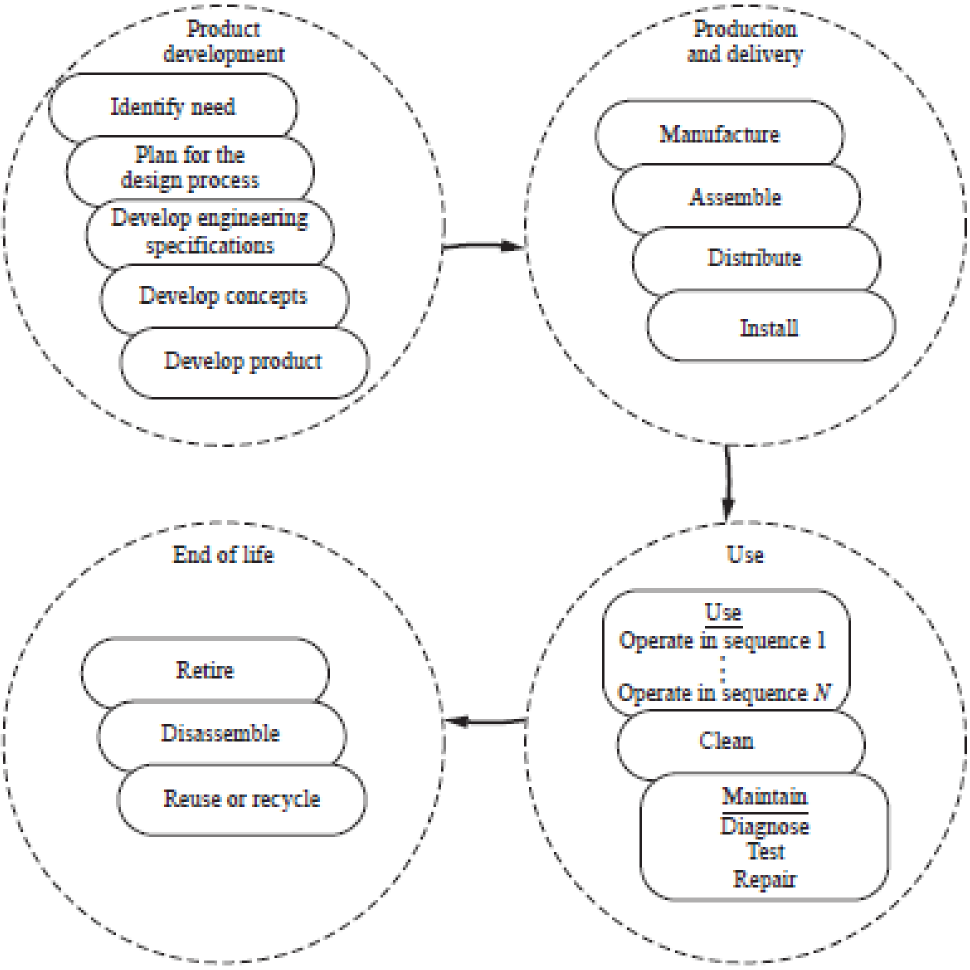


Figure 1.7 The life of a product.

The design process not only gives birth to a product but is also responsible for its life and death.

Plan for the design process. Efficient product development requires planning for the process to be followed. Planning for the design process is the topic of Chap. 4.

Develop engineering requirements. The importance of developing a good set of specifications has become one of the key points in concurrent engineering. It has recently been realized that the time spent evolving complete specifications prior to developing concepts saves time and money and improves quality. A technique to help in developing specifications is covered in Chap. 6.

Develop concepts. Chapters 7 and 8 focus on techniques for generating and evaluating new concepts. This is an important phase in the development of a product, as decisions made here affect all the downstream phases.

Develop product. Turning a concept into a manufacturable product is a major engineering challenge. Chapters 9–12 present techniques to make this a more reliable process. This phase ends with manufacturing specifications and release to production.

These first five phases all must take into account what will happen to the product in the remainder of its lifetime. When the design work is completed, the product is released for production, and except for engineering changes, the design engineers will have no further involvement with it.

The production and delivery phases include:

Manufacture. Some products are just assemblies of existing components. For most products, unique components need to be formed from raw materials and thus require some manufacturing. In the over-the-wall design philosophy, design engineers sometimes consider manufacturing issues, but since they are not experts, they sometimes do not make good decisions. Concurrent engineering encourages having manufacturing experts on the design team to ensure that the product can be produced and can meet cost requirements. The specific consideration of *design for manufacturing* and product cost estimation is covered in Chap. 11.

Assemble. How a product is to be assembled is a major consideration during the product design phase. Part of Chap. 11. is devoted to a technique called *design for assembly,* which focuses on making a product easy to assemble.

Distribute. Although distribution may not seem like a concern for the design engineer, each product must be delivered to the customer in a safe and cost-effective manner. Design requirements may include the need for the product to be shipped in a prespecified container or on a standard pallet. Thus, the design engineers may need to alter their product just to satisfy distribution needs.

Install. Some products require installation before the customer can use them. This is especially true for manufacturing equipment and building industry products. Additionally, concern for installation can also mean concern for how customers will react to the statement, "Some assembly required."

The goal of product development, production, and delivery is the use of the product. The "Use" phases are:

Operate. Most design requirements are aimed at specifying the use of the product. Products may have many different operating sequences that describe their use. Consider as an example a common hammer that can be used to put in nails or take them out. Each use involves a different sequence of operations, and both must be considered during the design of a hammer.

Clean. Another aspect of a product's use is keeping it clean. This can range from frequent need (e.g., public bathroom fixtures) to never. Every consumer has experienced the frustration of not being able to clean a product. This inability is seldom designed into the product on purpose; rather, it is usually simply the result of poor design.

Maintain. As shown in Fig. 1.7, to *maintain* a product requires that problems must be *diagnosed,* the diagnosis may require *tests,* and the product must be *repaired*.

Finally, every product has a finite life. End-of-life concerns have become increasingly important.

Retire. The final phase in a product's life is its retirement. In past years designers did not worry about a product beyond its use. However, during the 1980s increased concern for the environment forced designers to begin considering the entire life of their products. In the 1990s the European Union enacted legislation that makes the original manufacturer responsible for collecting and reusing or recycling its products when their usefulness is finished. This topic will be further discussed in Section 12.8.

Disassemble. Before the 1970s, consumer products could be easily disassembled for repair, but now we live in a "throwaway" society, where disassembly of consumer goods is difficult and often impossible. However, due to legislation requiring us to recycle or reuse products, the need to design for disassembling a product is returning.

Reuse or recycle. After a product has been disassembled, its parts can either be reused in other products or recycled—reduced to a more basic form and used again (e.g., metals can be melted, paper reduced to pulp again).

This emphasis on the life of a product has resulted in the concept of Product Life-cycle Management (PLM). The term PLM was coined in the fall of 2001 as a blanket term for computer systems that support both the definition or authoring of product information from cradle to grave. PLM enables management of this information in forms and languages understandable by each constituency in the product life cycle—namely, the words and representations that the engineers understand are not the same as what manufacturing or service people understand.

A predecessor to PLM was Product Data Management (PDM), which evolved in the 1980s to help control and share the product data. The change from "data" in PDM to life cycle in PLM reflects the realization that there is more to a product than the description of its geometry and function—the processes are also important.

As shown in Fig. 1.8, PLM integrates six different major types of information. In the past these were separate, and communications between the communities

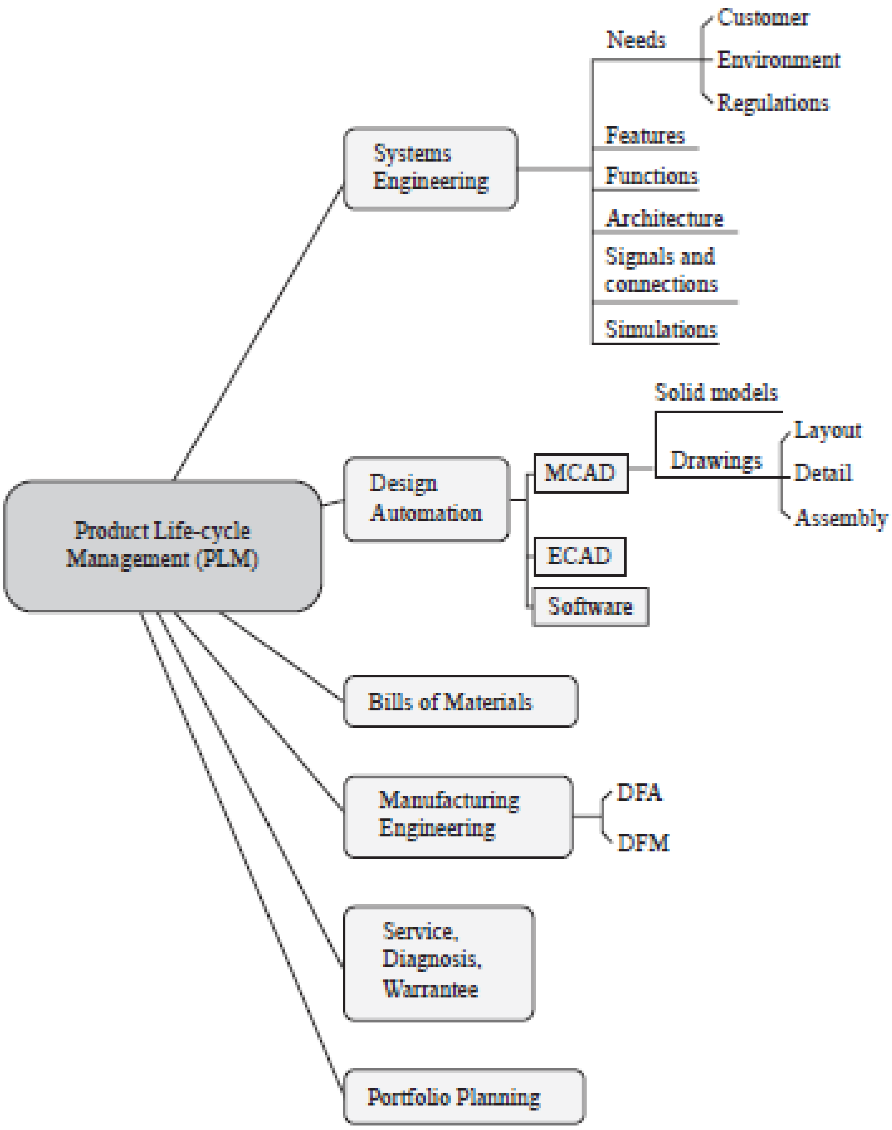


Figure 1.8 Product Life-cycle Management.

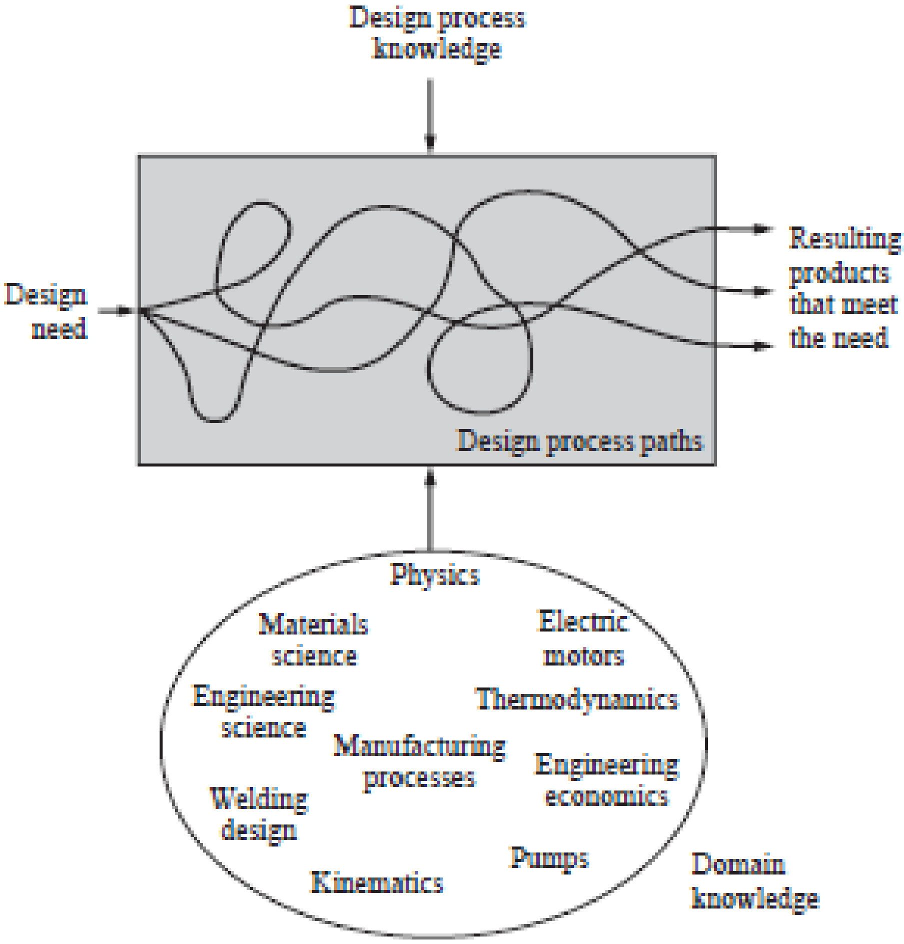


Figure 1.10 The many results of the design process.

1.6 THE BASIC ACTIONS OF PROBLEM SOLVING

Regardless of what design problem we are solving, we always, consciously or unconsciously, take six basic actions:

1. *Establish* the need or realize that there is a problem to be solved.
2. *Plan* how to solve the problem.

3. *Understand* the problem by developing requirements and uncovering existing solutions for similar problems.
4. *Generate* alternative solutions.
5. *Evaluate* the alternatives by comparing them to the design requirements and to each other.
6. *Decide* on acceptable solutions.

This model fits design whether we are looking at the entire product (see the product life-cycle diagram, Fig. 1.7) or the smallest detail of it.

These actions are not necessarily taken in 1-2-3 order. In fact they are often intermingled with solution generation and evaluation improving the understanding of the problem, enabling new, improved solutions to be generated. This iterative nature of design is another feature that separates it from analysis.

The list of actions is not complete. If we want anyone else on the design team to make use of our results, a seventh action is also needed:

7. *Communicate* the results.

The need that initiates the process may be very clearly defined or ill-defined. Consider the problem statements for the design of the simple lap joint of two pieces of metal given earlier (Fig. 1.9). The need was given by the problem statement in both cases. In the first statement, understanding is the knowledge of what parameters are needed to characterize a problem of this type and the equations that relate the parameters to each other (a model of the joint). There is no need to generate potential solutions, evaluate them, or make any decision, because this is an analysis problem. The second problem statement needs work to understand. The requirements for an acceptable solution must be developed, and then alternative solutions can be generated and evaluated. Some of the evaluation may be the same as the analysis problem, if one of the concepts is a bolt.

Some important observations:

- New needs are established throughout the design effort because new design problems arise as the product evolves. Details not addressed early in the process must be dealt with as they arise; thus, the design of these details poses new subproblems.
- Planning occurs mainly at the beginning of a project. Plans are always updated because understanding is improved as the process progresses.
- Formal efforts to understand new design problems continue throughout the process. Each new subproblem requires new understanding.
- There are two distinct modes of generation: concept generation and product generation. The techniques used in these two actions differ.
- Evaluation techniques also depend on the design phase; there are differences between the evaluation techniques used for concepts and those used for products.
- It is difficult to make decisions, as each decision requires a commitment based on incomplete evaluation. Additionally, since most design problems

are solved by teams, a decision requires consensus, which is often difficult to obtain.

- Communication of the information developed to others on the design team and to management is an essential part of concurrent engineering.

We will return to these observations as the design process is developed through this text.

1.7 KNOWLEDGE AND LEARNING DURING DESIGN

When a new design problem is begun, very little may be known about the solution, especially if the problem is a new one for the designer. As work on the project progresses, the designer's knowledge about the technologies involved and the alternative solutions increases, as shown in Fig. 1.11. Therefore, after completing a project, most designers want a chance to start all over in order to do the project properly now that they fully understand it. Unfortunately, few designers get the opportunity to redo their projects.

Throughout the solution process knowledge about the problem and its potential solutions is gained and, conversely, design freedom is lost. This can also be seen in Fig. 1.11, where the time into the design process is equivalent to exposure to the problem. The curve representing knowledge about the problem is a learning curve; the steeper the slope, the more knowledge is gained per unit time. Throughout most of the design process the learning rate is high. The second curve in Fig. 1.11 illustrates the degree of design freedom. As design decisions are made, the ability to change the product becomes increasingly limited. At the beginning the designer has great freedom because few decisions have been made and little capital has been committed. But by the time the product is in production,

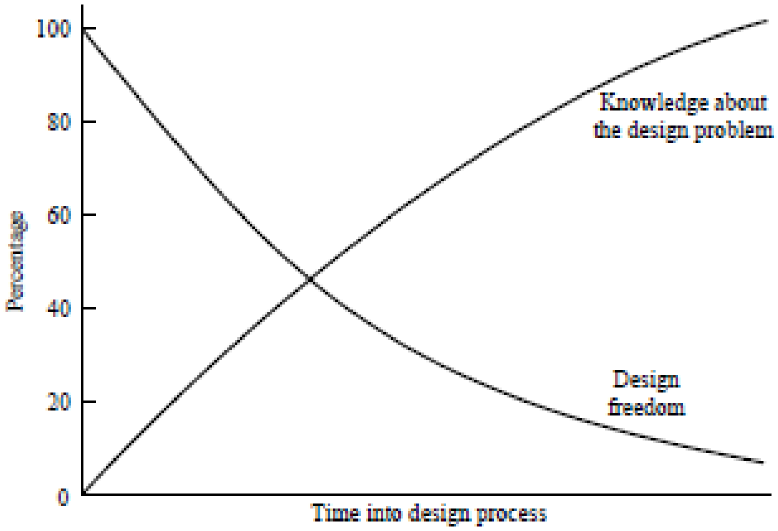


Figure 1.11 The design process paradox.

1.8 DESIGN FOR SUSTAINABILITY

It is important to realize that design engineers have much control over what products are designed and how they interact with the earth over their lifetime. The responsibility that goes with designing is well summarized in the Hannover Principles. These were developed for EXPO 2000, The World's Fair in Hannover, Germany. These principles define the basics of Designing For Sustainability (DFS) or Design For the Environment (DFE). DFS requires awareness of the short- and long-term consequences of your design decisions.

The Hannover Principles aim to provide a platform on which designers can consider how to adapt their work toward sustainable ends. According to the World Commission on Environment and Development, the high-level goal is "Meeting the needs of the present without compromising the ability of future generations to meet their own needs."

The Hannover Principles are:

1. **Insist on rights of humanity and nature to coexist** in a healthy, supportive, diverse, and sustainable condition.
2. **Recognize interdependence.** The elements of human design interact with and depend on the natural world, with broad and diverse implications at every scale. Expand design considerations to recognizing even distant effects.
3. **Accept responsibility for the consequences of design** decisions on human well-being, the viability of natural systems and their right to coexist.
4. **Create safe objects of long-term value.** Do not burden future generations with requirements for maintenance or vigilant administration of potential danger due to the careless creation of products, processes, or standards.
5. **Eliminate the concept of waste.** Evaluate and optimize the full life cycle of products and processes to approach the state of natural systems in which there is no waste.
6. **Rely on natural energy flows.** Human designs should, like the living world, derive their creative forces from perpetual solar income. Incorporate this energy efficiently and safely for responsible use.
7. **Understand the limitations of design.** No human creation lasts forever and design does not solve all problems. Those who create and plan should practice

humility in the face of nature. Treat nature as a model and mentor, not as an inconvenience to be evaded or controlled.

8. **Seek constant improvement by the sharing of knowledge.** Encourage direct and open communication between colleagues, patrons, manufacturers, and users to link long-term sustainable considerations with ethical responsibility, and reestablish the integral relationship between natural processes and human activity.
9. **Respect relationships between spirit and matter.** Consider all aspects of human settlement including community, dwelling, industry, and trade in terms of existing and evolving connections between spiritual and material consciousness.

We will work to respect these principles in the chapters that follow. We introduced the concept of "lean" earlier in this chapter as the effort to reduce waste (Principle 5). We will revisit this and the other principles throughout the book. In Chap. 11, we will specifically revisit DFS as part of Design for the Environment. In Chap. 12, we focus on product retirement. Many products are retired to landfills, but in keeping with the first three principles, and focusing on the fifth principle, it is best to design products that can be reused and recycled.

1.9 SUMMARY

The design process is the organization and management of people and the information they develop in the evolution of a product.

- The success of the design process can be measured in the cost of the design effort, the cost of the final product, the quality of the final product, and the time needed to develop the product.
- Cost is committed early in the design process, so it is important to pay particular attention to early phases.
- The process described in this book integrates all the stakeholders from the beginning of the design process and emphasizes both the design of the product and concern for all processes—the design process, the manufacturing process, the assembly process, and the distribution process.
- All products have a life cycle beginning with establishing a need and ending with retirement. Although this book is primarily concerned with planning for the design process, engineering requirements development, conceptual design, and product design phases, attention to all the other phases is important. PLM systems are designed to support life-cycle information and communication.

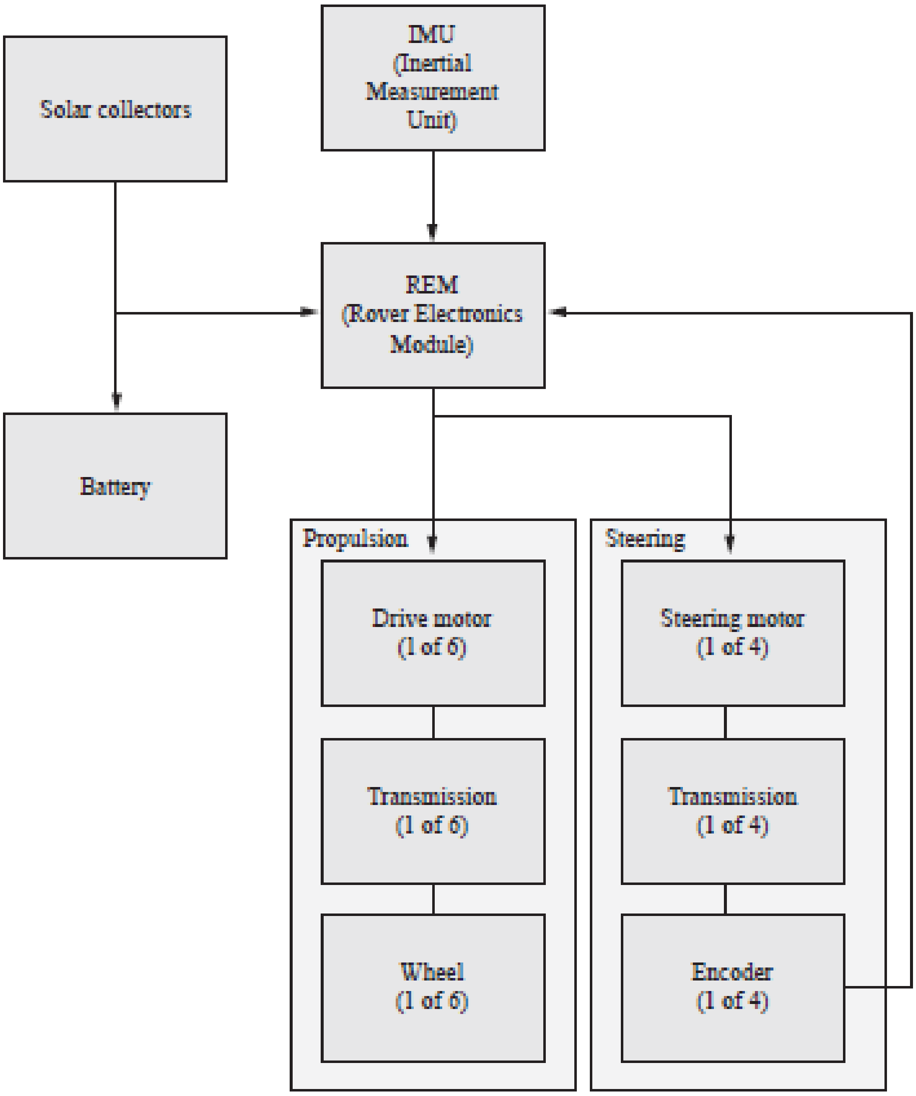


Figure 2.3 The MER Propulsion System showing some of the sub-systems and components.

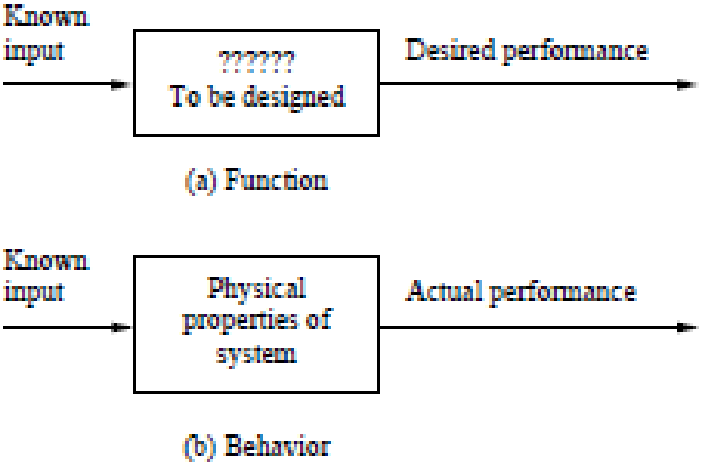


Figure 2.4 Function and behavior.

A skilled designer speaks many languages.

Extending this example further, if the component we are discussing is a bolt, then the word *bolt* is a textual (semantic or word) description of the component, a third language. Additionally, the bolt can be represented through equations (the final language) that describe its functionality and possibly its form. For example, the ability of the bolt to "carry shear stress" (a function) is described by the equation $\tau = F/A$; the shear stress τ is equal to the shear force F on the bolt divided by the stress area A of the bolt.

Based on this, we can use four different representations or languages to describe the bolt. These four can be used to describe any mechanical object:

Semantic. The verbal or textual representation of the object—for example, the word *bolt,* or the sentence, "The shear stress on the bolt is the shear force divided by the stress area."

Graphical. The drawings of the object—for example, scale representations such as solid models, orthogonal drawings, sketches, or artistic renderings.

Analytical. The equations, rules, or procedures representing the form or function of the object—for example, $\tau = F/A$.

Physical. The hardware or a physical model of the object.

In most mechanical design problems, the initial need is expressed in a semantic language as a written specification or a verbal request by a customer or supervisor. The result of the design process is a physical object. Although the designer produces a graphical representation of the product, not the hardware itself, all the languages will be used as the product is refined from its initial, abstract semantic representation to its final physical form.

Further complicating how we refer to objects being designed, consider two drawings for a MER wheel, as shown in Fig. 2.5. Figure 2.5*a* is a rough sketch, which gives only abstract information about the component. It centers on the

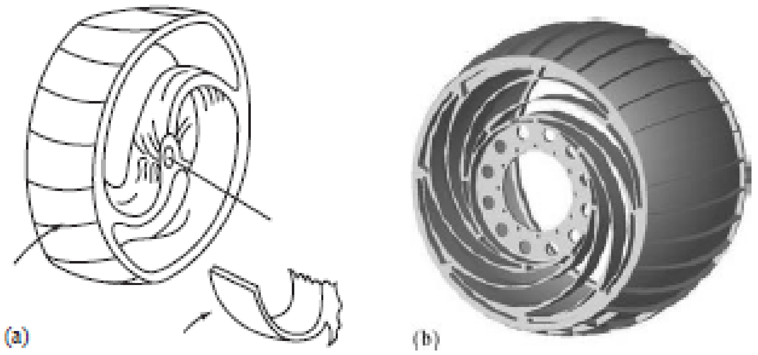
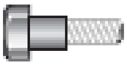
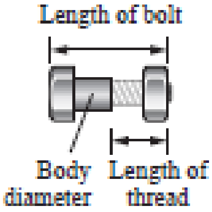
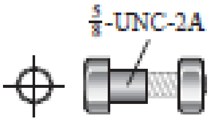
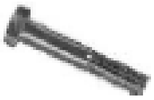


Figure 2.5 Abstract sketch and solid model of a MER wheel.

Table 2.1 Levels of abstraction in different languages

	Level of abstraction		
Language	**Abstract**	→	**Concrete**
Semantic	Qualitative words (e.g., *long, fast, lightest*)	Reference to specific parameters or components	Reference to the values of the specific parameters or components
Graphical	Rough sketches	Scale drawings	Solid models with tolerances
Analytical	Qualitative relations (e.g., *left of*)	Back-of-the-envelope calculations	Detailed analysis
Physical	None	Models of the product	Final hardware

Table 2.2 Levels of abstraction in describing a bolt

	Level of abstraction		
Language	**Abstract**	→	**Concrete**
Semantic	A bolt	A short bolt	A 1″ 1/4–20 UNC Grade 5 bolt
Graphical			
Analytical	Right-hand rule	$\tau = F/A$	$\tau = F/A$
Physical	—	—	

2.4 DIFFERENT TYPES OF MECHANICAL DESIGN PROBLEMS

Traditionally, we decompose mechanical engineering by discipline: fluids, thermodynamics, mechanics, and so on. In categorizing the types of mechanical design problems, this discipline-oriented approach is not appropriate. Consider, for example, the simplest kind of design problem, a selection design problem. Selection design means picking one (maybe more) item from a list such that the chosen item meets certain requirements. Common examples are selecting the correct bearing from a bearings catalog, selecting the correct lenses for an optical device, selecting the proper fan for cooling equipment, or selecting the proper heat exchanger for a heating or cooling process. The design process for each of these problems is essentially the same, even though the disciplines are very different. The goal of this section is to describe different types of design problems independently of the discipline.

Before beginning, we must realize that most design situations are a mix of various types of problems. For example, we might be designing a new type of consumer product that will accept a whole raw egg, break it, fry it, and deliver it on a plate. Since this is a new product, there will be a lot of *original design* work to be done. As the design process proceeds, we will *configure* the various parts. To determine the thickness of the frying surface we will analyze the heat conduction of the frying component, which is *parametric design*. And we will *select* a heating element and various fasteners to hold the components together. Further, if we are clever, we may be able to *redesign* an existing product to meet some or all of the requirements. Each of the italicized terms is a different type of design problem. It is rare to find a problem that is purely one type.

2.4.1 Selection Design

Selection design involves choosing one item (or maybe more) from a list of similar items. We do this type of design every time we choose an item from a catalog. It may sound simple, but if the catalog contains more than a few items and there are many different features to the items, the decision can be quite complex.

To solve a selection problem we must start with a clear need. The catalog or the list of choices then effectively generates potential solutions for the problem. We must evaluate the potential solutions with respect to our specific requirements to make the right choice. Consider the following example. During the process of designing a product, an engineer must select a bearing to support a shaft. The known information is given in Fig. 2.6. The shaft has a diameter of 20 mm (0.787 in.). There is a radial force of 6675 N (1500 lb) on the shaft at the bearing,

2.4.2 Configuration Design

A slightly more complex type of design is called configuration or packaging design. In this type of problem, all the components have been designed and the problem is how to assemble them into the completed product. Essentially, this type of design is similar to playing with an Erector set or other construction toy, or arranging living-room furniture.

2.4.3 Parametric Design

Parametric design involves finding values for the features that characterize the object being studied. This may seem easy enough—just find some values that meet the requirements. However, consider a very simple example. We want to design a cylindrical storage tank that must hold 4 m^3 of liquid. This tank is described by the parameters *r*, its radius, and *l*, its length and its volume is determined by

$$V = \pi r^2 l$$

Given a volume equal to 4 m^3, then

$$r^2 l = 1.273$$

We can see that an infinite number of values for the radius and length will satisfy this equation. To what values should the parameters be set? The answer is not obvious, nor even completely defined with the information given. (This problem will be readdressed in Chap. 10, where the accuracy to which the radius and the length can be manufactured will be used to help find the best values for the parameters.)

2.4.4 Original Design

Any time the design problem requires the development of a process, assembly, or component not previously in existence it calls for an original design. (It can be said that if we have never seen a wheel and we design one, then we have an original design.) Though most selection, configuration, and parametric problems are represented by equations, rules, or some other logical scheme, original design problems usually cannot be reduced to any algorithm. Each one represents something new and unique.

In many ways the other types of design problems—selection, configuration, and parametric—are simply constrained subsets of an original design. The potential solutions are limited to a list, an arrangement of components, or a set of related characterizing values. Thus, if we have a clear methodology for performing original design, we should be able to solve any design problem with a more limited set of potential solutions.

2.4.5 Redesign

Most design problems solved in industry are for the redesign of an existing product. Suppose a manufacturer of hydraulic cylinders makes a product that is 0.25 m long. If the customer needs a cylinder 0.3 m long, the manufacturer might lengthen the outer cylinder and the piston rod to meet this special need. These changes may require only parameter changes, or they may require something more extensive. What if the materials are not available in the needed length, or cylinder fill time becomes too slow with the added length? Then the redesign effort may require much more than parameter changes. Regardless of the change, this is an example of *redesign*, the modification of an existing product to meet new requirements.

2.4.6 Variant Design

Sometimes companies will produce a large number of variants as their products. A variant is a customized product designed to meet the needs of the customer. For example, when you order a new computer from companies such as Dell, you can specify one of three graphics cards, two battery configurations, three communication options, and two levels of memory. Any combination of these is a variant that is specifically tuned to your needs. Also, Volvo trucks estimates that of the 50,000 parts it has in its inventory it annually supplies over 5000 variants, different truck models specifically assembled to meet the needs of the customer.

2.4.7 Conceptual Design and Product Design

Two other terms that will be used throughout the book are *conceptual design* and *product design*. These are catchall terms for two parts of the product development process. First, you must develop a concept and then refine the concept into a product. The activities during the conceptual and product development phases may make use of original, parametric, and selection design and redesign as needed.

2.5 CONSTRAINTS, GOALS, AND DESIGN DECISIONS

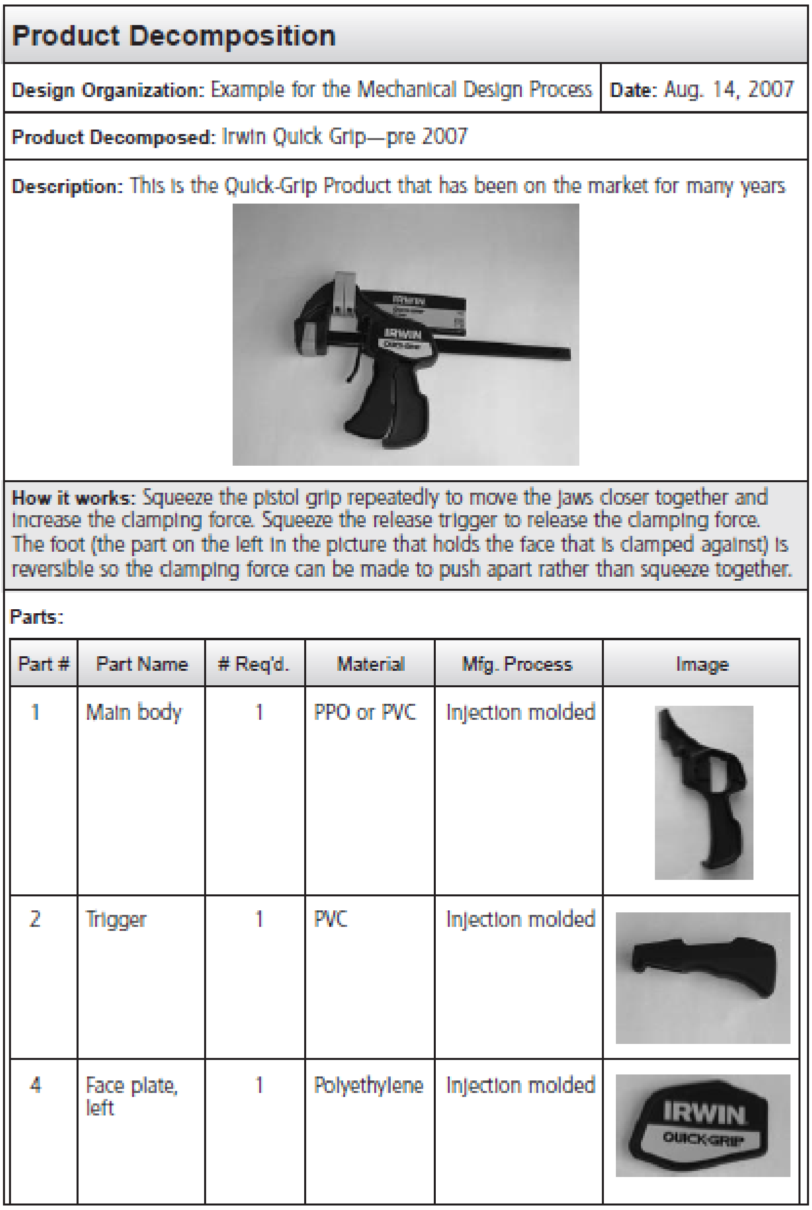
The progression from the initial need (the design problem) to the final product is made in increments punctuated by *design decisions*. Each design decision changes the *design state*. The state of a product is a snapshot of all the information known about it at any given time during the process. In the beginning, the design state is just the problem statement. During the process, the design state is a collection of all the knowledge, drawings, models, analyses, and notes thus far generated.

Two different views can be taken of how the design process progresses from one design state to the next. One view is that products evolve by a continuous comparison between the design state and the *goal,* that is, the requirements for the product given in the problem statement. This philosophy implies that all the requirements are known at the beginning of the design problem and that the difference between them and the current design state can be easily found. This difference controls the process. This philosophy is the basis for the methods in Chap. 6.

Another view of the design process is that when a new problem is begun, the design requirements effectively constrain the possible solutions to a subset of all possible product designs. As the design process continues, other *constraints* are added to further reduce the potential solutions to the problem, and potential solutions are continually eliminated until there is only one final design. In other

2.6 PRODUCT DECOMPOSITION

We will conclude this chapter with a method that can is the basis for understanding existing products. As such, it can serve as a starting point whether doing redesign, original design, or some other type of design, whether at the system or subsystem level. This *product decomposition* or "benchmarking" method helps us understand how a product is built, its parts, its assembly, and its function. It cannot be overemphasized how important it is to do decomposition and how it is the starting place for all design. In this chapter, we will decompose to understand the parts and assembly. In Chap. 7, the decomposition begun here will be extended to understand function.



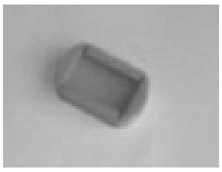
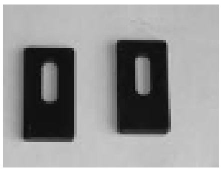
Product Decomposition

Design Organization: Example for the Mechanical Design Process	**Date:** Aug. 14, 2007
Product Decomposed: Irwin Quick Grip—pre 2007	
Description: This is the Quick-Grip Product that has been on the market for many years	

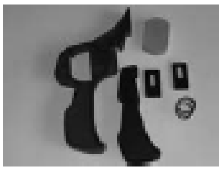
How it works: Squeeze the pistol grip repeatedly to move the jaws closer together and increase the clamping force. Squeeze the release trigger to release the clamping force. The foot (the part on the left in the picture that holds the face that is clamped against) is reversible so the clamping force can be made to push apart rather than squeeze together.

Parts:

Part #	Part Name	# Req'd.	Material	Mfg. Process	Image
1	Main body	1	PPO or PVC	Injection molded	
2	Trigger	1	PVC	Injection molded	
4	Face plate, left	1	Polyethylene	Injection molded	

Part #	Part Name	# Req'd.	Material	Mfg. Process	Image
8	Pad	2	??	Injection molded	
13	Power spring	1	Steel	Wound wire	
14	Jam plates	2	Steel	Stamped sheet	

Disassembly:

Step #	Procedure	Part #s removed	Image
1	Take off left face plate	4	
12	Remove jam plates and power spring from main body assembly	13, 14, 1	
13	Remove trigger from main body assembly	2	
14	Pry off pad from main body assembly	8	

The Mechanical Design Process Designed by Professor David G. Ullman

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Figure 2.11 Product decomposition samples for an older version of the Irwin Quick-Grip. (Photos reprinted with permission of Irwin Industrial Tools.)

2.7 SUMMARY

- A product can be divided into functionally oriented operating *systems*. These are made-up of mechanical *assemblies*, electronic circuits, and computer programs. Mechanical assemblies are built of various *components*.
- The important form and function aspects of mechanical devices are called *features*.
- Function and behavior tell *what* a device does; form describes *how* it is accomplished.
- Mechanical design moves from function to form.
- One component may play a role in many functions, and a single function may require many different components.
- There are many different types of mechanical design problems: selection, configuration, parametric, original, redesign, routine, and mature.
- Mechanical objects can be described semantically, graphically, analytically, or physically.
- The design process is a continuous constraining of the potential product designs until one final product evolves. This constraining of the design space is made through repeated decisions based on comparison of design alternatives with design requirements.
- Mechanical design is the refinement from abstract representations to a final physical artifact.
- Product dissection is a useful way to understand the structure of a product.

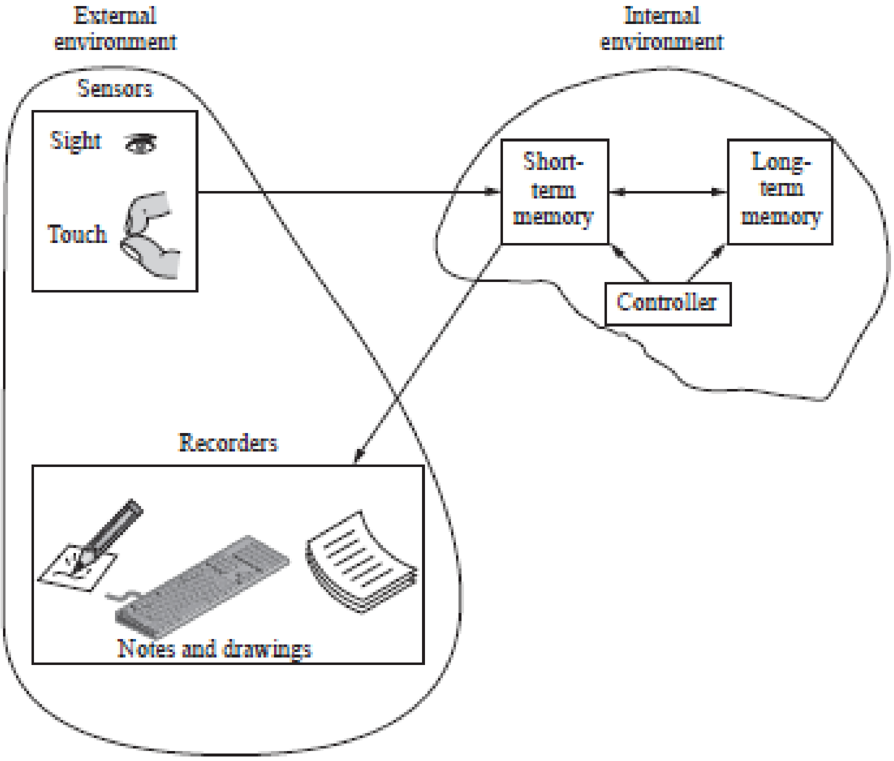


Figure 3.1 The human problem solver.

- *General knowledge,* information that most people know and apply without regard to a specific domain. For example, red is a color, the number 4 is bigger than the number 3, an applied force causes a mass to accelerate—all exemplify general knowledge. This knowledge is gained through everyday experiences and basic schooling.
- *Domain-specific knowledge,* information on the form or function of an individual object or a class of objects. For example, all bolts have a head, a threaded body, and a tip; bolts are used to carry shear or axial stresses; the proof stress of a grade 5 bolt is 85 kpsi. This knowledge comes from study and experience in the specific domain. It is estimated that it takes about ten years to gain enough specific knowledge to be considered an expert in a domain. Formal education sets the foundation for gaining this knowledge.
- *Procedural knowledge,* the knowledge of what to do next. For example, if there is no answer to problem X, then decomposing X into two independent easier-to-solve subproblems, X1 and X2, would illustrate procedural knowledge. This knowledge comes from experience, but some procedural knowledge is also based on general knowledge and some on domain-specific knowledge. We must often make use of procedural knowledge to solve mechanical design problems.

3.3.2 Generating Solutions

We have seen that in trying to understand a design problem, we compare the problem to information from the long-term memory. In order to retrieve information from the long-term memory, we need a way to index the knowledge stored there. We can index that information in many ways (Fig. 3.4). As in the gearbox example at the beginning of this chapter, the most efficient indexing method is by function. What are recalled and downloaded to the short-term memory are specific (usually abstract) visual images from past experience. Thus, we search by function and recall form or graphical representations. This is not always true: we can also index our memory by shape, size, or some other form feature. However, in solving design problems, function is usually the primary index. For some problems the information recalled meets all the design requirements and the problem is solved.

If, in understanding a problem, we must recall images of previous designs, we have a predisposition to use these designs. Some designers get stuck on these initially recalled images and have difficulty evaluating them objectively and generating other, potentially better ideas. Many of the techniques discussed in Chaps. 7 and 11 are specifically designed to overcome this tendency.

On the other hand, what happens if the problem being solved is new and we find no solution to it in the long-term memory? We then use a three-step approach: decompose the problem into subproblems, try to find partial solutions to the subproblems, and finally recombine the subsolutions to fashion a total solution. The subproblems are generally functional decompositions of the total problem. The creative part of this activity is in knowing how to decompose and recombine cognitive chunks.

3.3.3 Evaluating Solutions

Often people generate ideas but have no ability to evaluate them. Evaluation requires comparison between generated ideas and the laws of nature, the capability of technology, and the requirements of the design problem itself. Comparison, then, necessitates modeling the concept to see how it performs with respect to these measures. The ability to model is usually a function of knowledge in the domain. We will address evaluation techniques in Chaps. 8, 10, and 11.

3.3.4 Deciding

At the end of each problem-solving activity, a decision is made. It may be to accept an idea that was generated and evaluated, or more likely, it will be to address another topic that is related to the problem. The rationale for how decisions are made is not well understood, but Sections 3.3.5 and 3.3.6 should help clarify what is known.

3.3.5 Controlling the Design Process

To understand how designers progress through a design problem, subjects were videotaped as they worked. In the study of these videotapes, it became evident that the path from initial problem presentation to solution was not very straightforward. It seemed like an almost random process—efforts on a subproblem made the designer aware of another subproblem, and the designer then focused attention on this second problem without having solved the first. No model for the control of focus was found. However, it was clear that the process for some designers is so chaotic that they never find solutions to their problems, while other designers rapidly proceed through the design effort. The techniques discussed in this book are intended to give structure to the design process so that the path from problem statement to solution is as controlled and direct as possible.

3.3.6 Problem-Solving Behavior

Everybody has a unique manner of problem solving. A person's problem-solving behavior affects how decisions are made individually and has a significant impact on team effectiveness. The following discussion is centered around five personal problem-solving dimensions. These five are useful for describing how an individual solves a design problem because they describe an individual's information management and decision-making preferences. Since all the team members bring their individual problem-solving processes to team activities, it is the interaction of all the individuals' solution processes that determines the team's health. For each of the five dimensions, suggestions for how to counteract extreme behavior are given. Some of these are useful to the individual working alone, and all are important in team situations and will be referenced later in the chapter when we talk about team health. A template for easily evaluating your problem-solving

- Externals need to allow others time to think. Point out to them that it is not necessary to fill in all the pauses with words.
- Externals need to practice listening to the ideas and suggestions of others and pausing before they react. Brainstorming or another creativity-support activity can help here (see Section 7.4).
- Encourage externals to recap what has been said to make sure they have heard the contributions of others.
- Externals need to realize that silence does not always mean consent. Sometimes an external will overwhelm the internals, who will become quiet rather than argue the point.

Here are some suggestions to assist internals in getting their ideas out for consideration:

- Encourage internals to share more than their final response. There is value in thinking out loud, as even the most trivial idea may be part of a good solution. The process will judge the value of the ideas.
- Try suggesting techniques that enable internals to have an equal say in selecting ideas and plans, such as the techniques in Chaps. 5–12.

- Encourage internals to develop some nonverbal, body-language signals that indicate assent or dissent. Make sure that these signals are understood by other team members.
- Encourage internals to restate their ideas. This restating signifies to the internal that his or her ideas count and forces the externals to listen.
- Get internals to push externals for more clarity and meaning.

- Encourage objective team members to pay attention to the feelings of others. Gut feelings are often right, and sometimes a lack of information forces one to rely on these feelings.
- Help objective team members understand that how the team functions is as important as what is accomplished. If there is acrimony, no decisions will be made.
- Remind objective team members that not everyone likes to discuss a topic merely for the sake of argument. Others may drop out from exhaustion and be taken to be conceding the point.
- Encourage objective team members to express how they feel about the outcome once in a while. Objective decision-makers may have trouble expressing feelings.

  - Give flexible decision-makers plans in advance so that they can think about them in their own time.
  - Acknowledge the flexible decision-maker's contribution as a step toward moving to closure. Remind them that problems are solved one step at a time.
  - Set clear decision deadlines in advance.
  - Encourage feedback from flexible decision-makers so that they can think about the direction of their thoughts.
  - Encourage flexible decision-makers to settle on something and live with it a while before redesigning. Encourage them to take a clear position and stick to it. This may be difficult for them to do.

- Ask decisive people questions about their decision process. Remind them that most problems need to be subdivided into smaller problems to be solved.
- Let decisive people organize the data collection and review process.
- Utilize techniques, such as brainstorming, that suppress judgment. Do not let them settle on the first good idea they hear.
- Remind decisive people that they are not always right.

3.4 CHARACTERISTICS OF CREATORS

Creativity and intelligence. There appears to be little correlation between creativity and intelligence.

Creativity and visualization ability. Creative engineers have good ability to visualize, to generate and manipulate visual images in their heads. We have seen before that people represent information in their minds in three ways: as semantic information (words), as graphical information (visual images), and as analytical information (equations or relationships). Words and equations convey serial information. They are generally understood on the basis of word order or the order of variables and constants. Pictures, or visual images, on the other hand, contain parallel information—you can see many different

Creativity and knowledge. The model of the information-processing system implies that all designers start with what they know and modify this to meet the specific problem at hand. At every step of the way, the process involves small movements away from the known, and even these small movements are anchored in past experience. Since creative people form their new ideas out of bits of old designs, they must retain a storehouse of images of existing mechanical devices in their long-term memory. Thus, in order to be a creative mechanical designer, a person must have knowledge of existing mechanical products.

Additionally, part of being creative is being able to evaluate the viability of ideas. Without knowledge about the domain, the designer cannot evaluate the design. Knowledge about a domain is only gained through hard work in that domain. Thus, a firm foundation in engineering science is essential to being a creative designer of mechanical devices. For example, during World War II many people sent ideas for weapons to the Department of War. Some were very far-fetched ideas for death rays or for building 5-mile-high walls or domes over Europe to stop the bombers. These were very original but unworkable and were therefore not creative. The "inventors" had good intentions but lacked the knowledge to develop creative solutions to the war problems.

Creativity and partial solution manipulation. Since new ideas are born from the combination of parts of existing knowledge, the ability to decompose and manipulate this knowledge seems to be an important attribute of a creative designer. This attribute, more than any other so far discussed, appears to become stronger with exercise. Although there is no scientific evidence to support this contention, anecdotal evidence does support it.

Creativity and risk taking. Another attribute of creative engineers is the willingness to take an intellectual chance. Fear of making a mistake or of spending time on a design that in the end does not work is characteristic of a noncreative individual. Edison tried hundreds of different lightbulb designs before he found the carbon filament.

Creativity and conformity. Creative people also tend to be nonconformists. There are two types of nonconformists: constructive nonconformists and obstructive nonconformists. Constructive nonconformists take a stand because they think they are right. Obstructive nonconformists take a stand just to have an opposing view. The constructive nonconformist might generate a good idea; the obstructive nonconformist will only slow down the design progress. Creative engineers are constructive nonconformists who may be hard to manage since they want to do things their own way.

Creativity and technique. Creative designers have more than one approach to problem solving. If the process they initially follow is not yielding solutions, they turn to alternative techniques. A number of books listed in Section 3.7 give methods to enhance creativity. Many of the techniques covered in these are woven into the mechanical design techniques presented in the remainder of this book. This is especially true in the chapters on concept and product generation (Chaps. 7 and 9).

Creativity and environment. If the work environment allows risk taking and nonconformity and encourages new ideas, creativity will be higher. Further, if teammates and other colleagues are creative, the environment for creativity is greatly enhanced. In the discussion of teams in Section 3.5, it is stated that, on a team, the sum is greater than the parts. This is especially true for creativity.

Creativity and practice. Creativity comes with practice. Most designers find that they have creative phases in their careers—periods when they have many good ideas. During these times the environment is supportive and one good idea builds on another. However, even with a supportive environment, practice enhances the number and quality of ideas.

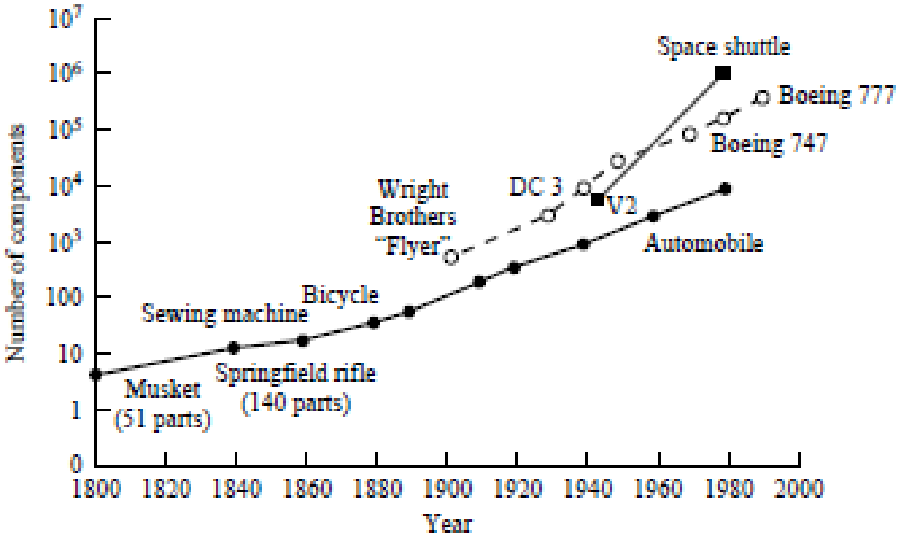


Figure 3.10 Increasing complexity in mechanical design.

1. Teamwork is central to success in engineering as most problems are made of many interdependent subparts, all of which must be solved concurrently. Teams bring together complementary skills and experiences, which are needed to solve many engineering problems.
2. Management takes risks in forming teams as a team must be empowered to make decisions, removing this responsibility from the management.
3. Teams establish communication to support real-time problem solving.
4. Teams develop decisions by consensus rather than by authority. This leads to more robust decisions.

> A team is a group of people in search of a common understanding.

However, there are some important differences.

- Team members must learn how to *collaborate* with each other. Collaboration means more than just working together—it means getting the most out of other team members. The suggestions that follow help develop a collaborative team.
- Teams are generally empowered to make decisions. Since these are team decisions, members must *compromise* to reach them. Empowering teams to make these decisions means that management takes a risk in giving up responsibility for them. Further, developing decisions by *consensus* rather than by authority leads to more robust decisions.
- Team members must establish *communication* to support real-time problem solving. Further, members need to ensure that the others have the same understanding of design ideas and evaluations that they have. It is very difficult for people with different areas of expertise to develop a shared vision of the problem and its potential solutions. Developing this shared vision requires the development of a rich understanding of the problem.
- It is important that team members and management be *committed* to the good of the team. If they are not, it will be difficult reaching the other team goals.

Product design engineer. The major design responsibility is carried by the product design engineer (hereafter referred to as the *design engineer*). This individual must be sure that the needs for the product are clearly understood and that engineering requirements are developed and met by the product. This usually requires both creative and analytical skills. The design engineer must bring knowledge about the design process and knowledge about specific technologies to the project. The person who fills this position usually has a four-year engineering degree. In smaller companies he or she may be a nondegreed designer who has extensive experience in the product area. For most product design projects, more than one design engineer will be involved.

Product manager. In many companies, this individual has the ultimate responsibility for the development of the product and represents the major link between the product and the customer. Because the product manager is accountable for the success of the product in the marketplace, he or she is also often referred to as the *marketing manager* or the *product marketing manager.* The product manager is often from the sales or customer service department.

In order to initiate a design project, management must appoint the nucleus of a design team—at a minimum, a design engineer and a product manager.

Manufacturing engineer. Design engineers generally do not have the necessary breadth or depth of knowledge about various manufacturing processes to fully support the design of most products. This knowledge is provided by the manufacturing or industrial engineer, who must have a grasp not only of in-house manufacturing capabilities but also of what the industry as a whole has to offer.

Designer. In many companies, the design engineer is responsible for specification development, planning, conceptual design, and the early stages of product design. The project is then turned over to *designers,* who finish detailing the product and developing the manufacturing and assembly documentation. Designers are often CAD experts with two-year technology degrees. At some companies designers are the same as design engineers.

Technician. The technician aids the design engineer in developing the test apparatus, performing experiments, and reducing data in the development of the product. The insights gained from the technician's hands-on experience are usually invaluable.

Materials specialist. In some products, the choice of materials is forced by availability. In others, materials may be designed to fit the needs of the product. The more a product moves away from the use of known, available materials, the more a materials specialist is needed as a member of the design team. This individual is usually a degreed materials engineer or a materials scientist. Often the materials specialist will be a vendor's representative who has extensive knowledge about the design potential and limitations of the vendor's materials. Many vendors actually provide design assistance as part of their service.

Quality control/quality assurance specialist. A quality control (QC) specialist has training in techniques for measuring a statistically significant sample to determine how well it meets specifications. This inspection is done on incoming raw materials, incoming products from vendors, and products produced in-house. A quality assurance (QA) specialist makes sure that the product meets any pertinent codes or standards. For example, for medical products, there are many FDA (Food and Drug Administration) regulations that must be met. Often QC and QA are covered by one person.

Analyst. Many engineers work as analysts. Analysts usually perform complex mathematical studies of design performance using finite-element methods, thermal system modeling, or other advanced software. They are generally specialists who focus on one type of system or method.

Industrial designer. Industrial designers are responsible for how a product looks and how well it interacts with consumers; they are the stylists who have a background in fine arts and in human factors analysis. They often design the envelope within which the engineer has to work.

Assembly manager. Where the manufacturing engineer is concerned with making the components from raw materials, the assembly manager is responsible for putting the product together. As you will see in Chap. 11, concern for the assembly process is an important aspect of product design.

Vendor's or supplier's representatives. Very few products are made entirely in one factory. In fact, many manufacturers outsource (i.e., have suppliers provide) 70% or more of their product. Usually there will be many suppliers of both raw and finished goods. There are three types of relationships with suppliers: (1) partnership—the supplier takes part in the process beginning with requirements and concept development; (2) mature—the supplier relies on the parent company's requirements and concepts to develop needed items; and (3) parental—the supplier builds only what the parent company specifies. Often it is important to have critical suppliers on the design team, as the success of the product may be highly dependent on them.

As Fig. 3.11 illustrates, having a design team made up of people with varying views may create difficulties, but teams are essential to the success of a product.

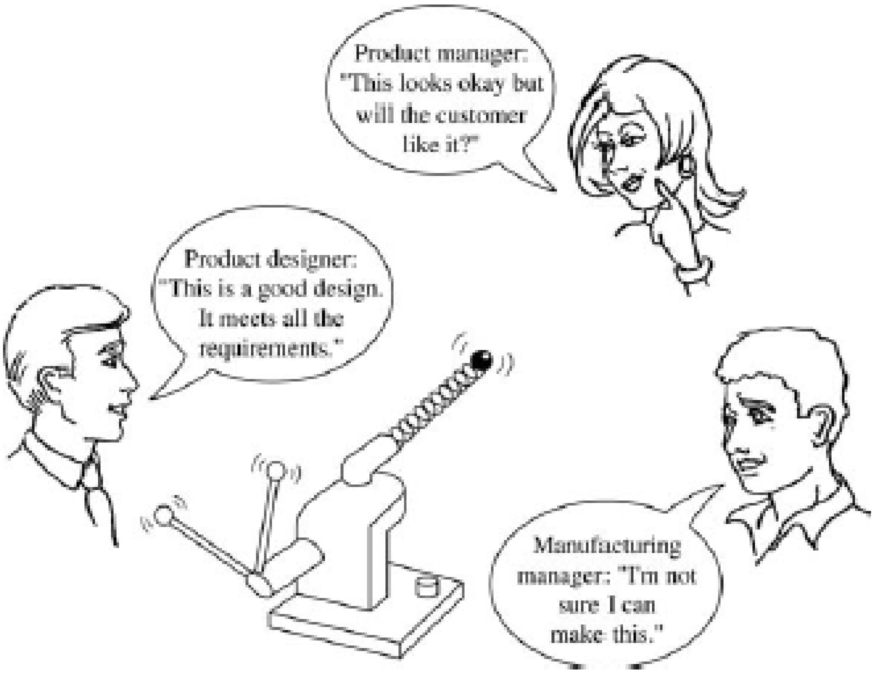


Figure 3.11 The design team at work.

3.5.2 Design Team Management

Since projects require team members with different domains of expertise, it is valuable to look at the different structures of teams in an organization. This is important because product design requires coordination across the functions of the product and across the phases in the product's development process. Listed next are the five types of project structures. The number in parentheses is the percentage of development projects that use that type. These results are from a study of 540 projects in a wide variety of industries.

> *Functional organization (13%).* Each project is assigned to a relevant functional area or group within a functional area. A functional area focuses on a single discipline. For aircraft manufacturers, Boeing, for example, the main functions are aerodynamics, structures, payload, propulsion, and the like. The project is coordinated by functional and upper levels of management.
>
> *Functional matrix (26%).* A project manager with limited authority is designated to coordinate the project across different functional areas or groups. The functional managers retain responsibility and authority for their specific segments of the project.
>
> *Balanced matrix (16%).* A project manager is assigned to oversee the project and shares with the functional managers the responsibility and authority for completing the project. Project and functional managers jointly direct many work-flow segments and jointly approve many decisions.
>
> *Project matrix (28%).* A project manager is assigned to oversee the project and has primary responsibility and authority for completing the project. Functional managers assign personnel as needed and provide technical expertise.
>
> *Project team (16%).* A project manager is put in charge of a project team composed of a core group of personnel from several functional areas or groups, assigned on a full-time basis. The functional managers have no formal involvement. Project teams are sometimes called "Tiger teams," "SWAT teams," or some other aggressive name, because this is a high-energy structure and the team is disbanded after the project is completed.

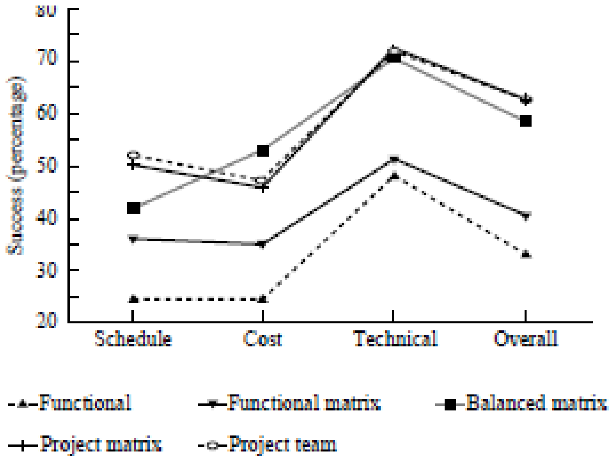


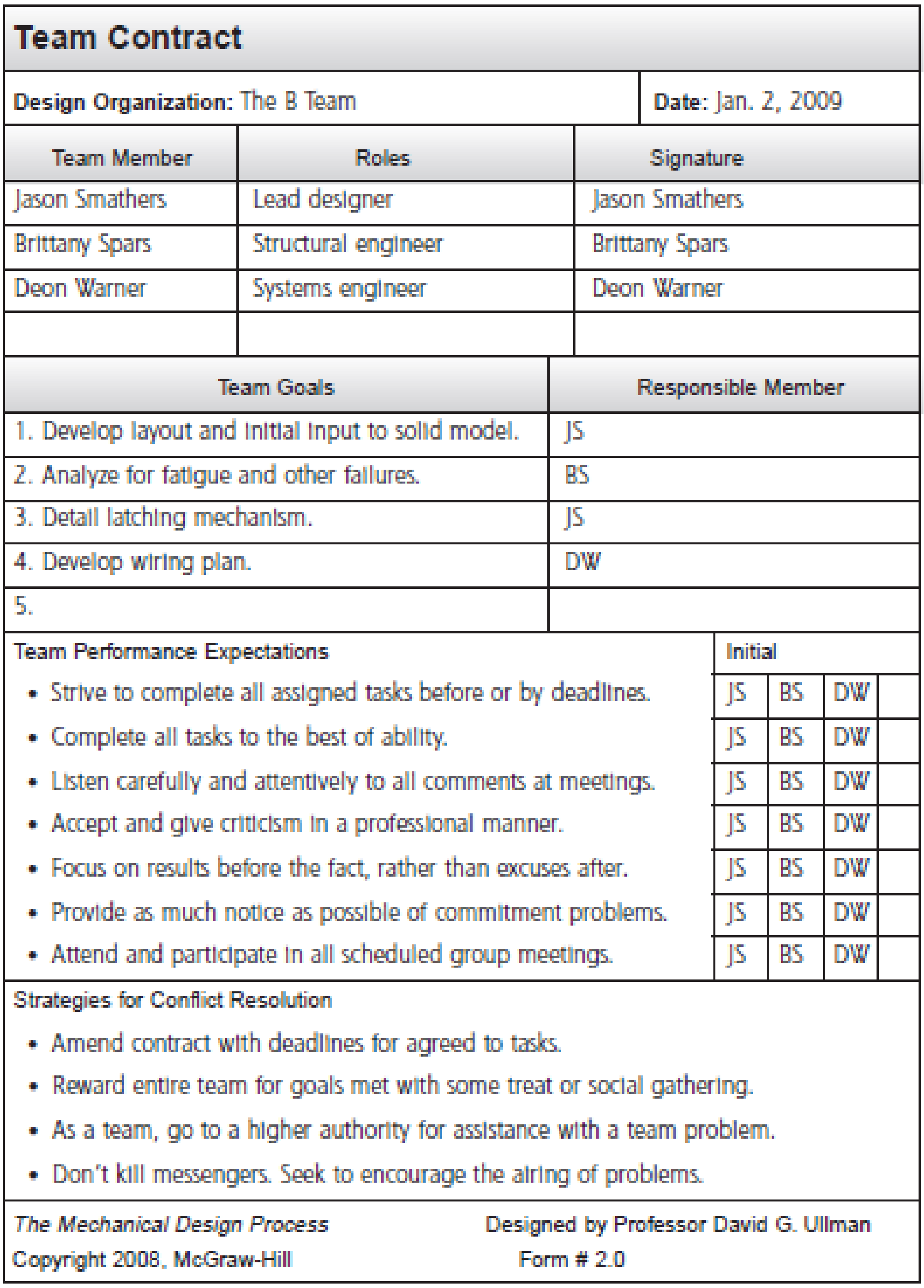
Figure 3.12 Project successes versus team structure.

3.6 BUILDING DESIGN TEAM PERFORMANCE

It can be very exciting being part of a team that is productive and is making good use of all the members. Conversely, it can be hellish working on a team that is not functioning very well. So the goal of this section is to help you build and maintain successful teams. To help ensure success, we will use *Team Contracts, Team Meeting Minutes,* and *Team Health Assessments*. Each of these encourages behavior that leads to a successful team experience.

According to a leading book on teams, there are ten characteristics of a successful team. Included in the description of each of these characteristics is a guide to where this text presents material to help make teams successful.

1. **Clarity in goals.** The process developed in this book focuses on goals during process planning in Chap. 4 and for the product itself in Chap. 6. Further, the Team Contract suggested later in this section encourages documenting the immediate team goals.
2. **Plan of action.** Chapter 4 is all about project planning.
3. **Clearly defined roles.** We have already discussed roles, and documenting them is part of the Team Contract.
4. **Clear communication.** Team Contracts, Team Meeting Minutes, and Team Health Assessments (all in this chapter) plus virtually all the process methods in this book are designed to help with communication.
5. **Beneficial team behaviors.** As with communication, the material in this book is designed to result in beneficial behaviors.
6. **Well-defined decision process.** The decision process is introduced in Chap. 4 and is the focus of Chap. 8.
7. **Balanced participation.** Equal division of work is very important for a successful team. This is further discussed later in this chapter.
8. **Established ground rules.** This is discussed later in this chapter.
9. **Awareness of team process.** This is what we are talking about in this entire chapter.
10. **Use of sound generation/evaluation approach.** As introduced in Chap. 1, the seven activities of the design process are: *Establish* the Need, *Plan, Understand, Generate, Evaluate, Decide, and Document.* Generate and Evaluate are covered in Chaps. 7–12.



Team Contract

Design Organization: The B Team	**Date:** Jan. 2, 2009

Team Member	Roles	Signature
Jason Smathers	Lead designer	Jason Smathers
Brittany Spars	Structural engineer	Brittany Spars
Deon Warner	Systems engineer	Deon Warner

Team Goals	Responsible Member
1. Develop layout and initial input to solid model.	JS
2. Analyze for fatigue and other failures.	BS
3. Detail latching mechanism.	JS
4. Develop wiring plan.	DW
5.	

Team Performance Expectations	Initial			
• Strive to complete all assigned tasks before or by deadlines.	JS	BS	DW	
• Complete all tasks to the best of ability.	JS	BS	DW	
• Listen carefully and attentively to all comments at meetings.	JS	BS	DW	
• Accept and give criticism in a professional manner.	JS	BS	DW	
• Focus on results before the fact, rather than excuses after.	JS	BS	DW	
• Provide as much notice as possible of commitment problems.	JS	BS	DW	
• Attend and participate in all scheduled group meetings.	JS	BS	DW	

Strategies for Conflict Resolution

- Amend contract with deadlines for agreed to tasks.
- Reward entire team for goals met with some treat or social gathering.
- As a team, go to a higher authority for assistance with a team problem.
- Don't kill messengers. Seek to encourage the airing of problems.

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Figure 3.13 Example team contract.

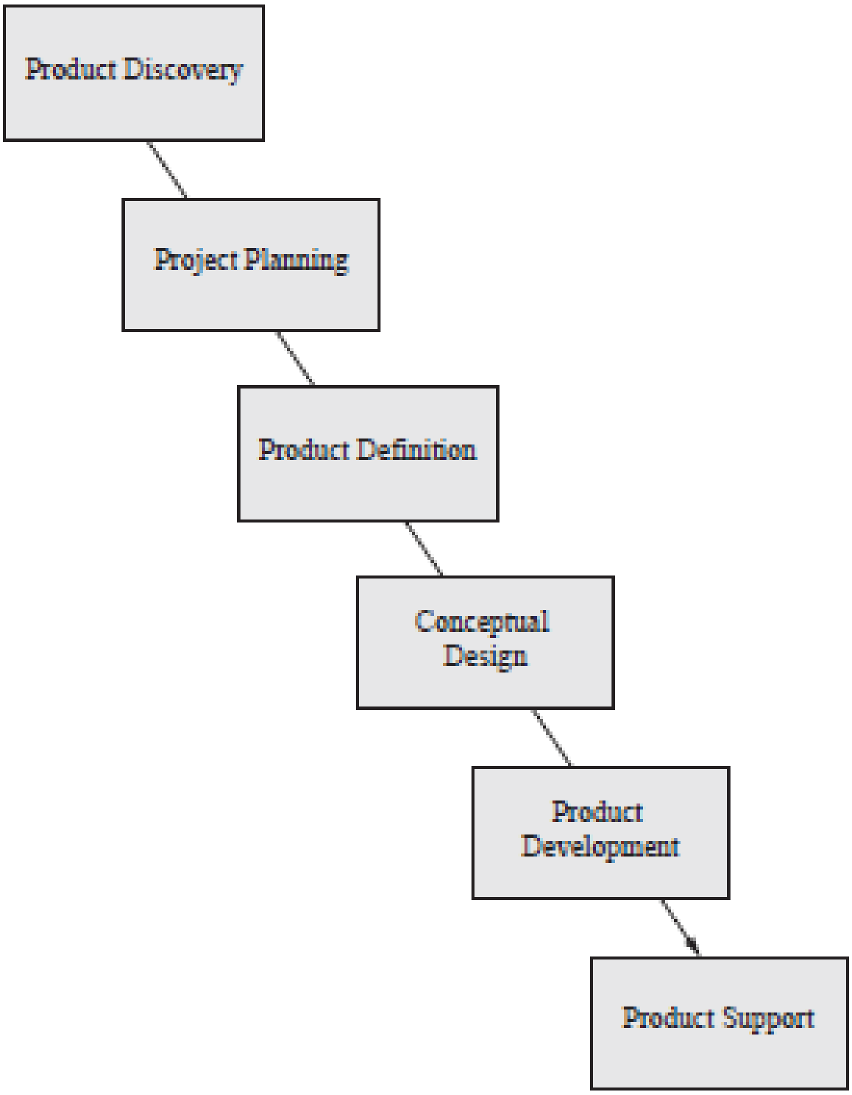


Figure 4.1 The mechanical design process.

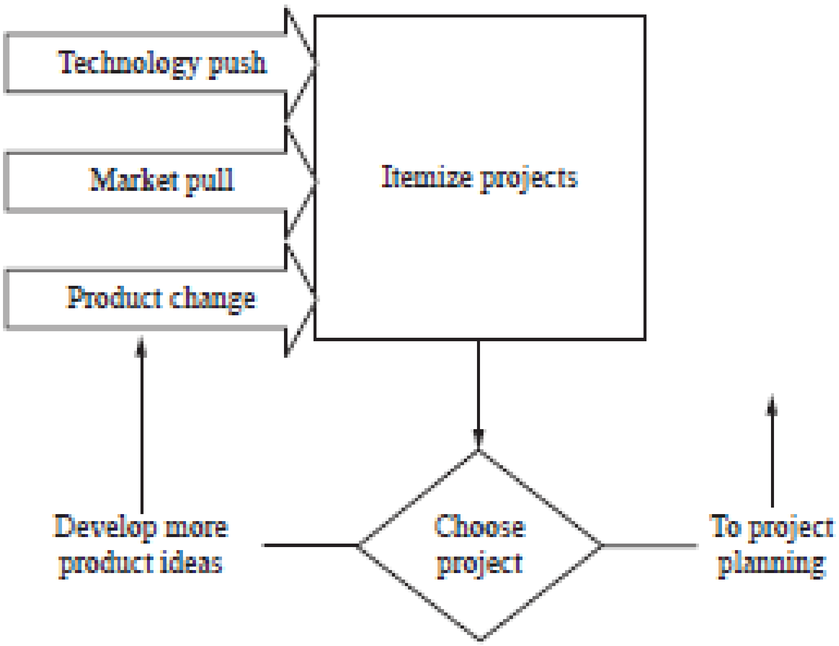


Figure 4.5 The Discovery phase of the mechanical design process.

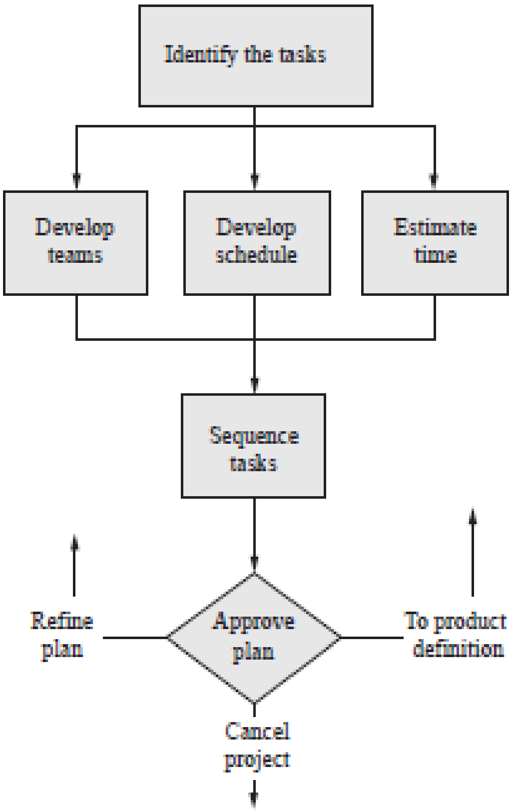


Figure 4.6 The Project Planning phase of the mechanical design.

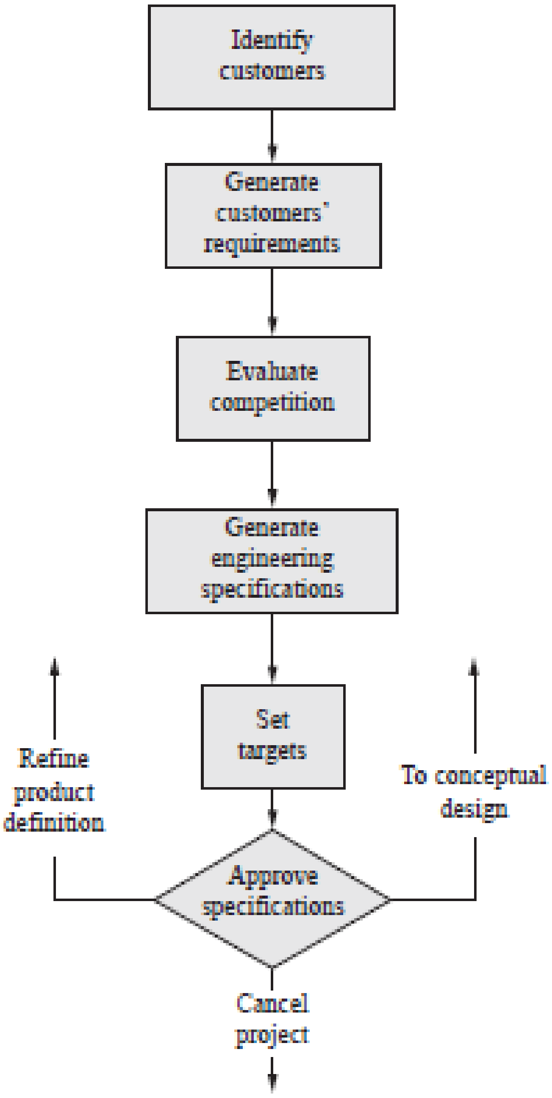


Figure 4.7 The Product Definition phase of the mechanical design.

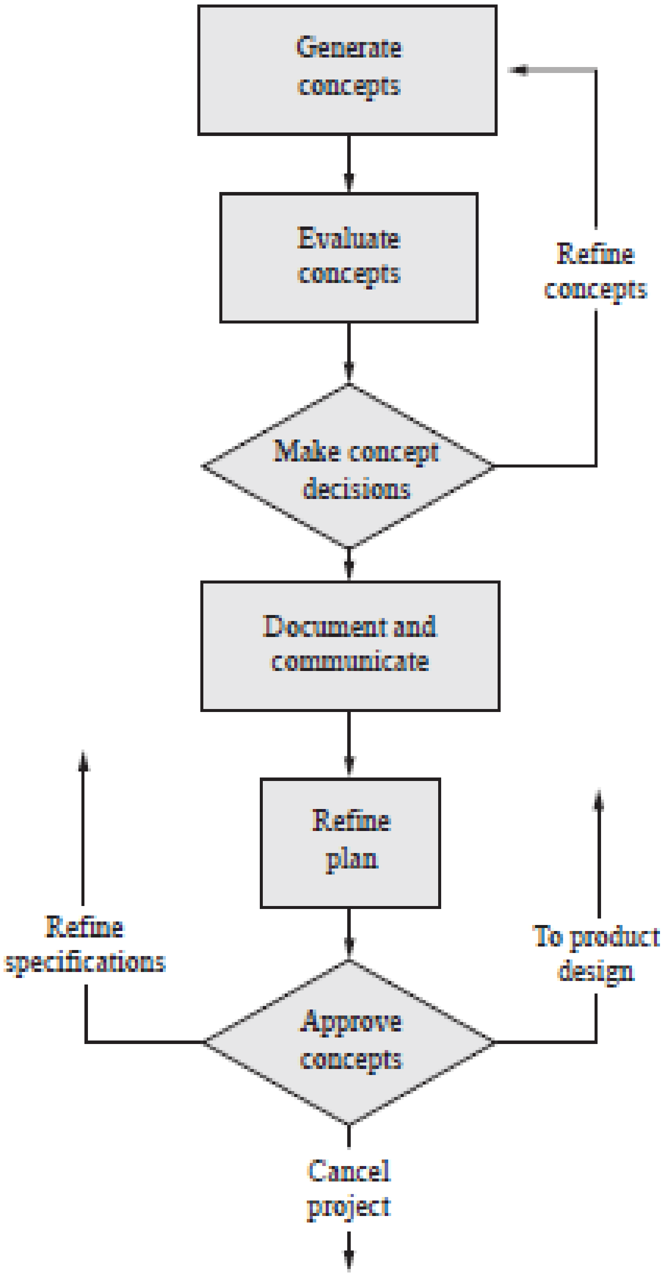


Figure 4.8 The Conceptual Design phase of the mechanical design process.

4.2.5 Product Development

After concepts have been generated and evaluated, it is time to refine the best of them into actual products (see Fig. 4.9). The Product Development phase is discussed in detail in Chaps. 9–11. Unfortunately, many design projects are begun here, without benefit of prior specification or concept development. This design approach often leads to poor-quality products and in many cases causes costly changes late in the design process. It cannot be overemphasized: *Starting a project by developing product, without concern for the earlier phases, is poor design practice.*

At the end of the Product Development phase, the product is released for production. At this time, the technical documentation defining manufacturing,

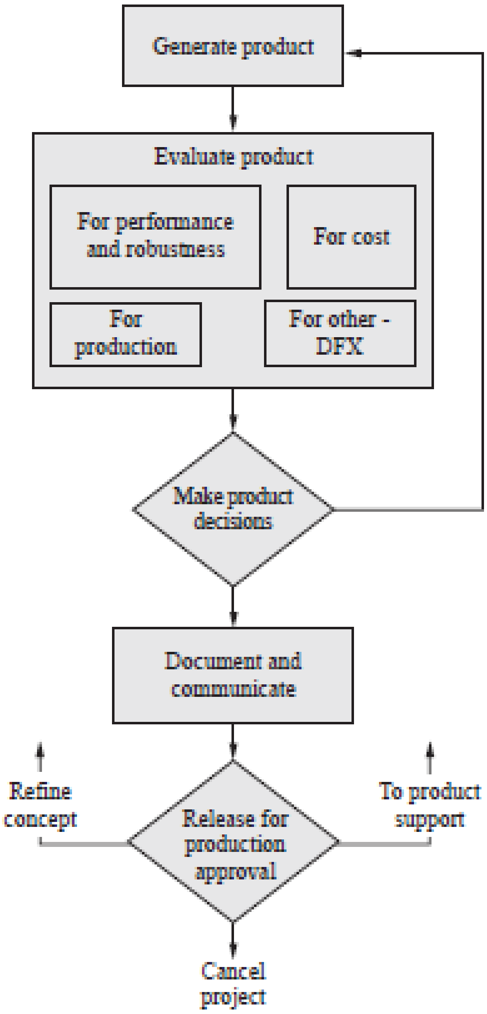


Figure 4.9 The Product Development phase of the mechanical design process.

4.2.6 Product Support

The design engineer's responsibility may not end with release to production. Often there is continued need for manufacturing and assembly support, support for vendors, and help in introducing the product to the customer (see Fig. 4.10). Additionally, design engineers are usually involved in the engineering change process. This is the process where changes made to the product, for whatever reason, are managed and documented. This is one of the Product Support topics discussed in Chap. 12.

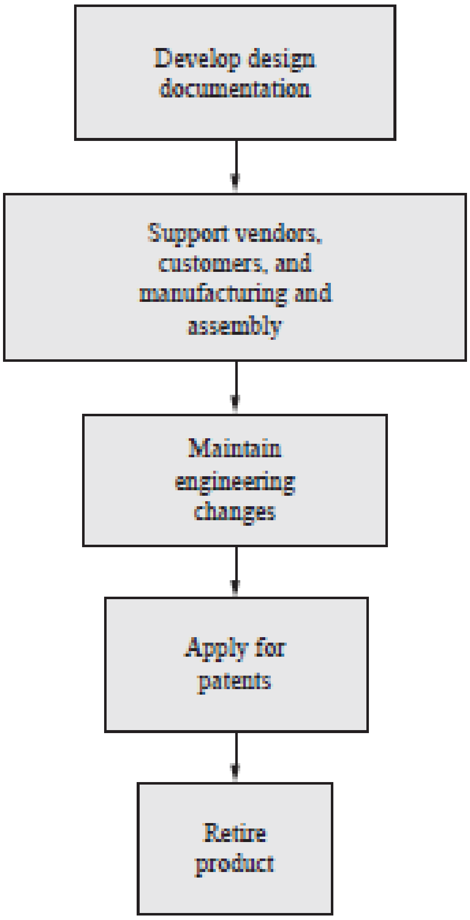


Figure 4.10 The Product Support phase of the mechanical design process.

Table 4.1 Best practices presented in this text

- **Project Planning (Chap. 5)**
    - Generating a product development plan
    - Managing the project
- **Specification Development (Chap. 6)**
    - Understanding the design problem
    - Developing customer's requirements
    - Assessing the competition
    - Generating engineering specifications
    - Establishing engineering targets
- **Conceptual Design**
    - **Generating concepts (Chap. 7)**
        - Functional decomposition
        - Generating concepts from functions
    - **Evaluating concepts (Chap. 8)**
        - Judging feasibility
        - Assessing technology readiness
        - Using the decision matrix
        - Robust decision making
- **Product Development**
    - **Product generation (Chap. 9)**
        - Form generation from function
        - Form representation
        - Materials and process selection
        - Vendor development
    - **Product evaluation (Chaps. 10 and 11)**
        - Functional evaluation
        - Evaluating performance
        - Tolerance analysis
        - Sensitivity analysis
        - Robust design
        - Design for cost
        - Design for value
        - Design for manufacture
        - Design for assembly
        - Design for reliability
        - Design for test and maintenance
        - Design for the environment
- **Product Support (Chap. 12)**
    - Developing design documentation
    - Maintaining engineering changes
    - Applying for a patent
    - Design for end of product life

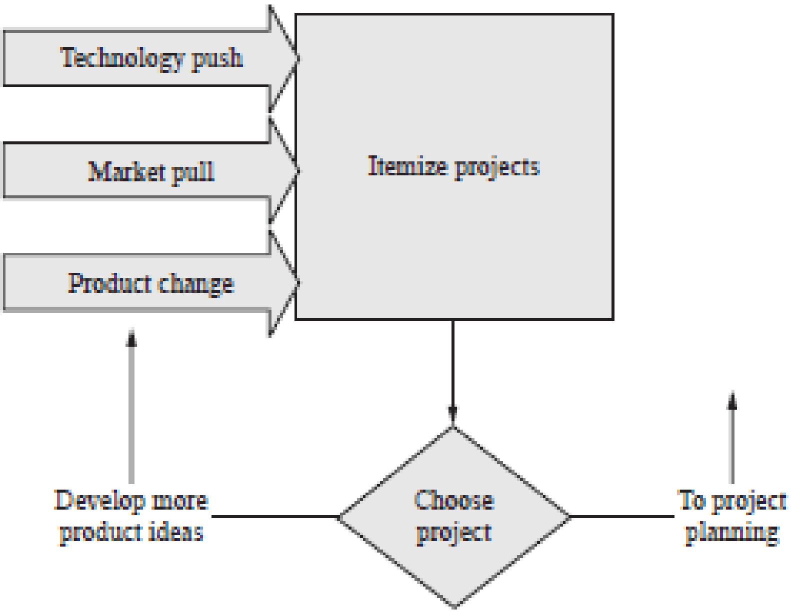


Figure 4.12 The Product Discovery phase of the mechanical design process.

4.4.1 Product Maturity

Let's explore the need for new products further by examining the technology maturity "S" curve shown in Fig. 4.13. This shows the stages a technology matures through as it goes from a new product to a mature product. Products are often introduced to the market while some of the technologies it uses are still in the "make it work properly" stage, some even sooner. Product changes and improvements occur as technologies mature over time. Think of each of these improvements as redesign projects—they are. By the time a technology begins to reach maturity, the market is saturated with competition and companies need to decide if they are going to continue to develop using the existing technologies or innovate, develop new technologies, and begin the "S" curve again, as shown in Fig. 4.14.

If companies stay with the current technologies and further refine them, they probably have much competition and little room for improvement. If they innovate, they are taking a risk as the product matures.

4.4.2 Kano's Model of Customer Satisfaction

Another way to look at the need for product development is to examine Kano's Model of Customer Satisfaction. The Kano model was developed by Dr. Noriaki Kano in the early 1980s to describe customer satisfaction. This model will help us understand how and why features mature. Kano's model plots customer

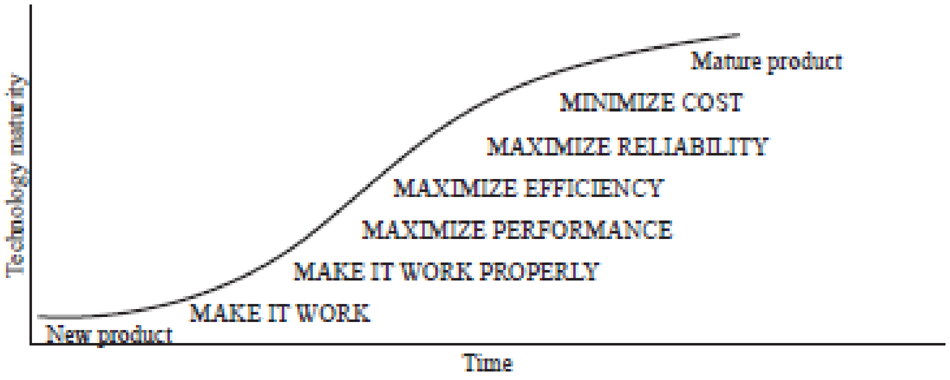


Figure 4.13 Product maturity "S" curve.

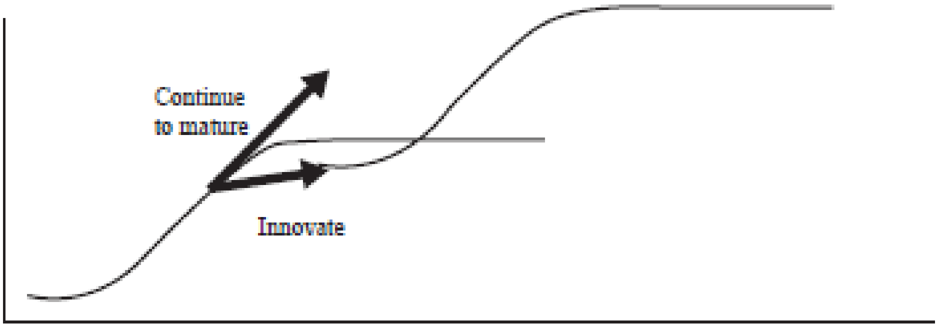


Figure 4.14 A decision point on the "S" curve.

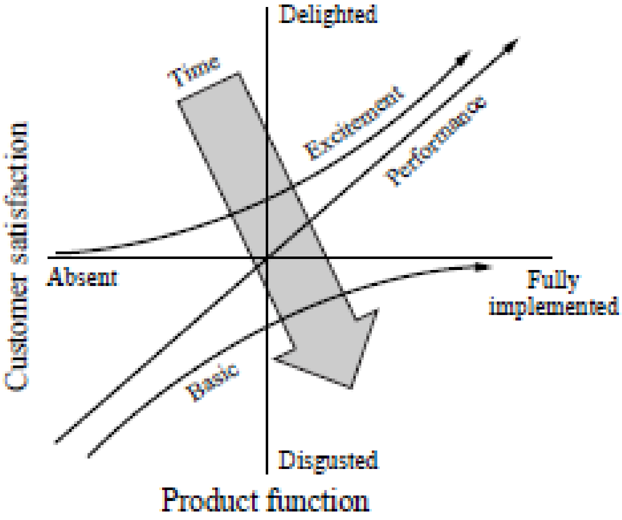


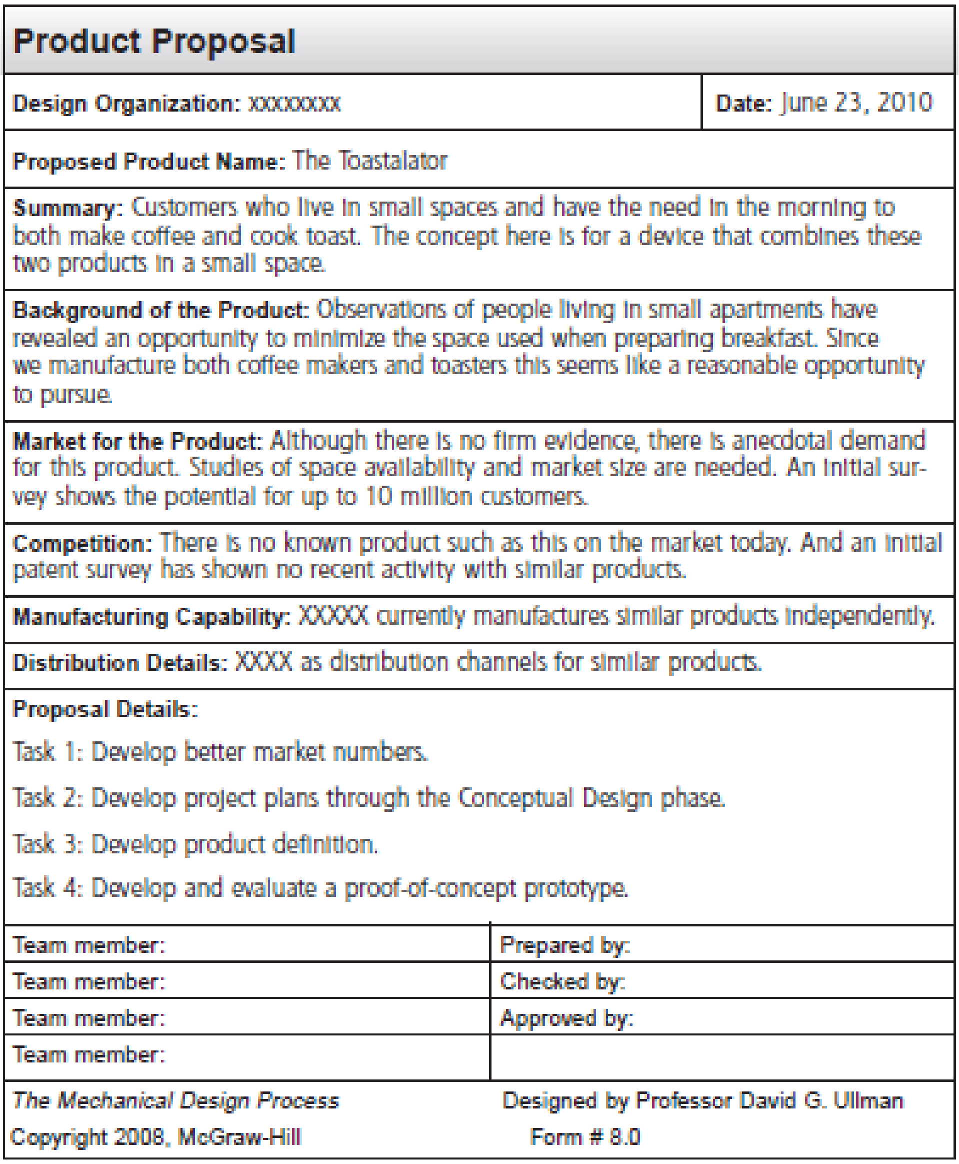
Figure 4.15 The Kano diagram for customer satisfaction.

- A vendor can no longer supply materials or components used in the product or has recommended improved ones. This may require the development of new plans, specifications, and concepts.
- Manufacturing, assembly, or another downstream phase in the product's life cycle has identified a quality, time, or cost improvement that results in a cost-effective change in the product.
- The product fails in some way and the design needs to be changed. This type of change can be very costly. Reflect back to Fig. 4.11, where the automobile manufacturer was still making design changes after release for production. As discussed there, these changes are very expensive.

4.4.3 Product Proposal

Regardless of the source, one deliverable from this phase of the design process is the product proposal. A template for developing such a proposal is available and is shown with a simplistic example in Fig. 4.16.

Note in this example that there is sufficient information to at least initiate discussions about how much resources should be allocated to following up on this proposal. In a real situation, much more documentation would be needed on each of these items.



Product Proposal

Design Organization: XXXXXXXX	**Date:** June 23, 2010

Proposed Product Name: The Toastalator

Summary: Customers who live in small spaces and have the need in the morning to both make coffee and cook toast. The concept here is for a device that combines these two products in a small space.

Background of the Product: Observations of people living in small apartments have revealed an opportunity to minimize the space used when preparing breakfast. Since we manufacture both coffee makers and toasters this seems like a reasonable opportunity to pursue.

Market for the Product: Although there is no firm evidence, there is anecdotal demand for this product. Studies of space availability and market size are needed. An initial survey shows the potential for up to 10 million customers.

Competition: There is no known product such as this on the market today. And an initial patent survey has shown no recent activity with similar products.

Manufacturing Capability: XXXXX currently manufactures similar products independently.

Distribution Details: XXXX as distribution channels for similar products.

Proposal Details:

Task 1: Develop better market numbers.

Task 2: Develop project plans through the Conceptual Design phase.

Task 3: Develop product definition.

Task 4: Develop and evaluate a proof-of-concept prototype.

Team member:	Prepared by:
Team member:	Checked by:
Team member:	Approved by:
Team member:	
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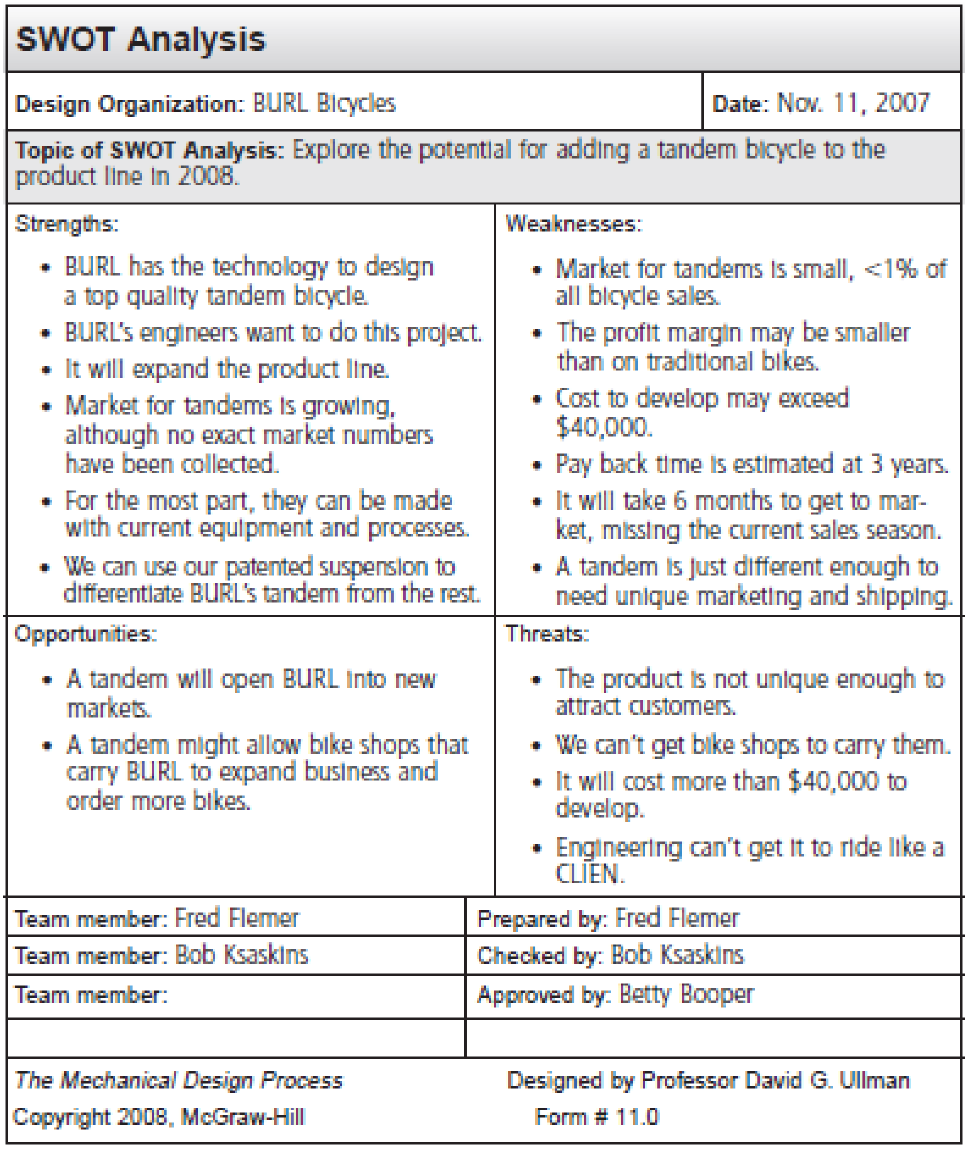
Figure 4.16 The product proposal template.



SWOT Analysis

Design Organization: BURL Bicycles	**Date:** Nov. 11, 2007

Topic of SWOT Analysis: Explore the potential for adding a tandem bicycle to the product line in 2008.

Strengths:

- BURL has the technology to design a top quality tandem bicycle.
- BURL's engineers want to do this project.
- It will expand the product line.
- Market for tandems is growing, although no exact market numbers have been collected.
- For the most part, they can be made with current equipment and processes.
- We can use our patented suspension to differentiate BURL's tandem from the rest.

Weaknesses:

- Market for tandems is small, <1% of all bicycle sales.
- The profit margin may be smaller than on traditional bikes.
- Cost to develop may exceed $40,000.
- Pay back time is estimated at 3 years.
- It will take 6 months to get to market, missing the current sales season.
- A tandem is just different enough to need unique marketing and shipping.

Opportunities:

- A tandem will open BURL into new markets.
- A tandem might allow bike shops that carry BURL to expand business and order more bikes.

Threats:

- The product is not unique enough to attract customers.
- We can't get bike shops to carry them.
- It will cost more than $40,000 to develop.
- Engineering can't get it to ride like a CLIEN.

Team member: Fred Flemer	Prepared by: Fred Flemer
Team member: Bob Ksaskins	Checked by: Bob Ksaskins
Team member:	Approved by: Betty Booper

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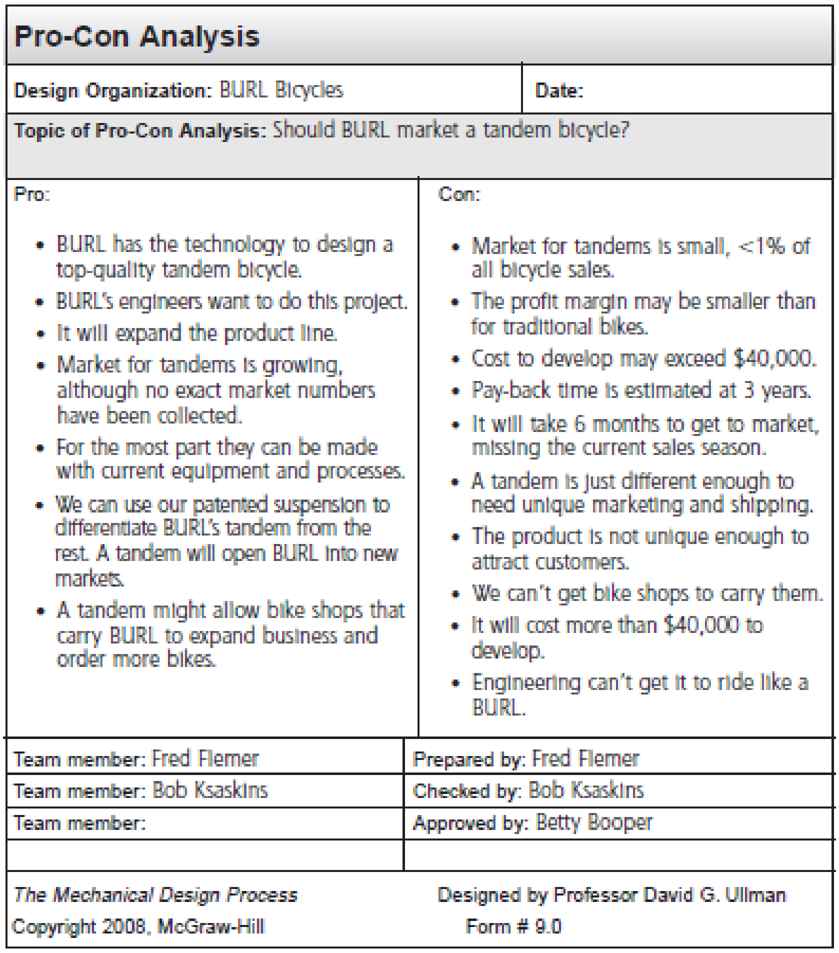
Figure 4.17 SWOT diagram example.

4.5.2 Pro-Con Analysis

To take the SWOT analysis one step further, consider a pro-con analysis. An early, recorded use of this type of analysis is by Ben Franklin. Besides being a statesman, he was a designer of stoves, bifocals and many other inventions. In a 1772 letter to Joseph Priestly (the discoverer of oxygen), Franklin explained how he analyzed his problems when intuition failed him.



Pro-Con Analysis

Design Organization: BURL Bicycles

Date:

Topic of Pro-Con Analysis: Should BURL market a tandem bicycle?

Pro:

- BURL has the technology to design a top-quality tandem bicycle.
- BURL's engineers want to do this project.
- It will expand the product line.
- Market for tandems is growing, although no exact market numbers have been collected.
- For the most part they can be made with current equipment and processes.
- We can use our patented suspension to differentiate BURL's tandem from the rest. A tandem will open BURL into new markets.
- A tandem might allow bike shops that carry BURL to expand business and order more bikes.

Con:

- Market for tandems is small, <1% of all bicycle sales.
- The profit margin may be smaller than for traditional bikes.
- Cost to develop may exceed $40,000.
- Pay-back time is estimated at 3 years.
- It will take 6 months to get to market, missing the current sales season.
- A tandem is just different enough to need unique marketing and shipping.
- The product is not unique enough to attract customers.
- We can't get bike shops to carry them.
- It will cost more than $40,000 to develop.
- Engineering can't get it to ride like a BURL.

Team member: Fred Flemer	Prepared by: Fred Flemer
Team member: Bob Ksaskins	Checked by: Bob Ksaskins
Team member:	Approved by: Betty Booper

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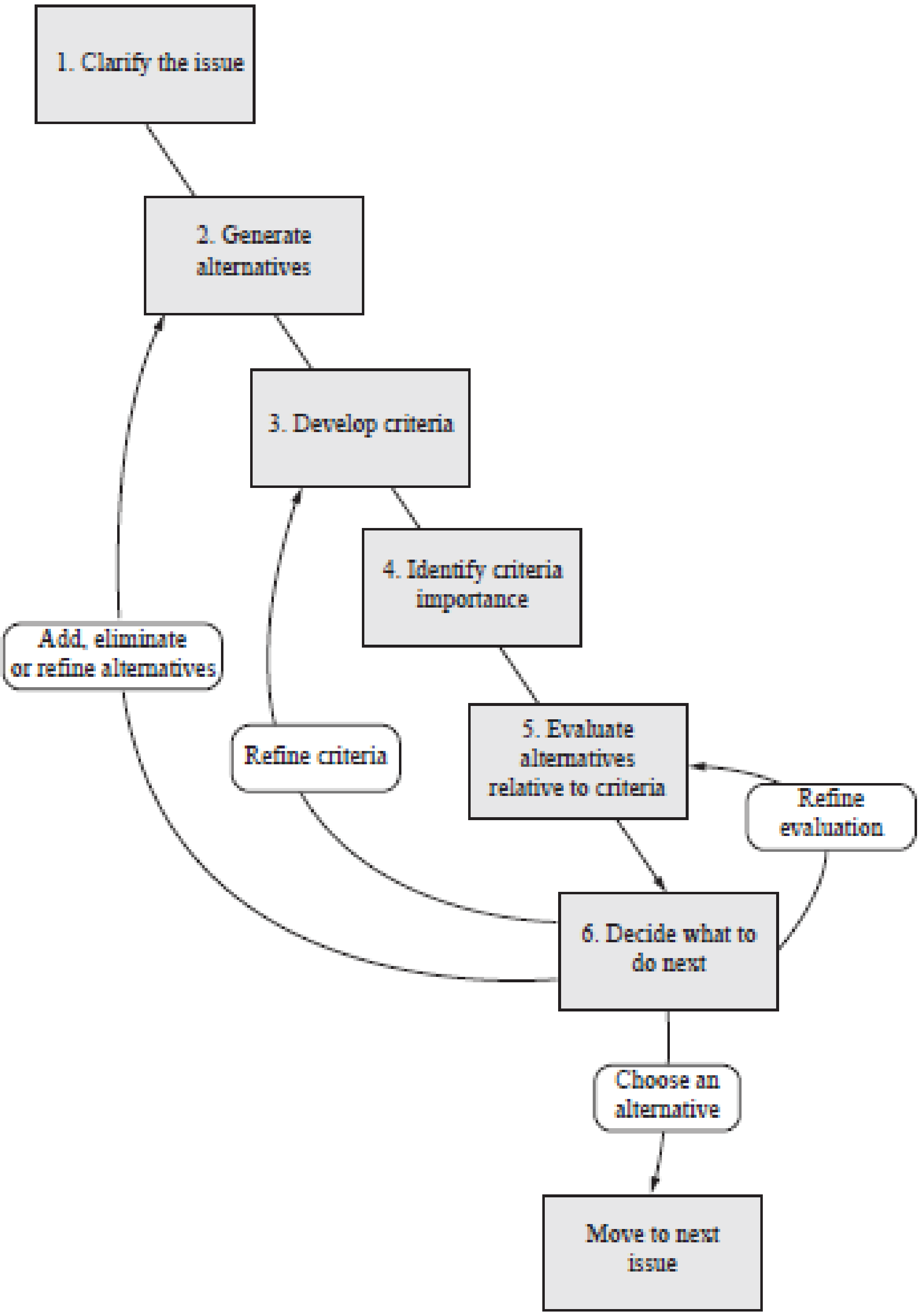
Figure 4.18 Pro-con analysis example.

4.5.3 Basics of Decision Making

Although the two methods just presented begin to get the information organized for good decision making, they are both limited to one alternative. In this section, we will formalize the entire decision-making process and make a protocol decision.

The basic structure of decision making is the same, whether addressing discovery issues or concept selection or choosing product details. In each case, there are six basic activities. Let's look at these activities in more detail:

1. **Clarify the issue** that needs a satisfactory solution.
2. **Generate alternatives**—itemize the potential solutions for the issue.
3. **Develop criteria** as they measure a satisfactory solution for the issue.
4. **Identify criteria importance** of each criterion relative to the others.
5. **Evaluate** the value of the alternatives by comparing them to the criteria.
6. Based on the evaluation results, **decide what to do next.** This decision will direct the process to
    a. Add, eliminate, or refine alternatives.
    b. Refine criteria.
    c. Refine evaluation—work to gain consensus and reduce uncertainty.
    d. Choose an alternative—you've made a decision, document it and address other issues.


1. Clarify the issue
2. Generate alternatives
3. Develop criteria
4. Identify criteria importance
5. Evaluate alternatives relative to criteria
6. Decide what to do next
Add, eliminate or refine alternatives
Refine criteria
Refine evaluation
Choose an alternative
Move to next issue

Activity 3. BURL develops criteria that are the basis for evaluating the alternatives. This is such an important activity that all of Chap. 6 is devoted to developing engineering specifications, the criteria for evaluating concepts and products. For many types of issues, those that are commonly repeated, a generic set of criteria can be used, at least as a starting place. For portfolio issues, the following list of criteria have evolved over time and can be used here:

- Acceptable program complexity: The complexity of the effort is within the experience of the organization or vendors. People are available with the skill sets needed to do the work.
- Clear market need: There is an established need in a market. (If evaluating innovative products, this may not be important.)
- Acceptable competitive intensity: The competitive intensity is reasonable and the alternative is not so new to the organization to impede commercialization.
- Acceptable five-year cash flow: The cash needed or generated over a five-year period is within reason.
- Reasonable payback time: The payback period for the needed investment and costs is acceptable.
- Acceptable start-up time: The time to realize cash flow is within the means of the organization.
- Good company fit: The newness or impact on the organization is acceptable—the new product or improvement fits the organization's image.
- Strong proprietary position: The ability to withstand the competition's efforts to erode the unique features that discriminate is good.
- Good platform for growth: The effort leads to future products or services.

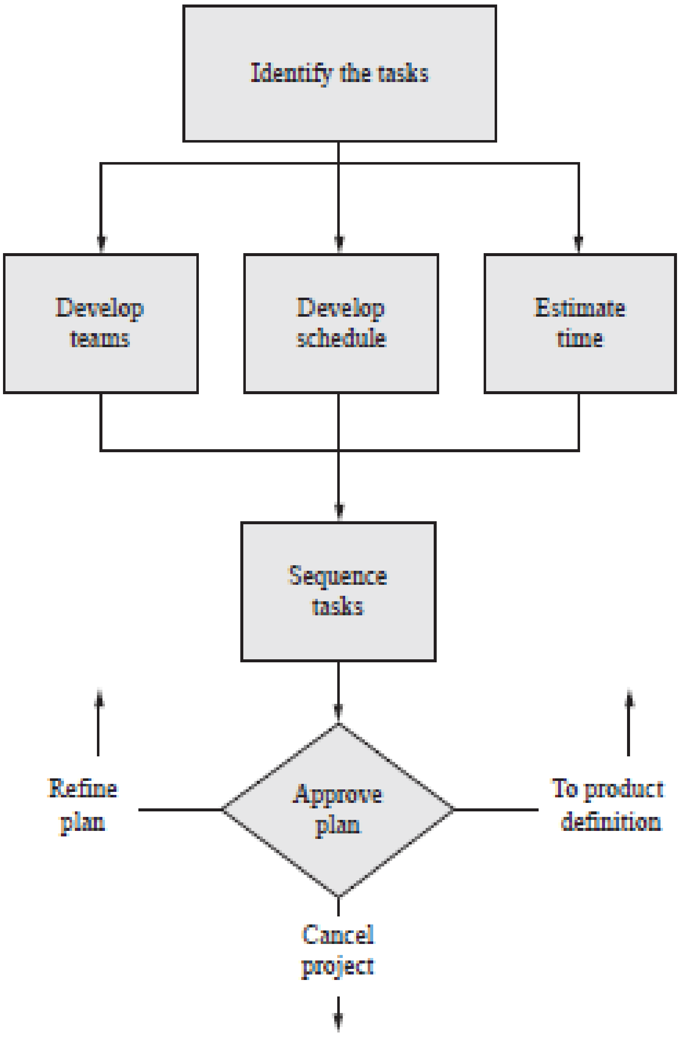


Figure 5.1 Project planning activities.

5.2 TYPES OF PROJECT PLANS

- Concept development
- Technical feasibility
- Cost targets and financials
- Concept validation by consumers
- Legal assessment of intellectual property

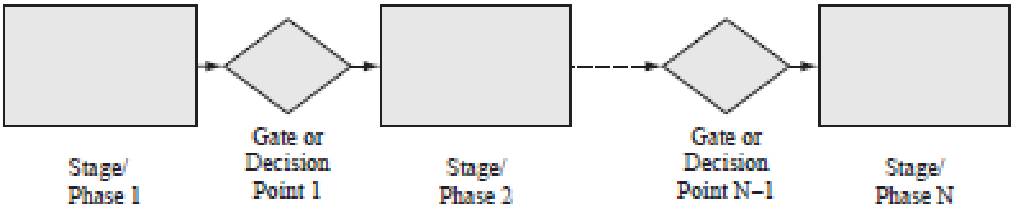


Figure 5.2 The Stage-Gate process.

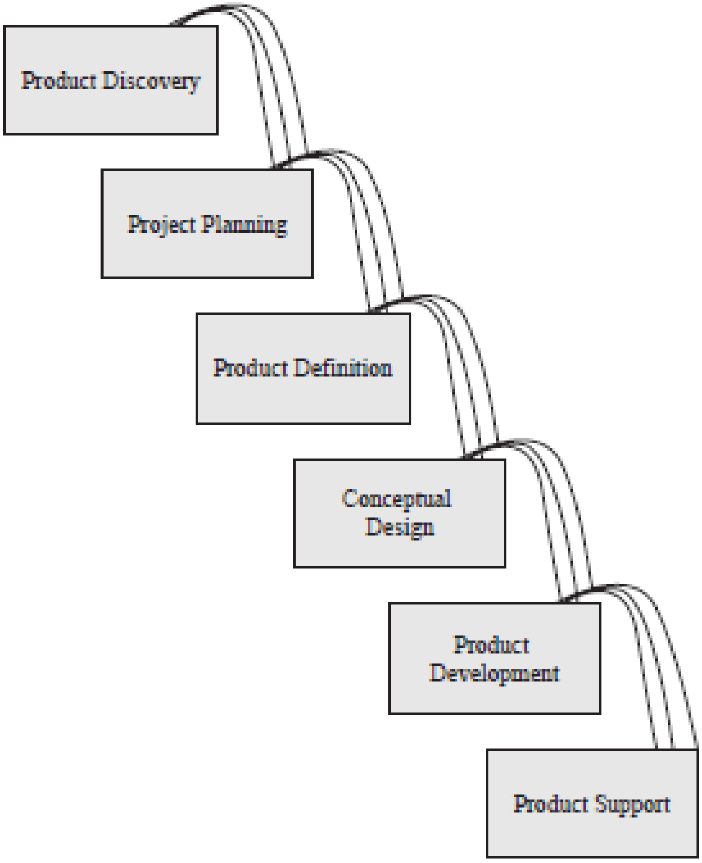


Figure 5.3 The Waterfall model.

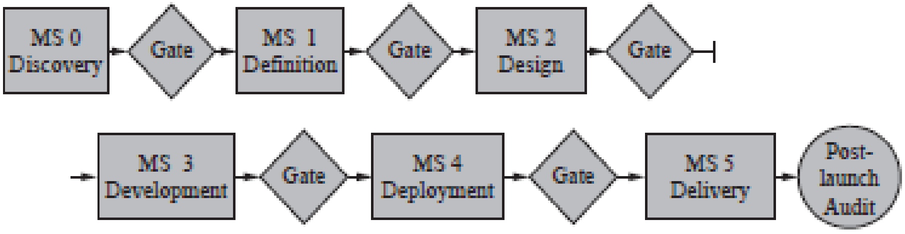


Figure 5.4 Irwin Tools product development process. (Reprinted with permission of Irwin Industrial Tools.)

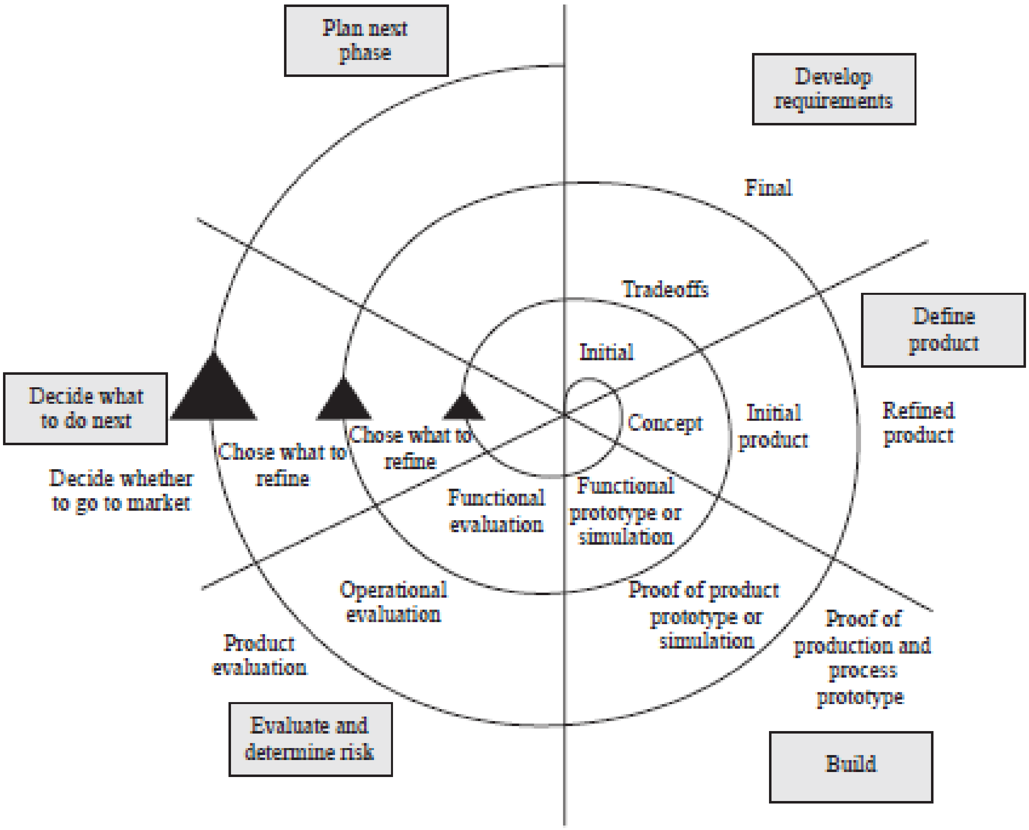


Figure 5.5 Spiral development of mechanical systems.

5.3 PLANNING FOR DELIVERABLES—THE DEVELOPMENT OF INFORMATION

Progress in a design project is measured by deliverables such as drawings, prototypes, bills of materials (e.g., parts lists), results of analysis, test results, and other representations of the information generated in the project. These deliverables are all models of the final product. During product development, many models (i.e., design information representations) are made of the evolving product. Some of these models are analytical models—quick calculations on a bit of paper or complex computer simulations; some will be graphical representations—simple sketches or orthographic mechanical drawings; some will be CAD solid models and some will be physical models—prototypes.

Each of these models or prototypes is a representation of information that describes the product. In fact, *design is the evolution of information punctuated by decisions*. Each model or prototype is not only the embodiment of what is known about the product, but knowledge is gained in building or developing it. So the deliverables serve two purposes—they are the embodiment of the information that describes the product and they are a means to communicate that information to others. Thus, it is important to understand the information developed during the design process.

5.3.1 Physical Models—Prototypes

Physical models of products are often called *prototypes*. The characteristics of prototypes that must be taken into account when planning when to use them and what types to use are their *purpose,* the *phase* in the design process when they are used, and the *media* used to build them.

The four *purposes* for prototypes are proof-of-concept, proof-of-product, proof-of-process, and proof-of-production. These terms are traditionally applied only to physical models; however, solid models in CAD systems can often replace these prototypes with less cost and time.

- A **proof-of-concept or proof-of-function prototype** focuses on developing the function of the product for comparison with the customers' requirements or engineering specifications. This kind of prototype is intended as a learning tool, and exact geometry, materials, and manufacturing process are usually not important. Thus, proof-of-concept prototypes can be built of paper, wood, parts from children's toys, parts from a junkyard, or whatever is handy.
- A **proof-of-product prototype** is developed to help refine the components and assemblies. Geometry, materials, and manufacturing process are as important as function for these prototypes. The recent development of *rapid prototyping* or *desktop prototyping,* using stereo lithography or other methods to form a part rapidly from a CAD representation, has greatly improved the time and cost efficiency of building proof-of-product prototypes.
- A **proof-of-process prototype** is used to verify both the geometry and the manufacturing process. For these prototypes, the exact materials and manufacturing processes are used to manufacture samples of the product for functional testing.
- A **proof-of-production prototype** is used to verify the entire production process. This prototype is the result of a *preproduction run,* the products manufactured just prior to production for sale.

1. Archive the geometric form of the design.
2. Communicate ideas between designers and between designers and manufacturing personnel.
3. Support analysis. Missing dimensions and tolerances are determined as the drawing or model is developed.
4. Simulate the operation of the product.
5. Check completeness. As sketches or other drawings are being made, the details left to be designed become apparent to the designer. This, in effect, helps establish an agenda of design tasks left to accomplish.
6. Act as an extension of the designer's short-term memory. Designers unconsciously use drawings as part of their problem-solving process and often consciously use drawings to store information they might otherwise forget.
7. Act as a synthesis tool. Sketches and formal drawings enable the piecing together of unconnected ideas to form new concepts.

Sketches. Sketching as a form of drawing is an extension of the short-term memory needed for idea generation (see Chap. 3). As the shape of components and assemblies evolve, drawings that are more formal are used to keep the information organized and easily communicated to others. Thus, a well-trained engineer has CAD skills and the ability to represent concepts that are more abstract and best represented as sketches.

Layout Drawings. A layout drawing is a working document that supports the development of the major components and their relationships. A typical layout drawing is shown in Fig. 5.6. Consider the characteristics of a layout drawing:

- A layout drawing is a working drawing and as such is frequently changed during the design process. Because these changes are seldom documented, information can be lost. Good records in the design notebook can compensate for this loss.
- A layout drawing is made to scale.
- Only the important dimensions are shown on a layout drawing. In Chap. 10, we see that starting with the spatial constraints sets the stage for developing the architecture and individual components in the product generation process. These constraints are best shown on a layout drawing.
- Tolerances are usually not shown, unless they are critical.
- Notes on the layout drawing are used to explain a design feature or the function of the product.
- A layout drawing often becomes obsolete. As detail drawings and assembly drawings are developed, the layout drawing becomes less useful. If the

Detail Drawings. As the product evolves on the layout drawing, the detail of individual components develops. These are documented on detail drawings. A typical detail drawing is shown in Fig. 5.7. Important characteristics of a detail include the following:

- All dimensions must be toleranced. In Fig. 5.7, many of the dimensions are made with unstated company-standard tolerances. Most companies have standard tolerances for all but the most critical dimensions. The upper and lower limits of the critical dimensions in Fig. 5.7 are given.
- Materials and manufacturing detail must be in clear and specific language. Special processing must be spelled out clearly.

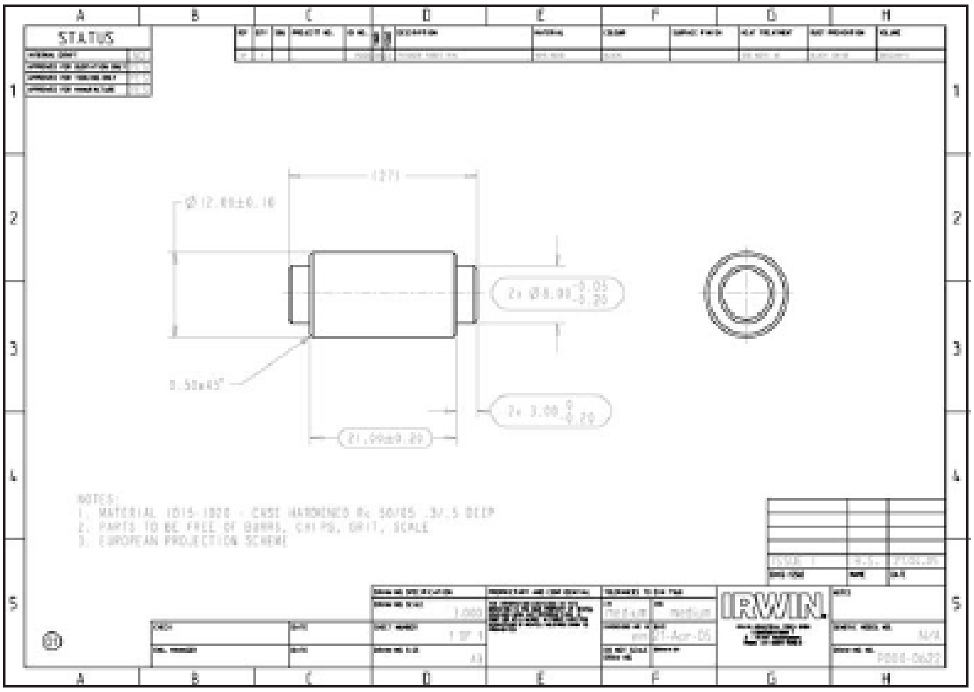


Figure 5.7 Typical detail drawing. (Reprinted with permission of Irwin Industrial Tools.)

Assembly Drawings. The goal in an assembly drawing is to show how the components fit together. There are many types of drawing styles that can be used to show this. Assembly drawings are similar to layout drawings except that their purpose, and thus the information highlighted on them, is different. An assembly drawing has these specific characteristics:

- Each component is identified with a number or letter keyed to the Bill of Materials (BOM). Some companies put their Bill of Materials on the assembly drawings; others use a separate document. (The contents of the Bill of Materials are discussed in Section 9.2.)
- References can be made to other drawings and specific assembly instructions for additional needed information.

Graphical Models Produced in Modern CAD Systems. As mentioned in the introduction to this section, in modern solid-modeling CAD systems, layout, detail, and assembly drawings are not distinct. These systems enable the designer to make a solid model of the components and assemblies and, from these, semiautomatically make detail and assembly drawings. In these systems, the layout of components and assemblies and the details of the components and how they fit together into assemblies, all coevolve. This is both a blessing and a curse. On the positive side:

- Solid models enable rapid representation of concepts and the ability to see how they assemble and operate without the need for hardware.
- The use of solid-modeling systems improves the design process because features, dimensions, and tolerances are developed and recorded only once. This reduces the potential for error.
- Interfaces between components are developed so that components share the same features, dimensions, and tolerances, ensuring that mating components fit together.
- Detail and assembly drawings are produced semiautomatically, reducing the need to have expert knowledge of drafting methods and drawing standards.
- Files created are usable for making prototypes using rapid prototyping methods; developing figures for manufacturing and assembly; and providing diagrams for sales, service, and other phases of the product life cycle.

However, these tools also have a negative side:

- There is a tendency to abandon sketching. Sketches are a rapid way to develop a high number of ideas. The time required to develop a solid model is much longer than the time to make a sketch. This means the number of alternatives developed may be lower than it should be.
- Too much time is often spent on details too soon. Solid-modeling systems usually require details in order to even make a “rough drawing.” Thinking through these details in conceptual design may not be a good use of time, and once drawn there is a reluctance to abandon poor designs because of the time invested.
- Often valuable design time is spent just using the tool. Learning a solid-modeling system takes time and using it often requires time-consuming control of the program. This design time is lost.
- Many solid-modeling systems require the components and assemblies to be planned out ahead of time. These systems are more like an automated drafting system than a design aid.

5.3.3 Analytical Models

Often the level of approximation of an analytical model is referred to as its fidelity. *Fidelity* is a measure of how well a model or simulation analysis represents the state and behavior of a real-world object. For example, up until the late seven-

Table 5.1 Types of models

	Medium			
Phase	**Physical (form and function)**	**Analytical (mainly function)**	**Graphical (Traditional) (mainly form)**	**Graphical (CAD) (form and function)**
Concept	Proof-of-concept prototype	Back-of-the-envelope analysis	Sketches	Hand sketches and solid models
↓	Proof-of-product prototype	Engineering science analysis	Layout drawings	↓
Final product	Proof-of-process and proof-of-production prototypes	Finite element analysis; detailed simulation	Detail and assembly drawings	Solid models

5.4 BUILDING A PLAN

A project plan is a document that defines the tasks that need to be completed during the design process. For each task, the plan states the objectives; the personnel requirements; the time requirements; the schedule relative to other tasks, projects, and programs; and, sometimes, cost estimates. In essence, a project plan is a document used to keep that project under control. It helps the design team and management to know how the project is actually progressing relative to the progress anticipated when the plan was first established or last updated. There are five steps to establishing a plan. A template such as that in Fig. 5.10 can be used to support these steps. In this example, one task is detailed for a plan to develop a Baja car for an SAE (Society of Automotive Engineers) student contest. The plan is detailed in Fig. 5.16.

5.4.1 Step 1: Identify the Tasks

As the design team gains an understanding of the design problem, the tasks needed to bring the problem from its current state to a final product become clearer. Tasks are often initially thought of in terms of the activities that need to be performed (e.g., "generate concepts" or other terms used in Figs. 4.5–4.10). The tasks should be made as specific as possible, and as detailed in the next step, they should focus on what needs to be achieved rather than the activities. In some industries, the

Project Planning

Design Organization: Oregon State University Baja Team
Date: Oct. 2, 2007

Proposed Product Name: Killer Beaver

Task 6

Name of Task: Preliminary Engine Compartment Design

Objective: Develop solid model of the engine compartment
Run initial FEM
Analyze human factors for assembly and maintenance

Deliverables: CAD solid model
FEM results showing weak points based on static and fatigue analysis
Simulation of assembly of engine and components
Simulation of routine maintenance

Decisions needed:
Decision 1: Choose configuration for compartment
Decision 2: Identify work needed to finalize the design

Personnel needed:

Title: student	Hours: 75	Percent full time: 20%
Title:	Hours:	Percent full time:

Time estimate: Total hours: 75
Elapsed time (include units): 3 weeks

Sequence: Predecessors: Task 4, Preliminary roll cage design
Successors: Task 7, Final Engine Compartment Design
Start Date: Oct. 12 Finish Date: Nov. 2

Costs: Capital Equipment
Disposables:

Team member: James	Prepared by: James
Team member: Tim	Checked by: Pat
Team member: Pat	Approved by:
Team member:	

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Figure 5.10 Example plan template.

5.4.2 Step 2: State the Objective for Each Task

Each task must be characterized by a clearly stated objective. This objective takes some existing information about the product—the input—and, through some activity, refines it for output to other tasks. Even though tasks are often initially conceived as activities to be performed, they need to be refined so that the results of the activities are the stated objectives. Although the output information can be only as detailed and refined as the present understanding of the design problem, each task objective must be

- Defined as information to be refined or developed and communicated to others, not as activities to be performed. This information is contained in *deliverables,* such as completed drawings, prototypes built, results of calculations, information gathered, or tests performed. If the deliverables cannot be itemized, the objective is not clear—then you know you are done only when you run out of time.
- Presented in terms of the decisions that need to be made and who will be involved in making them.
- Easily understood by all on the design team.
- Specific in terms of exactly what information is to be developed. If concepts are needed, then tell how many are sufficient.
- Feasible, given the personnel, equipment, and time available. See step 3.

5.4.3 Step 3: Estimate the Personnel, Time, and Other Resources Needed to Meet the Objectives

For each task, it is necessary to identify who on the design team will be responsible for meeting the objectives, what percentage of their time will be required, and over what period they will be needed. In large companies, it may only be necessary to specify the job title of the workers on a project, as there will be a pool of workers, any of whom could perform the given task. In smaller companies or groups within companies, specific individuals might be identified.

Table 5.2 The time it takes to design

Task	Personnel/time
Design of elemental components and assemblies. All design work is routine or requires only simple modifications of an existing product.	One designer for one week
Design of elemental devices such as mechanical toys, locks, and scales, or complex single components. Most design work is routine or calls for limited original design.	One designer for one month
Design of complete machines and machine tools. Work involved is mainly routine, with some original design.	Two designers for four months
Design of high-performance products that may utilize new (proven) technologies. Work involves some original design and may require extensive analysis and testing.	Five designers for eight months

especially if the design project is not routine or new technologies are used. Some pessimists claim that after making the best estimate of time required, the number should be doubled and the units increased one step. For example, an estimate of one day should really be two weeks.

A more accurate method for estimating the total time required for a project is based on the complexity of the product's function. The theory is that the more complex the function, the more complex the product and the longer the time needed to design the product. Product function development is a key part of concept generation and is covered in detail in Chap. 7. Thus, in order to use this method for time estimation, there has to be some understanding of the functions of the product. During the product development process, often a task in the conceptual design phase is titled "refine plans" to reflect the dependence of the plan on the concept being developed.

The total time required for a project can be estimated by

$$\text{Time (in hours)} = A * \text{PC} * D^{0.85}$$

where

A = a constant based on past projects in the company. This constant is dependent on the size of the company and how well information is communicated among the various functions. Typically, $A = 30$ for a small company with good communication and $A = 150$ for a large company with average communication. Note that communication and thus time is estimated at five times greater in a large organization.

PC = product complexity based on function (discussed shortly).

D = project difficulty: $D = 1$, not too difficult (i.e., using well-known technologies); $D = 2$, difficult (i.e., some new technologies); $D = 3$, extremely difficult (i.e., many new technologies).

Everything takes twice as long.

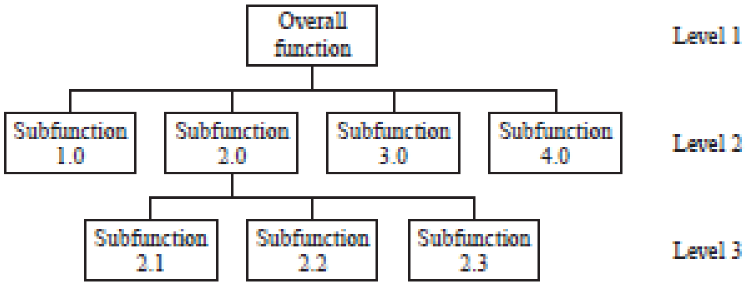


Figure 5.11 Example of a function diagram.

Product complexity is based on the functions of the product. A function diagram will typically look as shown in Fig. 5.11. Details on how to develop such a diagram will be covered in Chap. 7.

The product complexity is estimated by

$$\mathrm{PC} = \sum j * F_j$$

where

j = the level in the function diagram
F_j = the number of functions at that level

For the example in Fig. 5.11, there is 1 function on the top layer (always there), 4 on the second level, and 3 on the third:

$$\mathrm{PC} = 1 * 1 + 2 * 4 + 3 * 3 = 18$$

For example, a small company with good communication ($A = 30$) is designing a difficult product ($D = 2$) that has PC = 18, then an estimate of the total time is 973 hours, or two designers working for 3 months. This method has been shown to be fairly accurate within a single company that has calibrated the value for A, and models function in a consistent manner.

Time estimation is very difficult and subject to error. Thus, it is recommended that task time be based on three estimates: an optimistic estimate o, a most-likely estimate m, and a pessimistic estimate p. From these three, the statistical best estimate of task time is

$$\text{Time estimate} = \frac{o + 4m + p}{6}$$

This formula is used as part of the PERT (Program Evaluation and Review Technique) method. See the sources in Section 5.8 for more details on PERT.

Finally, note that the distribution of time across the phases of the design process is generally in the following ranges:

Project planning: 3 to 5%
Specification definition: 10 to 15%

5.4.4 Step 4: Develop a Sequence for the Tasks

The next step in working out the plan is to develop a task sequence or schedule. Scheduling tasks can be complex. The goal is to have each task accomplished before its result is needed and, at the same time, to make use of all of the personnel, all of the time. Additionally, it is necessary to schedule design reviews or other forms of approval to continue the project. The tasks and their sequence is often referred to as a *work breakdown structure*.

5.4.5 Step 5: Estimate the Product Development Costs

The planning document generated here can also serve as a basis for estimating the cost of designing the new product. Even though design costs are only about 5% of the manufacturing costs of the product (Fig. 1.2), they are not trivial.

The cost estimate needed here is for the project, not the product. Product cost estimates are covered in Chap. 11. A majority of project costs are in salaries. Some basic guidelines for making a project cost estimate are

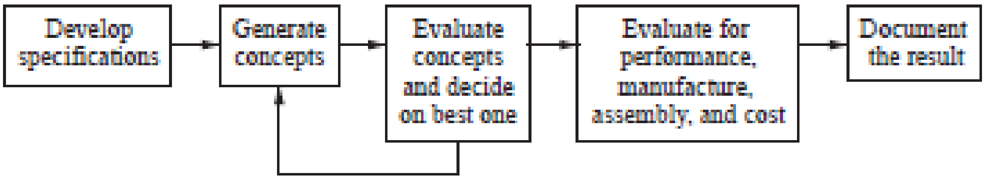


Figure 5.15 Design process for a more complex lap joint.

5.6.2 Documents Communicating with Management

During the design process, periodic presentations to managers, customers, and other team members will be made. These presentations are usually called *design reviews* and are shown as an "approve plan" decision point in Fig. 5.1. Although there is no set form for design reviews, they usually require both written and oral communication. Whatever the form, these guidelines are useful in preparing material for a design review.

Make it understandable to the recipient. Clear communication is the responsibility of the sender of the information. It is essential in explaining a concept to others that you have a clear grasp of what they already know and do not know about the concept and the technologies being used.

Carefully consider the order of presentation. How should a bicycle be described to someone who has never seen one? Would you describe the wheels first, then the frame, the handlebars, the gears, and finally the whole assembly? Probably not, as the audience would understand very little about how all these bits fit together. A three-step approach is best: (1) Present the whole concept or assembly and explain its overall function, (2) describe the major parts and how they relate to the whole and its function, and (3) tie the parts together into the whole. This same approach works in trying to describe the progress in a project: *Give the whole picture; detail the important tasks accomplished; then give the whole picture again.* There is a corollary to this guideline: *New ideas must be phased in gradually.* Always start with what the audience knows and work toward the unknown. Above all, do not use jargon or terms with which the audience is not familiar. If in doubt about a concept or TLA (Three Letter Acronym), define it.

Be prepared with quality material. The best way to make a point, and to have any meeting end well, is to be prepared. This implies (1) having good visual aids and written documentation, (2) following an agenda, and (3) being ready for questions beyond the material presented.

5.6.3 Documents Communicating the Final Design

The most obvious form of documentation to result from a design effort is the material that describes the final design. Such materials include computer solid models, drawings (or computer data files) of individual components (detail drawings) and of assemblies to convey the product to manufacturing. They also include written documentation to guide manufacture, assembly, inspection, installation, maintenance, retirement, and quality control. These topics will be covered in Chaps. 9 and 12.

Often it is necessary to produce a design report. The following format is a good outline to follow.

1. **Title page:** The title of the design project is to be in the center of the page. Below it, list the following items:
    a. Date:
    b. Course/Section:
    c. Instructor:
    d. Team Members:
2. **Executive summary:**
    a. The purpose of the Executive Summary is to provide key information up front, such that while reading the report, a reader has expectations that are fulfilled on a continuous basis. Key to a good summary is the *first* sentence, which *must* contain the most essential information that you wish to convey.

   b. The summary is to be written as if the reader is totally uninformed about your project and is not necessarily going to read the report itself.
   c. It must include a short description of the project, the process and the results.
   d. The Executive Summary is to be one page or less with one figure maximum.
3. **Table of contents:** Include section titles and page numbers.
4. **Design problem and objectives:** Give a clear and concise definition of the problem and the intended objectives. Outline the design constraints and cost implications.
   a. Include appropriate background on the project for the reader to be able to put the information provided in context.
   b. The final project objectives *must* also be presented in the form of a set of engineering specifications.
5. **Detailed design documentation:** Show all elements of your design including an explanation of
   a. Assumptions made, making sure to justify your design decisions.
   b. Function of the system.
   c. Ability to meet engineering specifications.
   d. Prototypes developed, their testing and results relative to engineering specifications.
   e. Cost analysis.
   f. Manufacturing processes used.
   g. DFX results.
   h. Human factors considered.
   i. All diagrams, figures, and tables should be accurately and clearly labeled with meaningful names and/or titles. When there are numerous pages of computer-generated data, it is preferable to put this information in an appendix with an explanation in the report narrative. For each figure in the report, ensure that every feature of it is explained in the text.
6. **Laboratory test plans and results** for all portions of the system that you built and tested. Write a narrative description of test plan(s). Use tables, graphs, and whatever possible to show your results. Also, include a description of how you plan to test the final system, and any features you will include in the design to facilitate this testing. This section forms the written record of the performance of your design against specifications.
7. **Bills of materials:** Parts costs include only those items included in the final design. A detailed bill of materials includes (if possible) manufacturer, part number, part description, supplier, quantity, and cost.
8. **Gantt chart:** Show a complete listing of the major tasks to be performed, a time schedule for completing them, and which team member has the primary responsibility (and who will be held accountable) for each task.

9. **Ethical consideration:** Provide information on any ethical considerations that govern the product specifications you have developed or that need to be taken into account in potentially marketing the product.
10. **Safety:** Provide a statement of the safety consideration in your proposed design to the extent that is relevant.
11. **Conclusions:** Provide a reasoned listing of only the most significant results.
12. **Acknowledgments:** List individuals and/or companies that provided support in the way of equipment, advice, money, samples, and the like.
13. **References:** Including books, technical journals, and patents.
14. **Appendices:** As needed for the following types of information:
    a. Detailed computations and computer-generated data.
    b. Manufacturers' specifications.
    c. Original laboratory data.

5.7 SUMMARY

- Planning is an important engineering activity.
- The use of prototypes and models is important to consider during planning.
- Every product is developed through five phases: discovery, specification development, conceptual design, product development, and product support. Planning is needed to get through these phases in a timely, cost-effective manner.
- There are five planning steps: identify the tasks, state their objectives, estimate the resources needed, develop a sequence, and estimate the cost.
- There are many types of project plans. A goal is to design a plan to meet the needs of the project.
- Communication through reports and drawings are key to the success of any project.

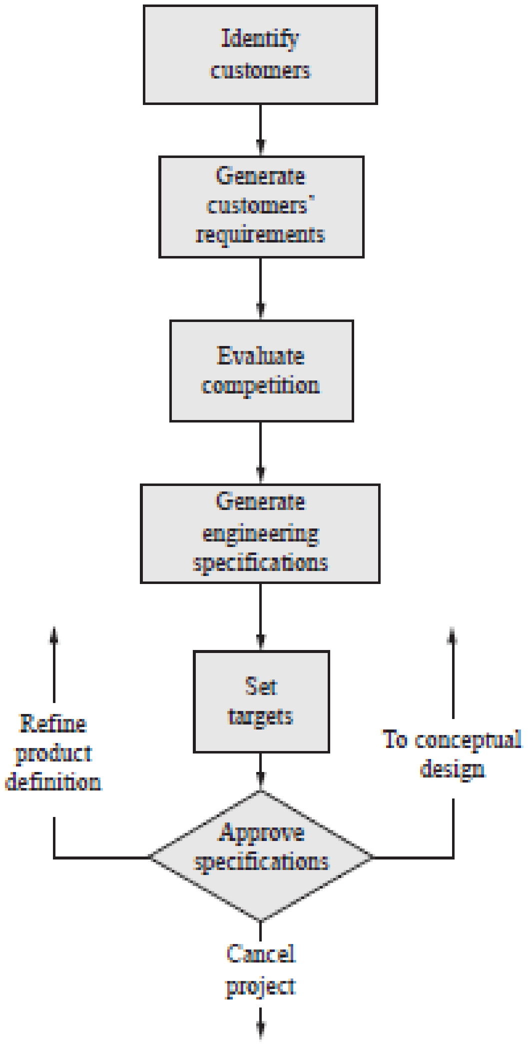


Figure 6.2 The Product Definition phase of the mechanical design process.

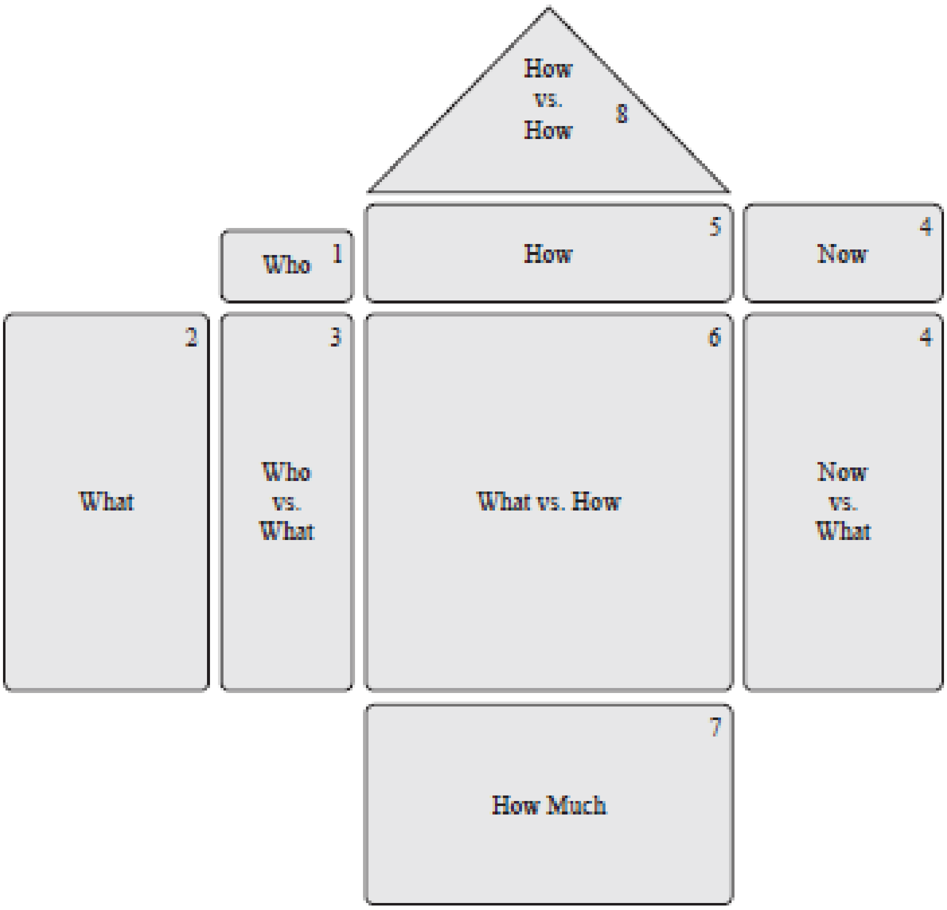


Figure 6.3 The house of quality, also known as the QFD diagram.

6.2 STEP 1: IDENTIFY THE CUSTOMERS: WHO ARE THEY?

6.3 STEP 2: DETERMINE THE CUSTOMERS' REQUIREMENTS: *WHAT* DO THE CUSTOMERS WANT?

Step 2.1: Specify the Information Needed Reduce the problem to a single statement describing the information needed. If no single statement represents what is needed, more than one data-collecting effort may be warranted.

Step 2.2: Determine the Type of Data-Collection Method to Be Used Base the use of focus groups, observations, or surveys on the type of information being collected.

Step 2.3: Determine the Content of Individual Questions A clear goal for the results expected from *each question* should be written. Each question should have a single goal. For a focus group or observation, this may not be possible for all questions, but it should be for the initial questions and other key questions.

Step 2.4: Design the Questions Each question should seek information in an unbiased, unambiguous, clear, and brief manner. Key guidelines are

Do not assume the customers have more than common knowledge.
Do not use jargon.
Do not lead the customer toward the answer you want.
Do not tangle two questions together.
Do use complete sentences.

Questions can be in one of four forms:

- Yes–no–don't know. (Poor for focus groups.)
- Ordered choices (1, 2, 3, 4, 5; strongly agree, mildly agree, neither agree nor disagree, mildly disagree, strongly disagree; or A = absolutely important, E = extremely important, I = important, O = ordinary, or U = unimportant [AEIOU]). Be sure that any ordered list is complete (i.e., that it covers the full range possible and that the choices are unambiguously worded). Scales with five gradations, as in the examples here, have proven best.
- Unordered choices (a, b, and/or c).
- Ranking (a is better than b is better than c).

The best questions ask about attributes, not influences. Attributes express what, where, how, or when. *Why* questions should lead to what, where, how, or when as they describe time, quality, and cost.

Step 2.5: Order the Questions Order the questions to give context. This will help participants in focus groups or surveys follow the logic.

Step 2.6: Take Data It usually takes repeated application to generate usable information. The first application of any set of questions should be considered a test or verification experiment.

Step 2.7: Reduce the Data A list of customers' requirements should be made in the customers' own words, such as "easy," "fast," "natural," and other abstract terms. A later step of the design process will be to translate these terms into engineering parameters. The list should be in positive terms—what the customers want, not what they don't want. We are not trying to patch a poor design; we are trying to develop a good one.

- Easy positioning of seat height of the aisle chair so that it matches the wheelchair and the plane's seat so that the passenger can easily slide from on to the other.
- Once in the aisle chair it should be easy to move and stable.
- The aisle chair should fit in all aircraft aisles
- When transferring between chairs, the passenger with possibly some help from the agent must lift their weight enough to slide from chair to chair, so there needs to be a good lifting position for both of them so they can exert minimal effort.
- All want the transfer from seat to seat to be as fast as possible.
- It should be easy to position chairs next to each other and have them not slide apart.

6.4 STEP 3: DETERMINE RELATIVE IMPORTANCE OF THE REQUIREMENTS: *WHO VERSUS WHAT*

6.5 STEP 4: IDENTIFY AND EVALUATE THE COMPETITION: HOW SATISFIED ARE THE CUSTOMERS *NOW*?

The goal here is to determine how the customer perceives the competition's ability to meet each of the requirements. Even though you may be working with a totally new design, there is competition, or at least products that come close to filling the same need that your product does. The purpose for studying existing products is twofold: first, it creates an awareness of what already exists (the "now"), and second, it reveals opportunities to improve on what already exists. In some companies, this process is called *competition benchmarking* and is a major aspect of understanding a design problem. In benchmarking, each competing product must be compared with customers' requirements (now versus what). Here we are concerned only with a subjective comparison that is based on customer opinion. Later, in step 8, we will do a more objective comparison. For each customer's requirement, we rate the existing design on a scale of 1 to 5:

1. The product does not meet the requirement at all.
2. The product meets the requirement slightly.
3. The product meets the requirement somewhat.
4. The product meets the requirement mostly.
5. The product fulfills the requirement completely.

6.6 STEP 5: GENERATE ENGINEERING SPECIFICATIONS: *HOW* WILL THE CUSTOMERS' REQUIREMENTS BE MET?

Table 6.1 Types of engineering specifications

- Functional performance
  - Flow of energy
  - Flow of information
  - Flow of materials
  - Operational steps
  - Operation sequence
- Human factors
  - Appearance
  - Force and motion control
  - Ease of controlling and sensing state
- Physical requirements
  - Physical properties
  - Available spatial envelope
- Reliability
  - Mean time between failures
  - Safety (hazard assessment)
- Life-cycle concerns
  - Distribution (shipping)
  - Maintainability
- Life-cycle concerns (continued)
  - Diagnosability
  - Testability
  - Reparability
  - Cleanability
  - Installability
  - Retirement
- Resource concerns
  - Time
  - Cost
  - Capital
  - Unit
  - Equipment
  - Standards
  - Environment
- Manufacturing/assembly requirements
  - Materials
  - Quantity
  - Company capabilities

6.7 STEP 6: RELATE CUSTOMERS' REQUIREMENTS TO ENGINEERING SPECIFICATIONS: *HOW* TO MEASURE *WHAT?*

6.8 STEP 7: SET ENGINEERING SPECIFICATION TARGETS AND IMPORTANCE: *HOW MUCH* IS GOOD ENOUGH?

In this step we fill in the basement of the house of quality. Here we set the targets and establish how important it is to meet each of them. There are three parts to this effort, as shown in Fig. 6.6, calculate the specification importance, measure how well the competition meets the specification, and develop targets for your effort.

6.8.1 Specification Importance

The first goal in this step is determining the importance for each specification. If a target is important, then effort needs to be expended to meet the target. If it is not important, then meeting the goal can be more easily relaxed. In the development of products, it is seldom that all targets can be met in the time available and so this effort helps guide what to work on. The method to find importance is as follows:

Step 2.1: For each customer multiply the importance weighting from step 3 with the 0-1-3-9 relationship values from step 6 to get the weighted values.

Step 2.2: Sum the weighted values for each specification. For specification "steps to adjust seat height" in Fig. 6.6, the passenger score is:

$4*9+6*0+15*0+10*0+3*1+7*0+24*0+6*0+5*9+15*3+5*1 = 134.$

Step 2.3: Normalize these sums across all specifications. The sum across all the specifications is 1475 so this specification has importance of 134/1475 = 9%.

Figure 6.6 shows the importance from both the passengers' and agents' viewpoints. Note that for the passenger specifications revolving around moving from their chair to the aisle chair are most important. From the agents' viewpoint both these specifications and time measures are important.

6.8.2 Measuring How Well the Competition Meets the Specifications

In step 4, the competitions' products were compared to customers' requirements. In this step, they will be measured relative to engineering specifications. This ensures that both knowledge and equipment exist for evaluation of any new products developed in the project. Also, the values obtained by measuring the competition give a basis for establishing the targets. This usually means obtaining actual samples of the competition's product and making measurements on them in the same way that measurements will be made on the product being designed. Sometimes this is not possible and literature or simulations are used to find values needed here.

The competition values are shown in Fig. 6.6.

6.8.3 Setting Specification Targets

Setting targets early in the design process is important; targets set near the end of the process are easy to meet but have no meaning as they always match what has been designed. However, setting targets too tightly may eliminate new ideas. Some companies refine their targets throughout concept development and then make them firm. The initial targets, set here, may have ±30% tolerance on them.

Most texts on QFD suggest that a single value be set as a target. However, once the design process is underway, often it is not possible to meet these exact values. In fact, a major part of engineering design is making decisions about how to manage targets and the tradeoff meeting them. There are two points to be made here. To make them, we will use a simple example.

Say you want to buy a new camera. You want to spend less than $300 and want at least 7.2 megapixels (your only two specifications). You look online and

6.9 STEP 8: IDENTIFY RELATIONSHIPS BETWEEN ENGINEERING SPECIFICATIONS: HOW ARE THE *HOWS* DEPENDENT ON EACH OTHER?

									■	Side tipping force at handles
								■	+	Fore/aft tipping force at handles
							■			Time to transfer between seats
						■				Force to push aisle chair
					■	+				Push force over 2cm bump
				■						Lifting force required by agent
			■	??			–			Force to slide 95% male passenger
		■								Force to adjust seat height
	■	–					–			Steps to adjust seat height
■										Seat width relative to frame width
Seat width relative to frame width	Steps to adjust seat height	Force to adjust seat height	Force to slide 95% male passenger	Lifting force required by agent	Push force over 2cm bump	Force to push aisle chair	Time to transfer between seats	Fore/aft tipping force at handles	Side tipping force at handles	
cm	#	kg	kg	kg	cm	kg	sec	kg	kg	
↓	↑	↓	↓	↓	↑	↓	↓	↓	↓	

Figure 6.7 Alternative QFD roof for a spreadsheet.

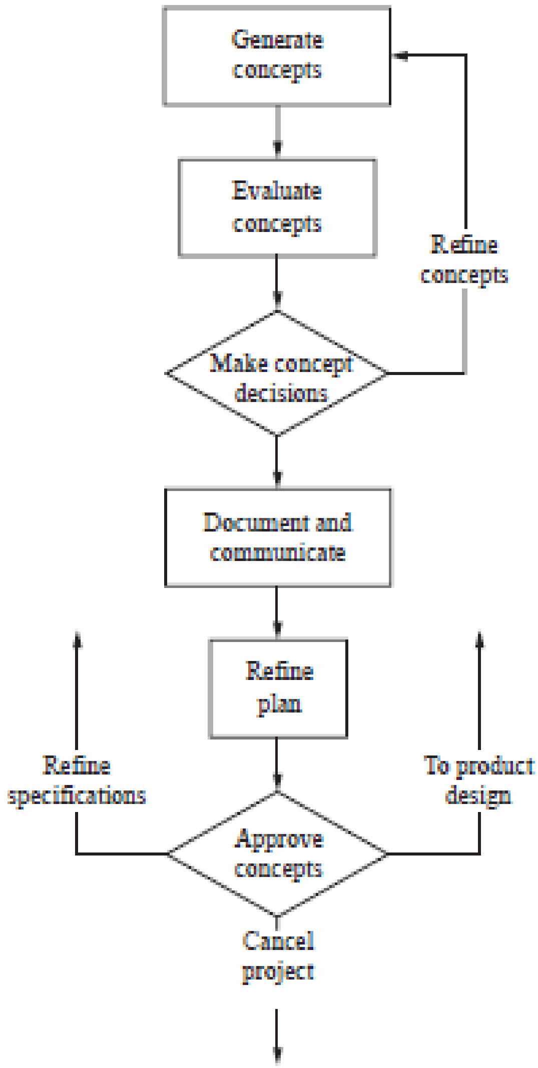


Figure 7.1 The Conceptual Design phase of the design process.

7.2 UNDERSTANDING THE FUNCTION OF EXISTING DEVICES

7.2.1 Defining "Function"

In reading this section, it is important to remember that *function* tells *what* the product must do, whereas its *form*, or *structure*, conveys *how* the product will do it. The effort in this chapter is to develop the *what* and then map the *how*. This is similar to the QFD in Chap. 6, where *what* the customer required was mapped into *how* the requirements were to be measured. Here we focus on *what* the product must do (its function) and then on *how* to do it (its form).

Function is the logical flow of energy (including static forces), material, or information between objects or the change of state of an object caused by one or more of the flows. For example, in order to attach any component to another, a person must *grasp* the component, *position* it, and *attach* it in place.

7.2.2 Using Reverse Engineering to Understand the Function of Existing Devices

Reverse engineering is a method to understand how a product works. Whereas we used product decomposition in Chap. 2 to understand a product's parts and assemblies, here we will focus on their function. In Chap. 2 we disassembled an Irwin Quick-Grip clamp (Fig. 7.4) and itemized the parts and how they were assembled. Here we will extend this decomposition to understand the function of the clamp—to reverse engineer it. This is more that just taking stuff apart, it is a key part of understanding how others solved the problem.

Reverse Engineering, functional decomposition, or benchmarking is a good practice because many hundreds of engineering hours have been spent developing the features of existing products, and to ignore this work is foolish. The QFD method, featured in Chap. 6, encourages the study of existing products as a basis for finding market opportunities and setting specification targets. Some organizations do not pay attention to products not developed within their walls—a very weak policy. These companies are said to have a case of "NIH" (i.e., Not Invented Here). Dissecting and reverse engineering the products of others helps overcome this policy.

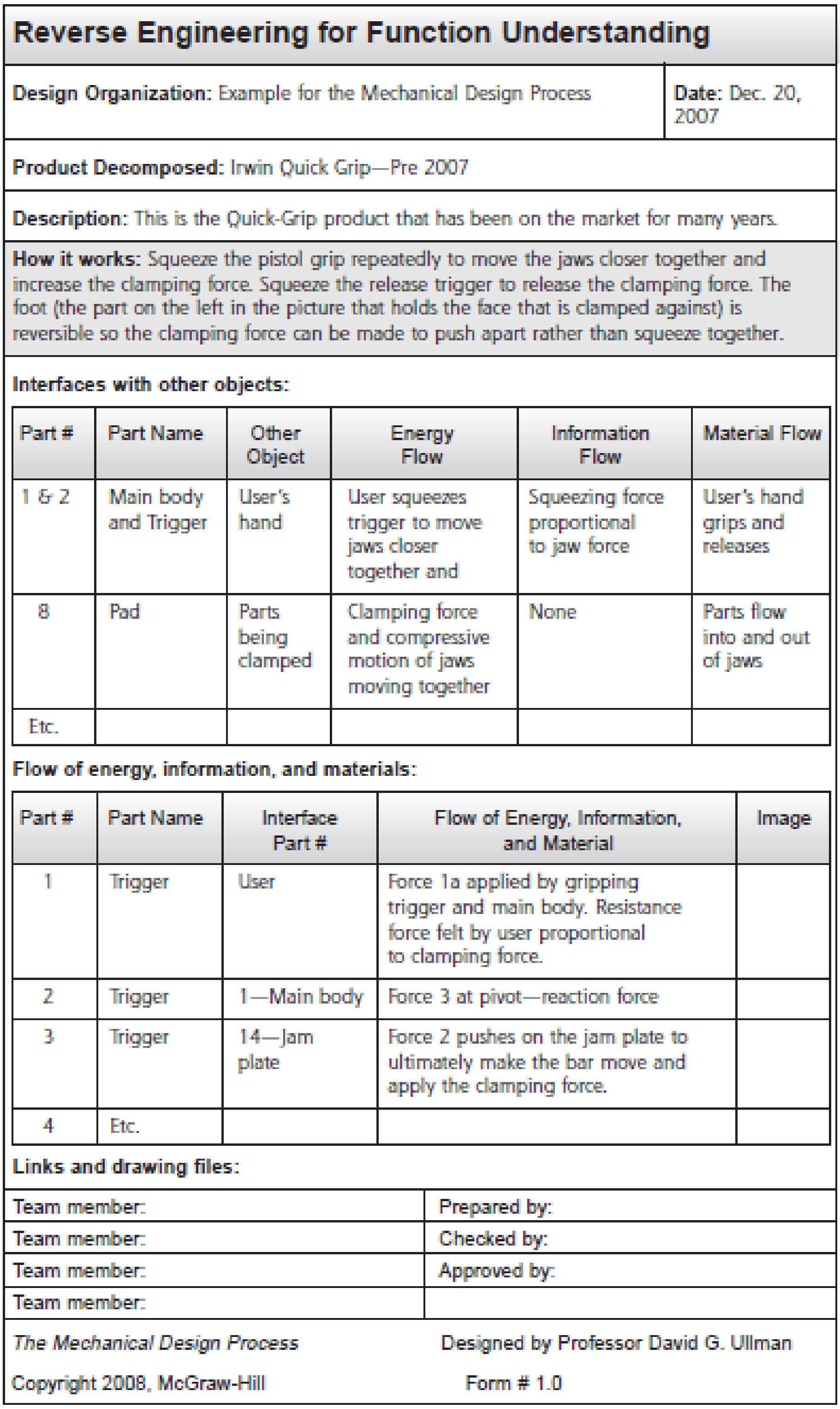
7.3 A TECHNIQUE FOR DESIGNING WITH FUNCTION

The goal of functional modeling is to decompose the problem in terms of the flow of energy, material, and information. This forces a detailed understanding at the beginning of the design project of *what* the product-to-be is to do. The functional decomposition technique is very useful in the development of new products.

There are four basic steps in applying the technique and several guidelines for successful decomposition. These steps are used iteratively and can be reordered as needed. This technique can be used with QFD to help understand the problem. In this discussion, the usefulness of the technique will be demonstrated with the one-handed bar clamp and with the GE X-ray CT Scanner introduced in Chap 4.

7.3.1 Step 1: Find the Overall Function That Needs to Be Accomplished

This is a good first step toward understanding the function. The goal here is to generate a single statement of the overall function on the basis of the customer requirements. All design problems have one or two "most important" functions. These must be reduced to a simple clause and put in a *black box*. The inputs to this box are all the energy, material, and information that flow into the boundary of the system. The outputs are what flows out of the system.



Reverse Engineering for Function Understanding

Design Organization: Example for the Mechanical Design Process

Date: Dec. 20, 2007

Product Decomposed: Irwin Quick Grip—Pre 2007

Description: This is the Quick-Grip product that has been on the market for many years.

How it works: Squeeze the pistol grip repeatedly to move the jaws closer together and increase the clamping force. Squeeze the release trigger to release the clamping force. The foot (the part on the left in the picture that holds the face that is clamped against) is reversible so the clamping force can be made to push apart rather than squeeze together.

Interfaces with other objects:

Part #	Part Name	Other Object	Energy Flow	Information Flow	Material Flow
1 & 2	Main body and Trigger	User's hand	User squeezes trigger to move jaws closer together and	Squeezing force proportional to jaw force	User's hand grips and releases
8	Pad	Parts being clamped	Clamping force and compressive motion of jaws moving together	None	Parts flow into and out of jaws
Etc.					

Flow of energy, information, and materials:

Part #	Part Name	Interface Part #	Flow of Energy, Information, and Material	Image
1	Trigger	User	Force 1a applied by gripping trigger and main body. Resistance force felt by user proportional to clamping force.	
2	Trigger	1—Main body	Force 3 at pivot—reaction force	
3	Trigger	14—Jam plate	Force 2 pushes on the jam plate to ultimately make the bar move and apply the clamping force.	
4	Etc.			

Links and drawing files:

Team member:	Prepared by:
Team member:	Checked by:
Team member:	Approved by:
Team member:	

The Mechanical Design Process Designed by Professor David G. Ullman

Copyright 2008, McGraw-Hill Form # 1.0

Figure 7.8 Reverse Engineering Template sample.

Some guidelines for step 1 are:

Guideline: Energy Must Be Conserved. Whatever energy goes into the system must come out or be stored in the system.

Guideline: Material Must Be Conserved. Materials that pass through the system boundary must, like energy, be conserved.

Guideline: All Interfacing Objects and Known, Fixed Parts of the System Must Be Identified. It is important to list all the objects that interact, or interface, with the system. Objects include all features, components, assemblies, humans, or elements of nature that exchange energy, material, or information with the system being designed. These objects may also constrain the system's size, shape, weight, color, and the like. Further, some objects are part of the system being designed that cannot be changed or modified. These too must be listed at the beginning of the design process.

Guideline: Ask the Question, How Will the Customer Know if the System Is Performing? Answers to this question will help identify information flows that are important.

Guideline: Use Action Verbs to Convey Flow. Action verbs such as those in Table 7.1 can be used to describe function. Obviously, many other verbs beyond those listed tell about the intended action.

> *Finding the Overall Function: The One-Handed Bar Clamp*
> For the one-handed bar clamp, the "most important" function is very simple "transform the grip force of one hand to a controllable force capable of clamping common objects together" (Fig. 7.9). This statement is brief, it tells that the goal is to alter the energy flow while sensing the force applied, and that the boundaries of the system are the one hand and the objects being clamped.
>
> *Finding the Overall Function: The X-Ray CT Scanner*
> For the CT Scanner shown in Fig. 7.10 (taken from Fig. 4.2), the top-level function is "convert electrical energy into an image of the organs of a patient."

Table 7.1 Typical mechanical design functions

Absorb/remove
Actuate
Amplify
Assemble/disassemble
Change
Channel or guide
Clear or avoid
Collect
Conduct
Control
Convert
Couple/interrupt
Direct
Dissipate
Drive
Hold or fasten
Increase/decrease
Interrupt
Join/separate
Lift
Limit
Locate
Move
Orient
Position
Protect
Release
Rectify
Rotate
Secure
Shield
Start/stop
Steer
Store
Supply
Support
Transform
Translate
Verify

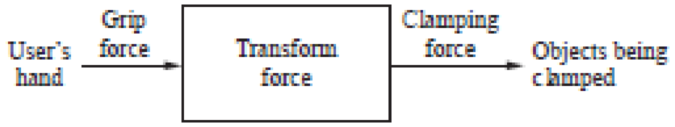


Figure 7.9 Top-level function for the one-handed bar clamp.

This statement assumes the boundary considered is the entire CT Scanner and the computer and software that make the image. We could draw the boundary tighter, just around the device shown in the figure, and say "convert electrical energy into a signal that contains information about an image of the organs of a patient." The difference is small, but indicates the change in boundary.

7.3.2 Step 2: Create Subfunction Descriptions

The goal of this step and step 3 is to decompose the overall function. This step focuses on identifying the subfunctions needed, and the next step concerns their organization.

Guideline: Consider *What*, Not *How*. It is imperative that only *what* needs to happen—the function—be considered. Detailed, structure-oriented *how* considerations should be documented for later use as they add detail too soon here. Even though we remember functions by their physical embodiments, it is important that we try to abstract this information. If, in a specific problem solution, it is not possible to proceed without some basic assumptions about the form or structure of the device, then document the assumptions.

Guideline: Use Only Objects Described in the Problem Specification or Overall Function. To ensure that new components do not creep into the product unintentionally, use only nouns previously used (e.g., in the QFD or in step 1) to describe the material flow or interfacing objects. If any other nouns are used during this step, either something is missing in the first step (go back to step 1 and reformulate the overall function), the specifications are incomplete, or a design decision to add another object to the system has been made (consider very carefully). Adding objects is not bad as long as it is done consciously.

Guideline: Break the Function Down as Finely as Possible. This is best done by starting with the overall function of the design and breaking it into the separate functions. Let each function represent a change or transformation in the flow of material, energy, or information. Action verbs often used in this activity are given in Table 7.1.

Guideline: Consider All Operational Sequences. A product may have more than one operating sequence while in use (see Fig. 1.7). The functions of the device may be different during each of these. Additionally, prior to the actual *use* there may be some *preparation* that must be modeled, and similarly, after use there may be some *conclusion*. It is often effective to think of each function in terms of its preparation, use, and conclusion.

Guideline: Use Standard Notation When Possible. For some types of systems, there are well-established methods for building functional block diagrams. Common notation schemes exist for electrical circuits and piping systems, and block diagrams are used to represent transfer functions in system dynamics and control. Use these notation schemes if possible. However, there is no standard notation for general mechanical product design.

7.3.3 Step 3: Order the Subfunctions

The goal is to add order to the functions generated in the previous step. For many redesign problems, this occurs simultaneously with their identification in step 2, but for some material processing systems this is a major step. The goal here is to order the functions found in step 2 to accomplish the overall function in step 1. The guidelines and examples presented next should help with this step.

Guideline: The Flows Must Be in Logical or Temporal Order. The operation of the system being designed must happen in a logical manner or in a time sequence. This sequence can be determined by rearranging the subfunctions. First, arrange them in independent groups (preparation, uses, and conclusion). Then arrange them within each group so that the output of one function is the input of another. This helps complete the understanding of the flows and helps find missing functions.

Guideline: Redundant Functions Must Be Identified and Combined. Often there are many ways to state the same function. If each member of the design team has written his or her subfunctions on self-stick removable notepaper, all the pieces can be put on the wall and grouped by similarity. Those that are similar need to be combined into one subfunction.

Guideline: Functions Not Within the System Boundary Must Be Eliminated. This step helps the team come to mutual agreement on the exact system boundaries; it is often not as simple as it sounds.

Guideline: Energy and Material Must Be Conserved as They Flow Through the System. Match inputs and outputs to the functional decomposition.

Creating a Subfunction Description: The Irwin Quick-Grip Example

A functional decomposition for the one-handed bar clamp is shown in Fig. 7.11. Keep in mind when studying this figure that there is no one right way to do a functional decomposition and that the main reason for doing it is to ensure that the function of the device to be developed is understood. Note that each function statement begins with an action verb from the list in Table 7.1 and then follows with a noun. The boxes are oriented in a logical fashion. Also, note that in this example, the main flow is energy, but there is an information feedback to the user. Would a clamp be as useful, if there were no feedback?

Many functions on this diagram can be further refined. Not shown in the diagram is the release of any locking mechanism, a further refinement of the "hold force on object" box.

Creating Subfunction Description: The CT Scanner

The CT Scanner is a complex device. The functional diagram fills many pages. A partially completed segment, focusing on the X-ray tube, is shown in Fig. 7.12. Here, the function "Convert electrical power to X-rays" is shown

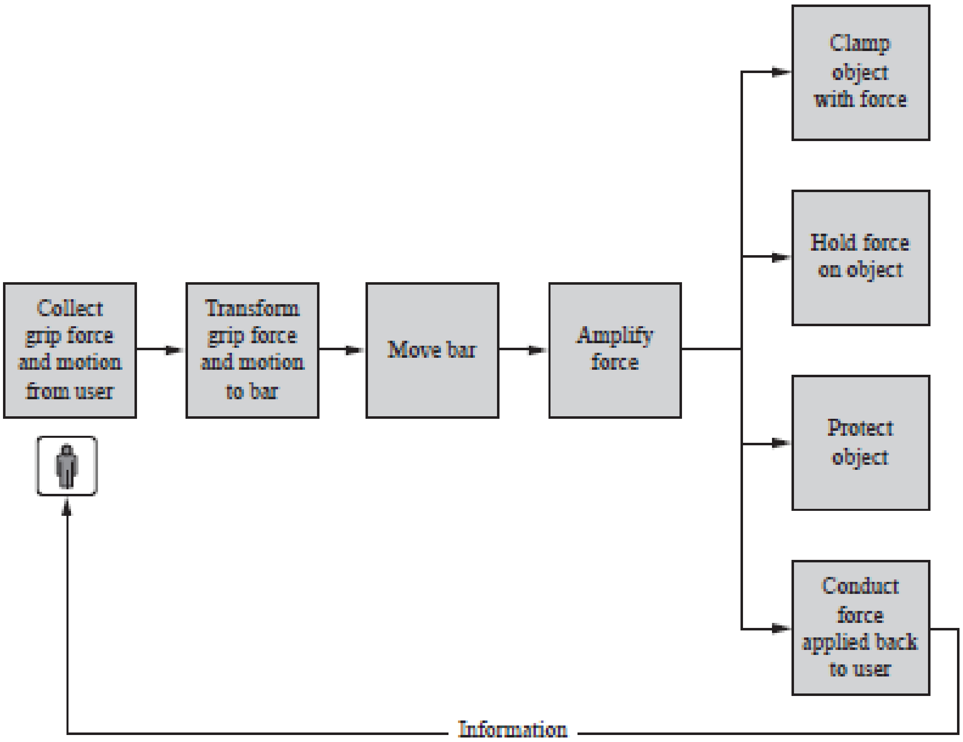


Figure 7.11 Functional decomposition for the one-handed bar clamp.

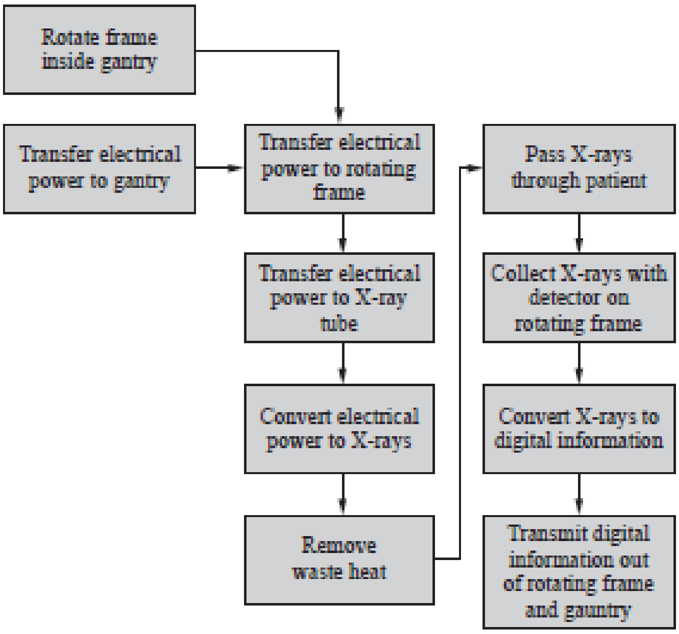


Figure 7.12 Functional decomposition of the CT Scanner.

with many subfunctions yet to be organized. Many of the functions are focused on the transformation of electrical energy. One of them, "Remove waste heat" is especially difficult as only about 1% of the energy is actually converted into X-rays, the other 60+ kW of energy is transformed into waste heat. The removal of this waste heat will be revisited in Chap. 10.

7.3.4 Step 4: Refine Subfunctions

The goal is to decompose the subfunction structure as finely as possible. This means examining each subfunction to see if it can be further divided into sub-subfunctions. This decomposition is continued until one of two things happens: "atomic" functions are developed or new objects are needed for further refinement. The term atomic implies that the function can be fulfilled by existing objects. However, if new objects are needed, then you want to stop refining because new objects require commitment to how the function will be achieved, not refinement of what the function is to be. Each noun used represents an object or a feature of an object.

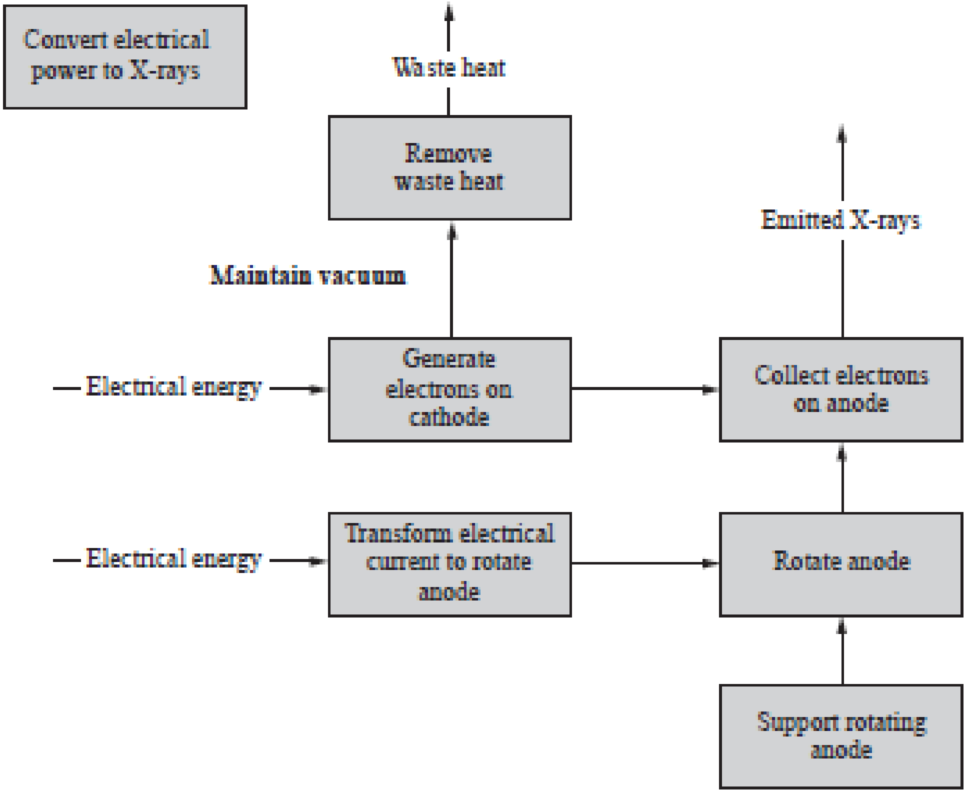


Figure 7.13 Refined functional decomposition for the conversion of electrical power to X-rays.

7.4 BASIC METHODS OF GENERATING CONCEPTS

7.4.1 Brainstorming as a Source of Ideas

Brainstorming, initially developed as a group-oriented technique, can also be used by an individual designer. What makes brainstorming especially good for group efforts is that each member of the group contributes ideas from his or her own viewpoint. The rules for brainstorming are quite simple:

1. Record all the ideas generated. Appoint someone as secretary at the beginning; this person should also be a contributor.
2. Generate as many ideas as possible, and then verbalize these ideas.
3. Think wild. Silly, impossible ideas sometimes lead to useful ideas.
4. Do not allow evaluation of the ideas; just the generation of them. This is very important. Ignore any evaluation, judgment, or other comments on the value of an idea and chastise the source.

In using this method, there is usually an initial rush of obvious ideas, followed by a period when ideas will come more slowly with periodic rushes. In groups, one member's idea will trigger ideas from the other team members. A brainstorming session should be focused on one specific function and allowed to run through at least three periods during which no ideas are being generated. It is important to encourage humor during brainstorming sessions as even wild, funny ideas can spark useful concepts. This is a proven technique that is useful when new ideas are needed.

7.4.2 Using the 6-3-5 Method as a Source of Ideas

A drawback to brainstorming is that it can be dominated by one or a few team members (see Section 3.3.6). The 6-3-5 method forces equal participation by all. This method is effectively brainstorming on paper and is called *brainwriting* by some. The method is similar to that shown in Fig. 7.14.

To perform the 6-3-5 method, arrange the team members around a table. The optimal number of participants is the "6" in the method's name. In practice, there can be as few as 3 participants or as many as 8. Each takes a clean sheet of paper and divides it into three columns by drawing lines down its length. Next, each team member writes 3 ideas for how to fulfill a specific agreed-upon function, one at the top of each column. The number of ideas is the "3" in the method's name. These ideas can be sketched or written as text. They must be clear enough that others can understand the important aspects of the concept.

After 5 minutes of work on the concepts, the sheets of paper are passed to the right. The time is the "5" in the method's name. The team members now have another 5 minutes to add 3 more ideas to the sheet. This should only be done after studying the previous ideas. They can be built on or ignored as seen fit. As the papers are passed in 5-minute intervals, each team member gets to see the input

7.4.3 The Use of Analogies in Design

Using analogies can be a powerful aid to generating concepts. The best way to think of analogies is to consider a needed function and then ask, *What else provides similar function?* An object that provides similar function may trigger ideas for concepts. For example, ideas for the one-handed bar clamp came from a caulking gun (Fig. 7.2).

Many analogies come from nature. For example, engineers are studying the skin of sharks to reduce drag on boats; how ants manage traffic to reduce congestion; and how moths, snakes, and dogs sense odors for bomb detection.

Analogies can also lead to poor ideas. For centuries, people watched birds fly by flapping their wings. By analogy, flapping wings lift birds, so flapping wings should lift people. It wasn't until people began to experiment with fixed wings that the real potential of manned flight became a reality. In fact, what occurred is that by the time of the Wright Brothers in the early 1900s, the problem of manned flight had been divided into four main functions, each solved with some independence of the others: lift, stability, control, and propulsion. The Wright Brothers actually approached each of these in the order listed to achieve controlled, sustained flight.

7.4.4 Finding Ideas in Reference Books and Trade Journals and on the Web

Most reference books give analytical techniques that are not very useful in the early stages of a design project. In some, you will find a few abstract ideas that are useful at this stage—usually in design areas that are quite mature and with ideas so decomposed that their form has specific function. A prime example is the area of linkage design. Even though a linkage is mostly geometric in nature, most linkages can be classified by function. For example, there are many geometries that can be classified by their function of generating a straight line along part of their cycle. (The function is to move in a straight line.) These straight-line mechanisms can be grouped by function. Two such mechanisms are shown in Fig. 7.15.

Many good ideas are published in trade journals that are oriented toward a specific discipline. Some, however, are targeted at designers and thus contain information from many fields. A listing of design-oriented trade journals is given in Sources at the end of this chapter (Section 7.11).

7.4.5 Using Experts to Help Generate Concepts

If designing in a new domain, one in which we are not experienced, we have two choices to gain the knowledge sufficient to generate concepts. We either find someone with expertise in that domain or spend time gaining experience on our own. It is not always easy to find an expert; the domain may even be one that has no experts.

> To steal ideas from one person is plagiarism;
> to steal from many is research.

7.5 PATENTS AS A SOURCE OF IDEAS

Patent literature is a good source of ideas. It is relatively easy to find patents on just about any subject imaginable and many that are not. Problems in using patents are that it is hard to find exactly what you want in the literature; it is easy to find other, interesting, distracting things not related to the problem at hand; and patents are not very easy to read.

There are two main types of patents: *utility patents* and *design patents*. The term *utility* is effectively synonymous with *function*, so the claims in a utility patent are about how an idea operates or is used. Almost all patent numbers you see on products are for utility patents. Design patents cover only the look or form of the idea, so here the term *design* is used in the visual sense. Design patents are not very strong, as a slight change in the form of a device that makes it look different is considered a different product. All design patent numbers begin with the letter "D." Utility patents are very powerful, because they cover how the device works, not how it looks.

7.6 USING CONTRADICTIONS TO GENERATE IDEAS

Contradictions are engineering "trade-offs." A contradiction occurs when something gets better, forcing something else to get worse. This means that the ability to fulfill the target for one requirement adversely affects the ability to fulfill another. Some examples are

- Increasing the speed with which squeezing the grip on the one-handed bar clamp moves the jaws together (good) lowers the clamping force (bad).
- The product gets stronger (good) but the weight increases (bad).
- More functions (good) make products larger and heavier (bad).
- An automobile airbag should deploy very fast, to protect the occupant (good), but the faster it deploys, the more likely it is to injure somebody (bad).

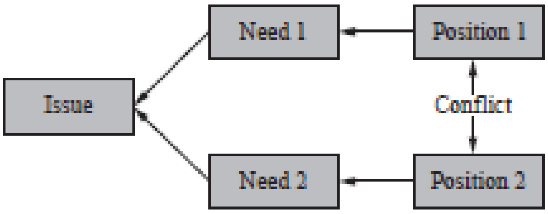


Figure 7.17 Basic structure of the Evaporating Cloud.

3. Identify the issue, the objective of the needs.
4. Generate the assumptions that underlie all of the above.
5. Articulate interjections that can relieve the conflict while meeting the objective.

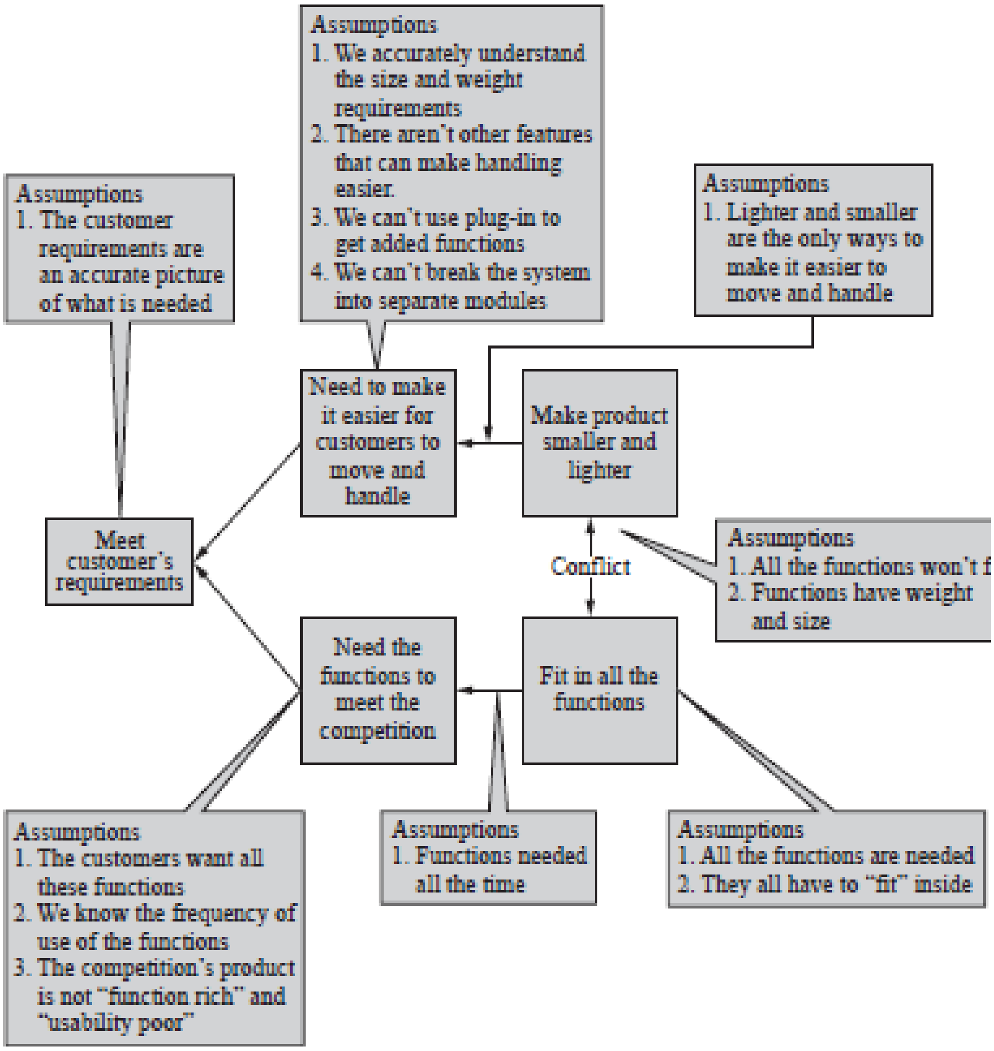


Figure 7.20 The assumptions.

7.8 BUILDING A MORPHOLOGY

The technique presented here uses the functions identified to foster ideas. It is a very powerful method that can be used formally, as presented here, or informally as part of everyday thinking. There are three steps to this technique. The first step is to list the decomposed functions that must be accomplished. The second step is to find as many concepts as possible that can provide each function identified in the decomposition. The third is to combine these individual concepts into overall concepts that meet all the functional requirements. The design engineer's knowledge and creativity are crucial here, as the ideas generated are the basis for the remainder of the design evolution. This technique is often called the "morphological method," and the resulting table a "morphology," which means "a study of form or structure." A partial Morphology for the redesign of the one-handed bar clamp is presented in Figure 7.21. This is highly modified from the morphology done at Irwin to protect their intellectual property. A blank morphology is available as a template.

7.8.1 Step 1: Decompose the Function

7.8.2 Step 2: Develop Concepts for Each Function

The designer making a fundamental assumption. For example, one function that has to occur in the system is "Collect grip force and motion from user." It is reasonable to assume that a gripping force will be used to provide motion and clamping force *only if the designer is aware that an assumption has been made.*

The function is directed at **how,** *not* **what.** If one idea gets built into the function, then it should come as no surprise that this is the only idea that gets generated. For example, if "Transform grip force and motion to bar" in Fig. 7.21 had been stated as "use jam plate to transform motion," then only jam plate ideas are possible. If the function statement has nouns that tell *how* the function is to be accomplished, reconsider the function statement.

The domain knowledge is limited. In this case, help is needed to develop other ideas. (See Sections 7.5, 7.6, or 7.7.)

7.8.3 Step 3: Combine Concepts

7.9 OTHER IMPORTANT CONCERNS DURING CONCEPT GENERATION

The techniques outlined in this chapter have focused on generating potential concepts. In performing these techniques, functional decomposition diagrams, literature and patent search results, function-concept mapping, and sketches of overall concepts are all produced. These are all important documents that can support communication to others and archive the design process.

> Follow the KISS rule: *Keep It Simple, Stupid.*

Additionally, conceptual design is a good time to review the Hannover Principles introduced in Chap. 1. Questions derived from the Principles that should be asked at this time are

1. Do your concepts enable humanity and nature to coexist in a healthy, supportive, diverse, and sustainable condition?
2. Do you understand the effects of your concepts on other systems, even the distant effects?
3. Are concepts safe and of long-term value?.
4. Do your concepts help eliminate the concept of waste throughout their life cycle?
5. Where possible, do they rely on natural energy flows?

7.10 SUMMARY

- The functional decomposition of existing products is a good method for understanding them.
- Functional decomposition encourages breaking down the needed function of a device as finely as possible, with as few assumptions about the form as possible.
- The patent literature is a good source for ideas.
- Exploring contradictions can lead to ideas.
- Listing concepts for each function helps generate ideas; this list is often called a *morphology*.
- Sources for conceptual ideas come primarily from the designer's own expertise; this expertise can be enhanced through many basic and logical methods.

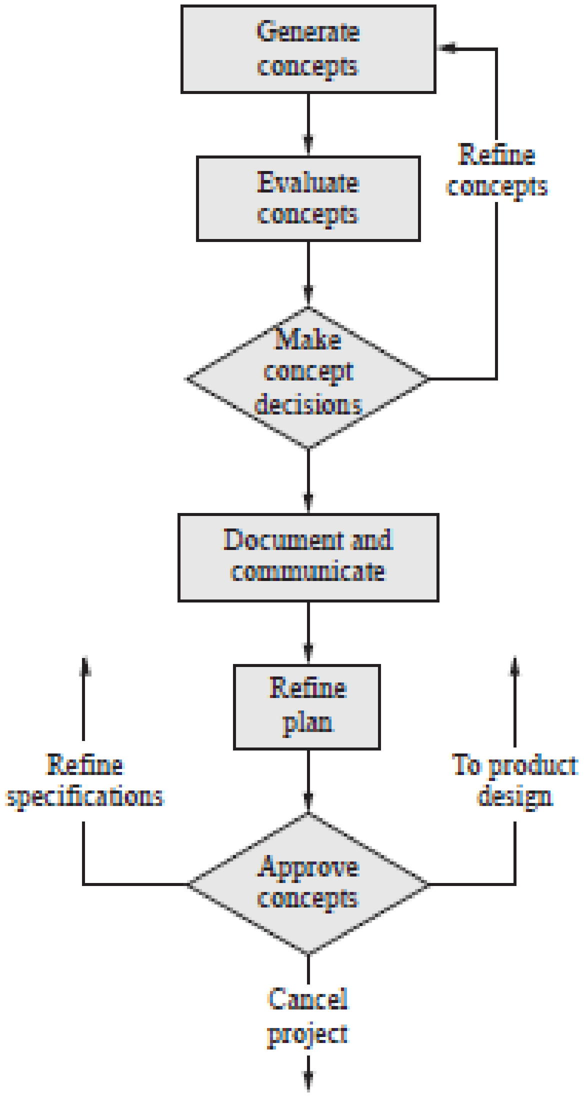


Figure 8.1 The conceptual design phase.

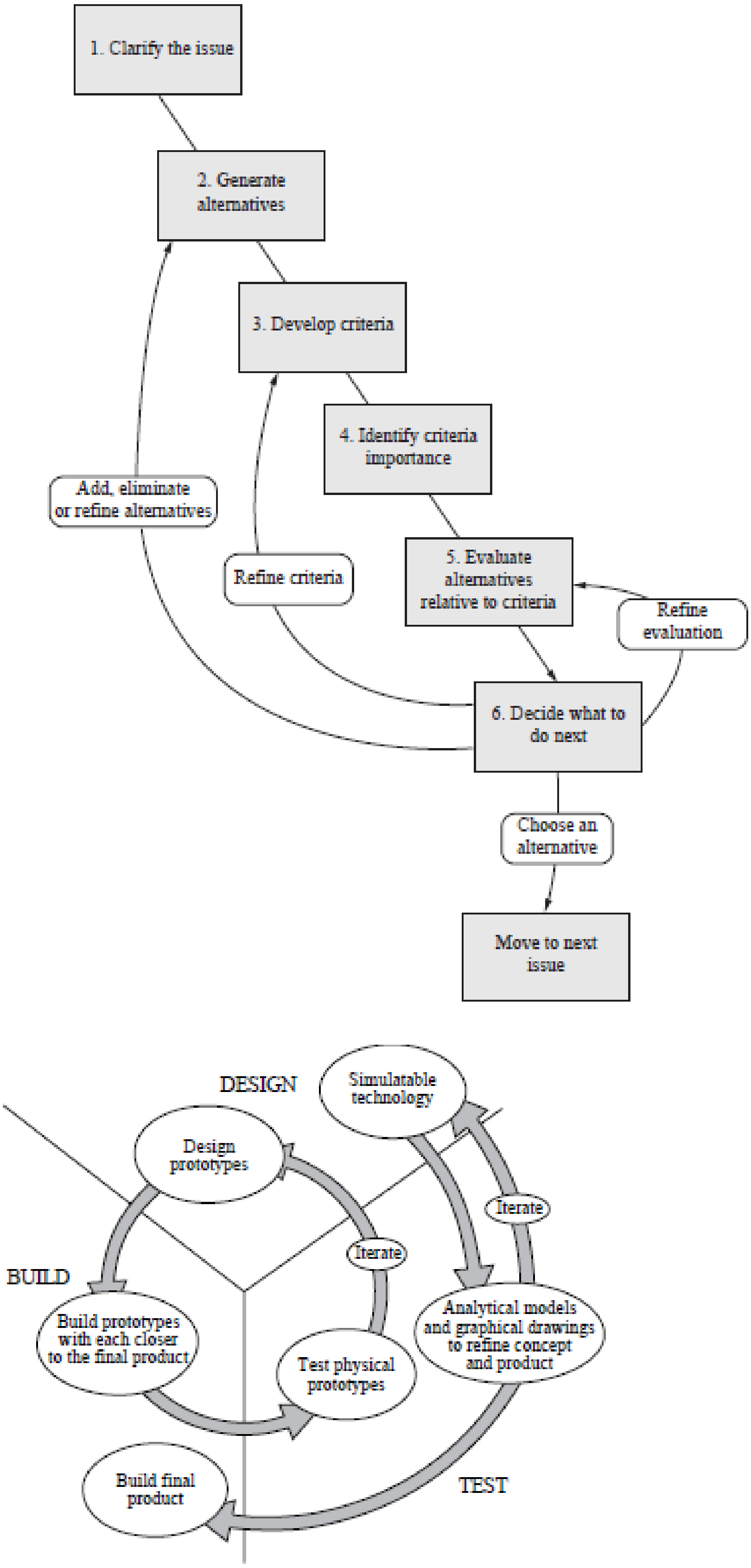


Figure 8.3 Design evaluation cycles.

8.3 FEASIBILITY EVALUATIONS

As a concept is generated, a designer usually has one of three immediate reactions: (1) it is not feasible, it will never work; (2) it might work if something else happens; and (3) it is worth considering. These judgments about a concept's feasibility are based on "gut feel," a comparison made with prior experience stored as design knowledge. The more design experience, the more reliable an engineer's knowledge and the decision at this point. Let us consider the implications of each of the possible initial reactions more closely.

It Is Not Feasible. If a concept seems infeasible, or unworkable, it should be considered briefly from different viewpoints before being rejected. Before an idea is discarded, it is important to ask, Why is it not feasible? There may be many reasons. It may be obviously technologically infeasible. It may not meet the customer's requirements. It may just be that the concept is different from the way things are normally done. Or it may be that because the concept is not an original idea, there is no enthusiasm for it. We will delay discussing the first two reasons until Section 8.4, and we will discuss the latter two here.

It Is Conditional. The initial reaction might be to judge a concept workable *if something else happens*. Typical of other factors involved are the readiness of technology, the possibility of obtaining currently unavailable information, or the development of some other part of the product.

It Is Worth Considering. The hardest concept to evaluate is one that is not obviously a good idea or a bad one, but looks worth considering. Engineering knowledge and experience are essential in the evaluation of such a concept. If sufficient knowledge is not immediately available for the evaluation, it must be developed. This is accomplished by developing models or prototypes that are easily evaluated.

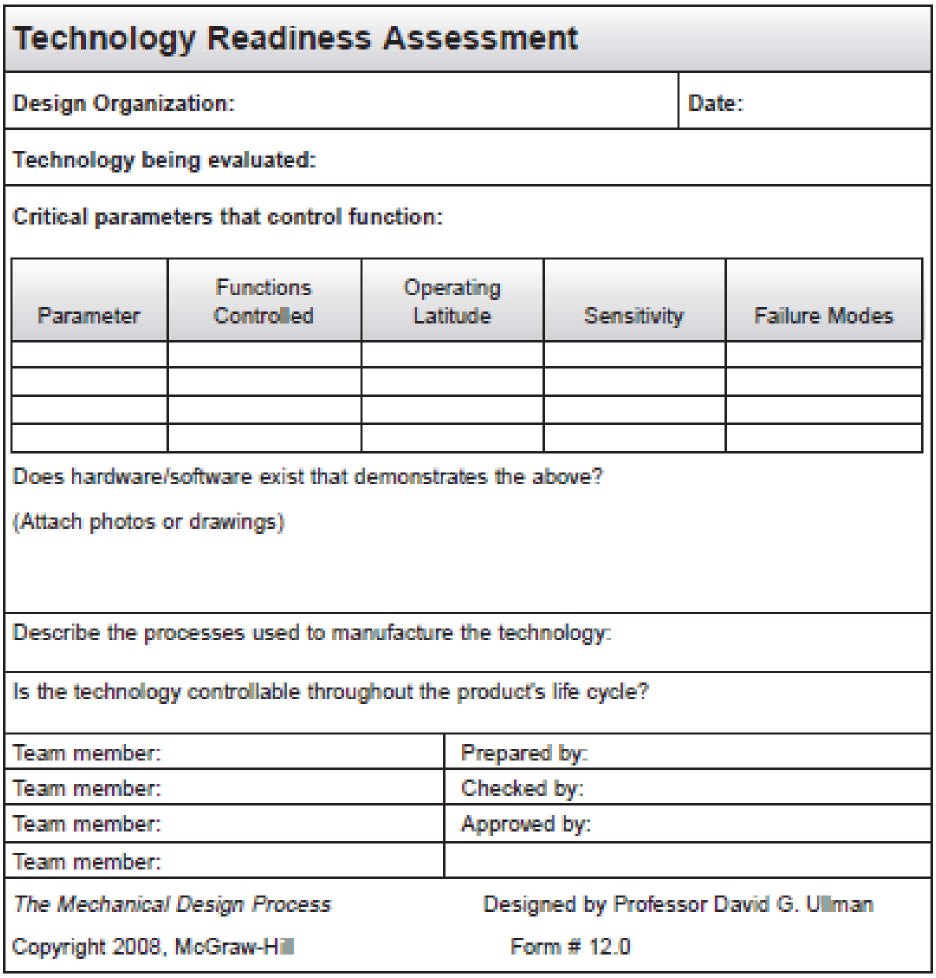
8.4 TECHNOLOGY READINESS

1. *Are the critical parameters identified?* Every design concept has certain parameters that are critical to its proper operation and use. It is important to know which parameters (e.g., dimensions, material properties, or other features) are critical to the function of the device. It has been estimated that only about 10 to 15% of the dimensions on a finished component are critical to the operation of the product. For a simple cantilever spring, the critical parameters are its length, its moment of inertia about the neutral axis, the distance from the neutral axis to the most highly stressed material, the modulus of elasticity, and the maximum allowable yield stress. These parameters allow for the calculation of the spring stiffness and the failure potential for a given force. The first three parameters are dependent on the geometry; the last two are dependent on the material properties. Say you need a ceramic spring in a

concept. Are the material properties modulus of elasticity and the maximum allowable yield stress the correct material properties to be considering?

Additional critical parameters determine a device's acceptability as a product (e.g., weight, size, and other physical parameters). These too must be identified, but may not be well known at this stage of development.

2. *Are the safe operating latitude and sensitivity of the parameters known?* In refining a concept into a product, the actual values of the parameters may have to be varied to achieve the desired performance or to improve manufacturability. It is essential to know the limits on these parameters and the sensitivity of the product's operation to them. This information is known in only a rough way during the early design phases; during the product evaluation, it will become extremely important.
3. *Have the failure modes been identified?* Every type of system has characteristic failure modes. It is generally useful to continuously evaluate the different ways a product might fail. This is expanded on in Chap. 11.
4. *Can the technology be manufactured with known processes?* If reliable manufacturing processes have not been refined for the technology, then, either the technology should not be used or there must be a separate program for developing the manufacturing capability. There is a risk in the latter alternative, as the separate program could fail, jeopardizing the entire project.
5. *Does hardware exist that demonstrates positive answers to the preceding four questions?* The most crucial measure of a technology's readiness is its prior use in a laboratory model or another product. If the technology has not been demonstrated as mature enough for use in a product, the designer should be very wary of assurances that it will be ready in time for production.
6. *Is the technology controllable throughout the product's life cycle?* This question addresses the later stages of the product's life cycle: its manufacture, use, service, and retirement. It also raises other questions. What manufacturing by-products come from using this technology? Can the by-products be safely disposed of? How will this product be retired? Will it degrade safely? Answers to these questions are the responsibility of the design engineer.



Technology Readiness Assessment

Design Organization:

Date:

Technology being evaluated:

Critical parameters that control function:

Parameter	Functions Controlled	Operating Latitude	Sensitivity	Failure Modes

Does hardware/software exist that demonstrates the above?

(Attach photos or drawings)

Describe the processes used to manufacture the technology:

Is the technology controllable throughout the product's life cycle?

Team member:	Prepared by:
Team member:	Checked by:
Team member:	Approved by:
Team member:	

The Mechanical Design Process Designed by Professor David G. Ullman

Copyright 2008, McGraw-Hill Form # 12.0

Figure 8.4 Technology readiness assessment.

Often, if these questions are not answered in the positive, a consultant or vendor can be added to the team to help. This is especially true for manufacturing technologies for which the design engineer cannot possibly know all the methods available to manufacture a product. In general, negative answers to these questions may imply that this is a research project not a product development project. This realization may have an impact on the project plan as research takes longer than design. A technology readiness assessment template, Fig. 8.4, can be used for this assessment.

Step 1: State the Issue. The issue is not always obvious, but here it is clearly "Choose a concept for continued development."

Step 2: Select the Alternatives to Be Compared. The alternatives to be compared are the different ideas developed during concept generation. It is important that all the concepts to be compared be at the same level of abstraction and in the same language. This means it is best to represent all the concepts in the same way. Generally, a simple sketch is best. In making the sketches, ensure that knowledge about the functionality, structure, technologies needed, and manufacturability is at a comparable level in every figure.

Step 3: Choose the Criteria for Comparison. First, it is necessary to know the basis on which the alternatives are to be compared with each other. Using the QFD method in Chap. 6, an effort was made to develop a full set of customer requirements for a design. These were then used to generate a set of engineering requirements and targets that will be used to ensure that the resulting product will meet the customer requirements. However, the concepts developed in Chap. 7 might not be refined enough to compare with the engineering targets for evaluation.

If they are not, we have a mismatch in the level of abstraction and use of the engineering targets must wait until the concept is refined to the point that actual measurements can be made on the product designs. Usually the basis for comparing the design concepts is a mix of customer requirements and engineering specifications, matched to the level of fidelity of the alternatives.

If the customers' requirements have not been developed, then the first step should be to develop criteria for comparison. The methods discussed in Chap. 6 should help with this task.

Additionally, the technology readiness measures can also help with evaluation here. This is especially true if the alternatives are dependent on new technologies.

Step 4: Develop Relative Importance Weightings. In step 3 of the QFD method (Section 6.4) there is a discussion of how to capture the relative importance of the criteria. The methods developed there can be used here to indicate which of the criteria are more important and which are less important. It is often worthwhile to measure the relative importance for different groups of customers, as discussed in Section 6.4.

Step 5: Evaluate Alternatives. By this time in the design process, every designer has a favorite alternative; one that he or she thinks is the best of the concepts that have yet to be developed. This concept is used as a *datum,* all other designs being compared with it as measured by each of the customer requirements. If the problem is for the redesign of an existing product, then the existing product, abstracted to the same level as the concepts, can be used as the datum.

For each comparison, the concept being evaluated is judged either better than, about the same as, or worse than the datum. If it is better than the datum, the concept is given a + score. If it is judged to be about the same as the datum or if there is some ambivalence, an S ("same") is used. If the concept does not meet the criterion as well as the datum does, it is given a – score. If the Decision Matrix is on a spreadsheet use +1, 0, –1 for scoring.

Note that if it is impossible to make a comparison to a design requirement, more information must be developed. This may require more analysis, further experimentation, or just better visualization. It may even be necessary to refine the design, through the methods to be described in Chaps. 9–11 and then return to make the comparison. Note that the frailty in doing this step is the topic of Sections 8.6 and 8.7.

In using the Decision Matrix there are two possible types of comparisons. The first type is *absolute* in that each alternative concept is directly (i.e., absolutely) compared with some target set by a criterion. The second type of comparison is *relative* in that alternative concepts are compared with each other using measures defined by the criteria. In choosing to use a datum the comparison is relative. However, many people use the method for absolute comparisons. Absolute comparisons are possible only when there is a target. Relative comparisons can be made only when there is more than one option.

Step 6: Compute the Satisfaction and Decide What to Do Next. After a concept is compared with the datum for each criterion, four scores are generated: the number of plus scores, the number of minus scores, the overall total, and the weighted total. The overall total is the difference between the number of plus scores and the number of minus scores. This is an estimate of the decision-makers' satisfaction with the alternative. The weighted total can also be computed. This is the sum of each score multiplied by the importance weighting, in which an S counts as 0, a + as +1, and a – as –1. Both the weighted and the unweighted scores must not be treated as absolute measures of the concept's value; they are for guidance only. The scores can be interpreted in a number of ways:

- If a concept or group of similar concepts has a good overall total score or a high + total score, it is important to notice what strengths they exhibit, that is, which criteria they meet better than the datum. Likewise, groupings of scores will show which requirements are especially hard to meet.
- If most concepts get the same score on a certain criterion, examine that criterion closely. It may be necessary to develop more knowledge in the area of the criterion in order to generate better concepts. Or it may be that the criterion is ambiguous, is interpreted differently by different members of the team, or is unevenly interpreted from concept to concept. If the criterion has a low importance weighting, then do not spend much time clarifying it. However, if it is an important criterion, effort is needed either to generate better concepts or to clarify the criterion.
- To learn even more, redo the comparisons, with the highest-scoring concept used as the new datum. This iteration should be redone until a clearly "best" concept or concepts emerge.

After each team member has completed this procedure, the entire team should compare each member's individual results. The results can vary widely, since neither the concepts nor the requirements may be refined. Discussion among the members of the group should result in a few concepts to refine. If it does

8.6 PRODUCT, PROJECT, AND DECISION RISK

1. What can go wrong?
2. How likely is it to happen?
3. What are the consequences of it happening?

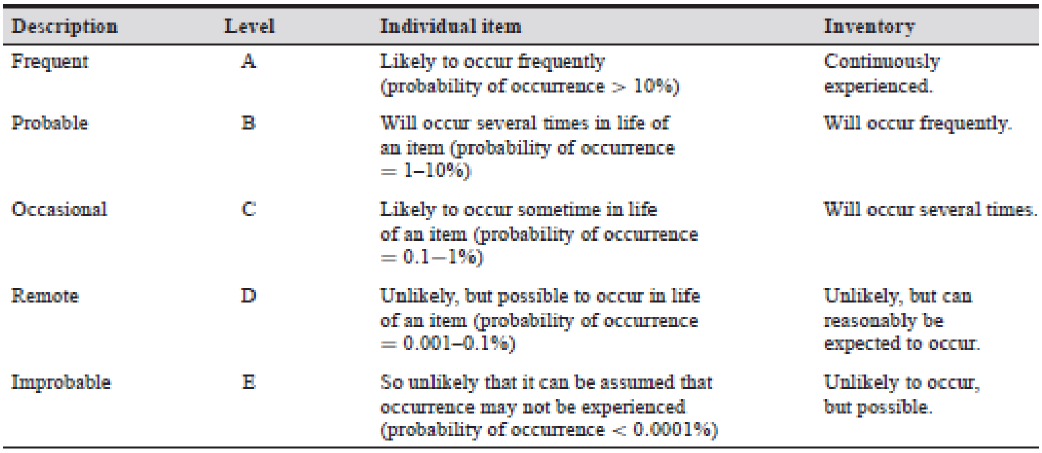
8.6.1 Product Safety, the Goal of Product Risk Understanding

8.6.2 Products Liability, the Result of Poor Risk Understanding

8.6.3 Measuring Product Risk

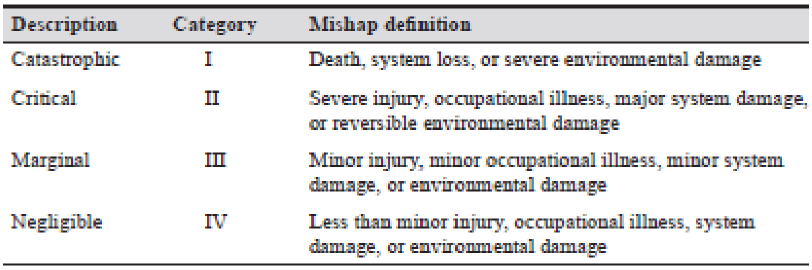
8.6.4 Project Risk

Table 8.2 The mishap probabilities



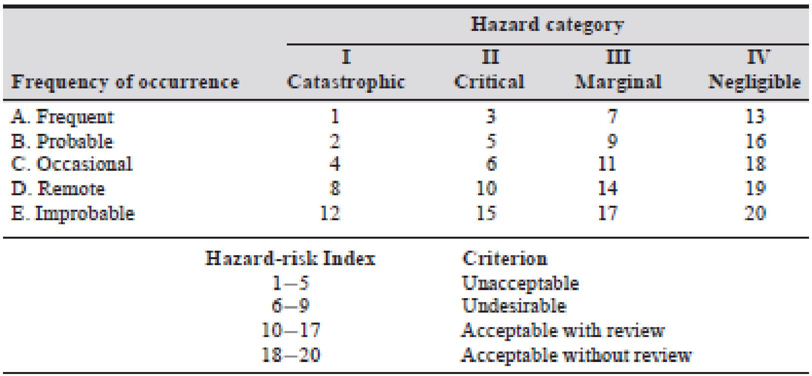
Description	Level	Individual item	Inventory
Frequent	A	Likely to occur frequently (probability of occurrence > 10%)	Continuously experienced.
Probable	B	Will occur several times in life of an item (probability of occurrence = 1–10%)	Will occur frequently.
Occasional	C	Likely to occur sometime in life of an item (probability of occurrence = 0.1–1%)	Will occur several times.
Remote	D	Unlikely, but possible to occur in life of an item (probability of occurrence = 0.001–0.1%)	Unlikely, but can reasonably be expected to occur.
Improbable	E	So unlikely that it can be assumed that occurrence may not be experienced (probability of occurrence < 0.0001%)	Unlikely to occur, but possible.

Table 8.3 The mishap severity categories



Description	Category	Mishap definition
Catastrophic	I	Death, system loss, or severe environmental damage
Critical	II	Severe injury, occupational illness, major system damage, or reversible environmental damage
Marginal	III	Minor injury, minor occupational illness, minor system damage, or environmental damage
Negligible	IV	Less than minor injury, occupational illness, system damage, or environmental damage

Table 8.4 The mishap-assessment matrix



	Hazard category			
Frequency of occurrence	I Catastrophic	II Critical	III Marginal	IV Negligible
A. Frequent	1	3	7	13
B. Probable	2	5	9	16
C. Occasional	4	6	11	18
D. Remote	8	10	14	19
E. Improbable	12	15	17	20

Hazard-risk Index	Criterion
1–5	Unacceptable
6–9	Undesirable
10–17	Acceptable with review
18–20	Acceptable without review

Source for Tables 8.2–8.4: MIL-STD 882D.

8.6.5 Decision Risk

Decision-making risks are the chance that choices made will not turn out as expected (What can go wrong?). In business and technology, you only know if you made a bad decision sometime in the future. Since decisions are calls to action and commitment of resources, it's only after the actions are taken that you really know whether the decision was a good one or a bad one.

Decision-making risk is a measure of the probability that a poor decision has been made (How likely is it to happen?) times the consequences of the decision (What are the consequences of it happening?). The goal is to understand the probabilities and consequences during the decision-making process and not have to wait until later, after the action has been taken.

Looking back at the Decision Matrix:

- What can go wrong? = A criterion is not met.
- What are the consequences of it happening? = The customer is not satisfied.
- How likely is it to happen? = It depends on the uncertainty. There is no real measure of uncertainty in the Decision Matrix.

8.7 ROBUST DECISION MAKING

The great challenge during conceptual design evaluation is to make good decisions in spite of the fact that the information about the concepts is uncertain, incomplete, and evolving. Recent methods have been developed that are especially designed to manage these types of decision problems. These methods are referred to as robust decision-making methods. The word "robust" will be used again in Chap. 10 to refer to final products that are of high quality because they are insensitive to manufacturing variation, operating temperature, wear, and other uncontrolled factors. Here we use the term "robust" to refer to decisions that are as insensitive as possible to the uncertainty, incompleteness, and evolution of the information that they are based on.

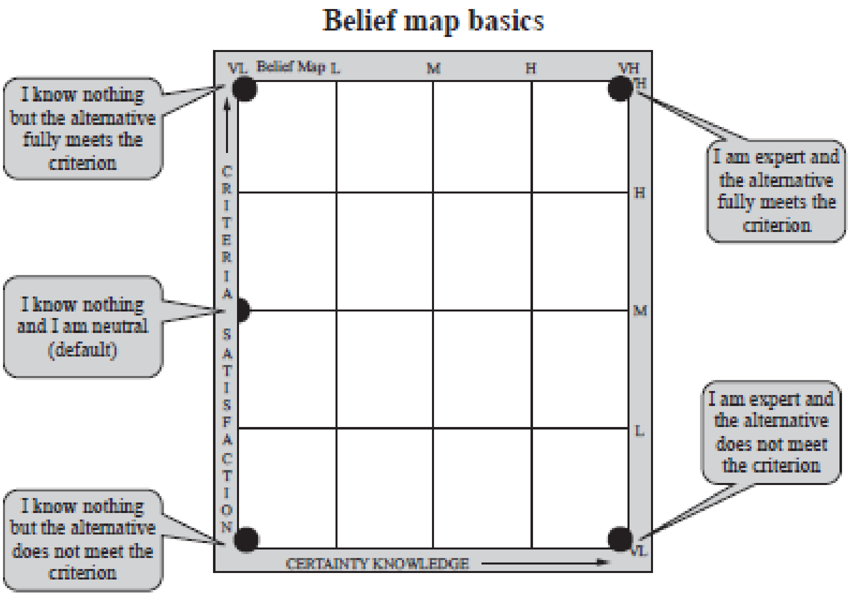


Figure 8.11 The four corners of the belief map.

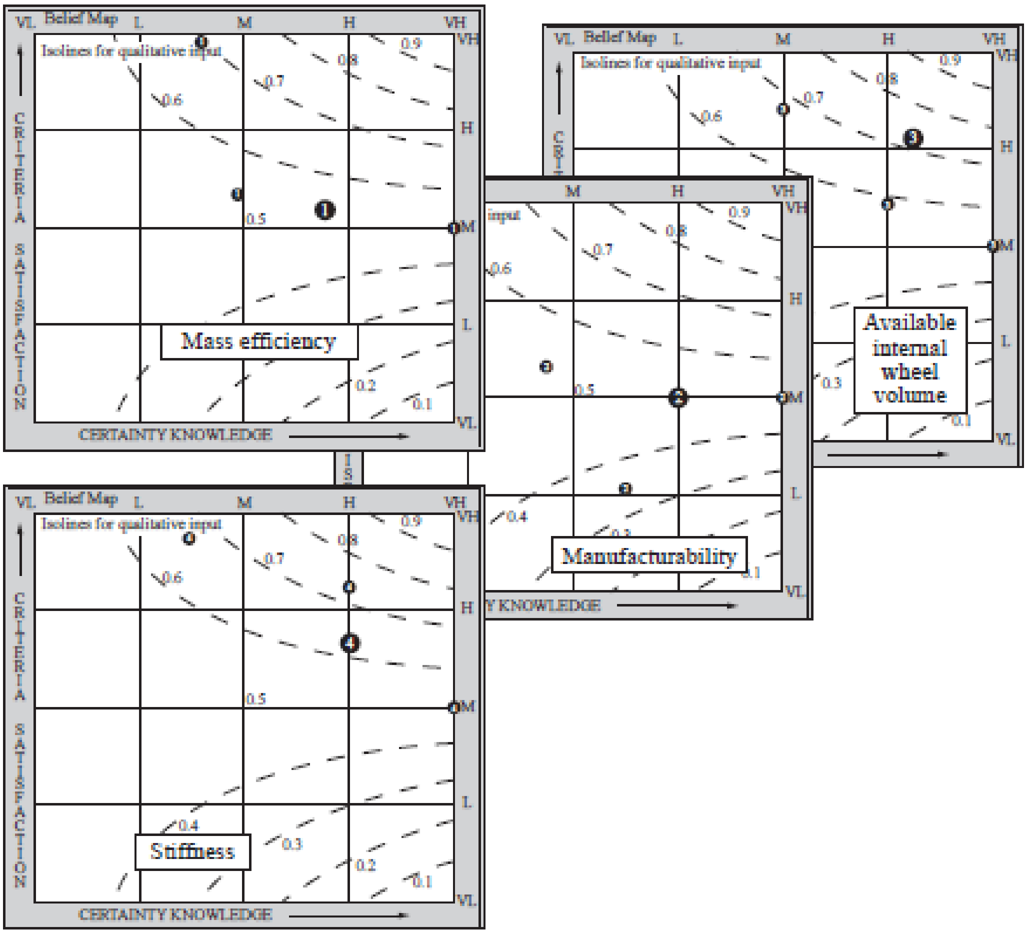


Figure 8.12 Belief Map example for the MER.

Issue: Choose a MER wheel configuration		Baseline	Cantilevered Beam	Hub Switchbacks	Spiral Flexures	Multipiece
Mass efficiency	35	0.5	0.55	0.55	0.77	0.71
Manufacturability	10	0.5	0.5	0.35	0.4	0.52
Available internal wheel volume	20	0.5	0.72	0.58	0.84	0.67
Stiffness	35	0.5	0.62	0.74	0.86	0.68
	Satisfaction	50	60	60	78	67

Figure 8.13 Decision Matrix with Belief Map results.

8.8 SUMMARY

- The feasibility of a concept is based on the design engineer's knowledge. Often it is necessary to augment this knowledge with the development of simple models.
- In order for a technology to be used in a product, it must be ready. Six measures of technology readiness can be applied.
- Product safety implies concern for injury to humans and for damage to the device itself, other equipment, or the environment.
- Safety can be designed into a product, added on, or warned against. The first of these is best.
- A mishap assessment is easy to accomplish and gives good guidance.
- The decision-matrix method provides means of comparing and evaluating concepts. The comparison is between each concept and a datum relative to the customers' requirements. The matrix gives insight into strong and weak areas of the concepts. The decision-matrix method can be used for subsystems of the original problem.
- An advanced decision matrix method leads to robust decisions by including the effects of uncertainty in the decision making process.
- Belief maps are a simple yet powerful way to evaluate alternatives and work to gain team consensus.

Product Development

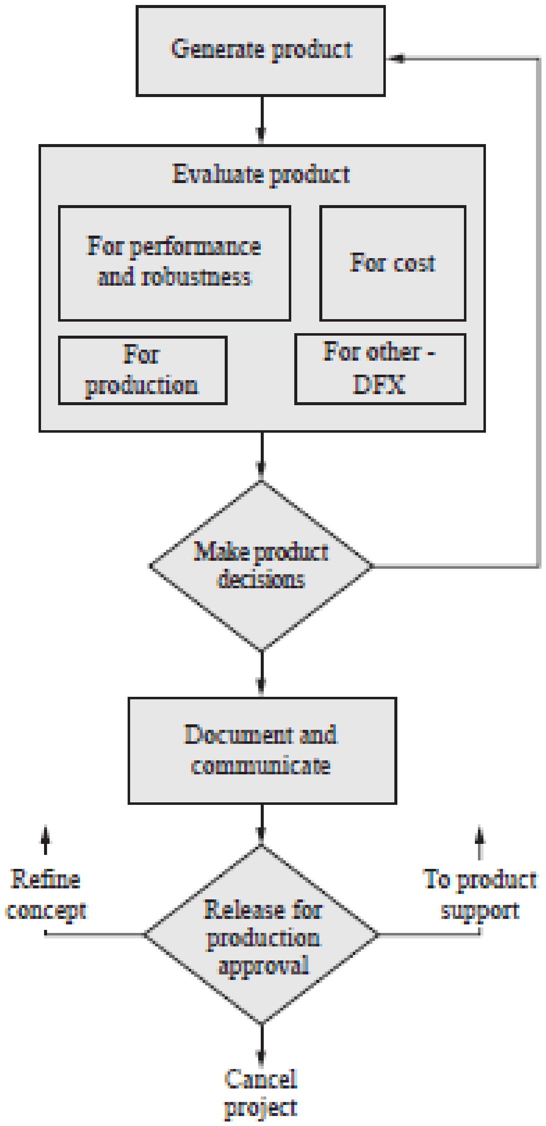


Figure 9.1 The product design phase of the design process.

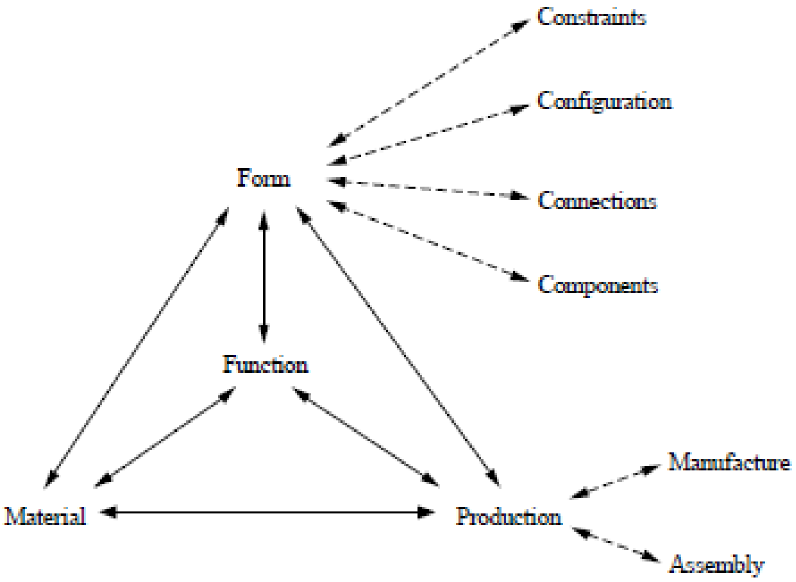


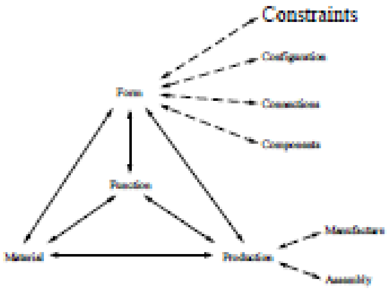
Figure 9.3 Basic elements of product design.

9.2 BOMs

The *Bill Of Materials (BOM),* or *parts list,* is like an index to the product. It evolves during this phase of the design process. BOMs are a key part of Product Life-cycle Management (PLM), as introduced in Chap. 1 (Figure 1.8). BOMs are often built on a spreadsheet, which is easy to update (a Word template can also be used). A typical bill of materials is shown in Fig. 9.4. To keep lists to a reasonable length, a separate list is usually kept for each assembly. There are a minimum of six pieces of information on a bill of materials:

1. *The item number or letter.* This is a key to the components on the BOM.
2. *The part number.* This is a number used throughout the purchasing, manufacturing, inventory control, and assembly systems to identify the component. Where the item number is a specific index to the assembly drawing, the part number is an index to the company system. Numbering systems vary greatly from company to company. Some are designed to have context, the part number indicates something about the part's function or assembly. These types of systems are hard to maintain. Most are simply a sequential number assigned to the part. Sometimes, the last digit will be used to indicate the revision number, as in the Fig. 9.4 example.
3. *The quantity needed* in the assembly.
4. *The name or description of the component.* This must be a brief, descriptive title for the component.
5. *The material from which the component is made.* If the item is a subassembly, then this does not appear in the BOM.
6. *The source of the component.* If the component is purchased, the name of the company is listed. If the component is made in-house, this line can be left blank.

9.3.1 Understand the Spatial Constraints

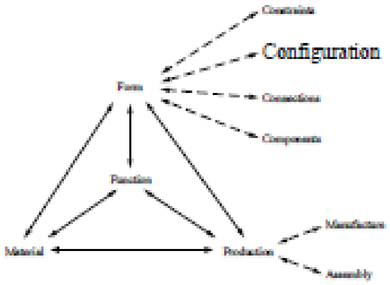


The spatial constraints are the walls or envelope for the product. Most products must work in relation to other existing, unchangeable objects. The relationships may define actual contact or be for needed clearance. The relationships may be based on the flow of material, energy, or information as well as being physical. For the one-handed clamp the interface with work and the user hand is physical and there is the flow of energy in the form of forces.

Some spatial constraints are for functionally needed space, such as optical paths, or to clear or interfere with the flow of some material such as air or water. Further, most products go through a series of operational steps as they are used. The functional relationships and spatial requirements may change during these. The varying relationships may require the development of a series of layout drawings or solid models.

Initially the spatial constraints are for the entire product, system, or assembly; however, as design decisions are made on one assembly or component, other spatial constraints are added. For large products that have independent teams working on different subassemblies, the coordination of the spatial constraint information can be very difficult. PLM and solid modeling systems help in managing the constraints.

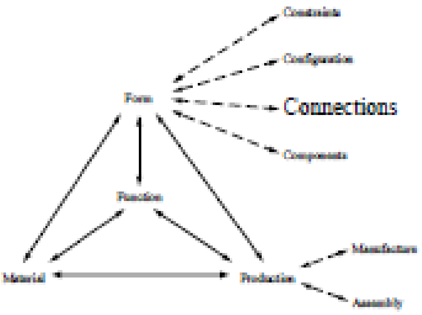
9.3.2 Configure Components



Configuration is the architecture, structure, or arrangement of the components and assemblies of components in the product. Developing the architecture or configuration of a product involves decisions that divide the product into individual components and develop the location and orientation of them. Even though the concept sketches probably contain representations of individual components, it is time to question the decomposition represented. There are only six reasons to decompose a product or assembly into separate components:

- Components must be separate if they need to move relative to each other. For example, parts that slide or rotate relative to each other have to be separate components. However, if the relative motion is small, perhaps elasticity can be built into the design to meet the need for motion. This is readily accomplished in plastic components by using elastic hinges, which are thin sections of fatigue-resistant material that act as a one-degree-of-freedom joint.
- Components must be separate if they need to be of different materials for functional purposes. For example, one area of the product may need to conduct heat and another must insulate and both these areas may be served by a single component, were it not for these thermal resistance needs.

9.3.3 Develop Connections: Create and Refine Interfaces for Functions



This is a key step when embodying a concept because *the connections or interfaces between components support their function and determine their relative positions and locations*. Here are guidelines to help develop and refine the interfaces between components:

- *Interfaces must always reflect force equilibrium and consistent flow of energy, material, and information.* Thus, they are the means through which the product will be designed to meet the functional requirements. Most design effort occurs at the connections between components, and attention to these interfaces and the flows through them, is key to product development. During the redesign of an existing product, it is useful to disassemble it; note the flows of energy, information, Complexity occurs primarily at interfaces.

and materials at each joint; and develop the functional model one component at a time.

- *After developing interfaces with external objects, consider the interfaces that carry the most critical functions.* Unfortunately it is not always clear which functions are most critical. Generally, they are those functions that seem hardest to achieve (about which the knowledge is the weakest) or those described as most important in the customers' requirements.
- *Try to maintain functional independence in the design of an assembly or component.* This means that the variation in each critical dimension in the assembly or component should affect only one function. If changing a parameter changes multiple functions, then affecting one function without altering others may be impossible.
- *Exercise care when separating the product into separate components.* Complexity arises since one function often occurs across many components or assemblies and since one component may play a role in many functions. For example, a bicycle handlebar (discussed in Section 2.2) enables many functions but does none of them without other components.
- *Creating and refining interfaces may force decompositions that result in new functions or may encourage the refinement of the functional breakdown.*

As the interfaces are refined, new components and assemblies come into existence. One step in the evaluation of each potential embodiment is to determine how each new component changes the functionality of the design.

In order to generate the interface, it may be necessary to treat it as a new design problem and utilize the techniques developed in Chaps. 7 and 8. When developing a connection, classify it as one or more of these types:

- *Fixed, nonadjustable connection.* Generally one of the objects supports the other. Carefully note the force flow through the joint (see Section 9.3.4). These connections are usually fastened with rivets, bolts, screws, adhesives, welds, or by some other permanent method.
- *Adjustable connection.* This type must allow for at least one degree of freedom that can be locked. This connection may be field-adjustable or intended for factory adjustment only. If it is field-adjustable, the function of the adjustment must be clear and accessibility must be given. Clearance for adjustability may add spatial constraints. Generally, adjustable connections are secured with bolts or screws.
- *Separable connection.* If the connection must be separated, the functions associated with it need to be carefully explored.
- *Locator connection.* In many connections, the interface determines the location or orientation of one of the components relative to another. Care

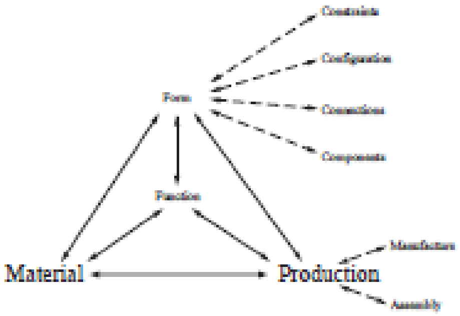
Determine how constrained a component needs to be,
and constrain it exactly that amount—no more, nor no less.

must be taken in these connections to account for errors that can accumulate in joints.

- *Hinged or pivoting connection.* Many connections have one or more degrees of freedom. The ability of these to transmit energy and information is usually key to the function of the device. As with the separable connections, the functionality of the joint itself must be carefully considered.

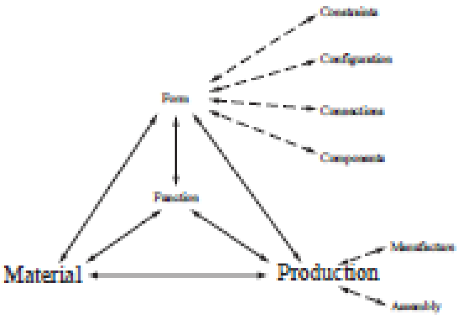
9.3.4 Develop Components

It has been estimated that fewer than 20% of the dimensions on most components in a device are critical to performance. This is because most of the material in a component is there to connect the functional interfaces and therefore is not dimensionally critical. Once the functional interfaces between components have been determined, designing the body of the component is often a sophisticated connect-the-dots problem.



9.4 MATERIALS AND PROCESS SELECTION

At the same time form is being developed, it is important to identify materials and production techniques and to be aware of their specific engineering requirements. An experienced designer has a short list of materials and processes in mind even with the earliest concepts.



In developing an understanding of the product, we may have set requirements on materials, manufacturing, and assembly. At a minimum we did competitive benchmarking on similar devices, studying them for conceptual ideas and for what they were made of and how they were made. All this information influences the embodiment of the product in several ways:

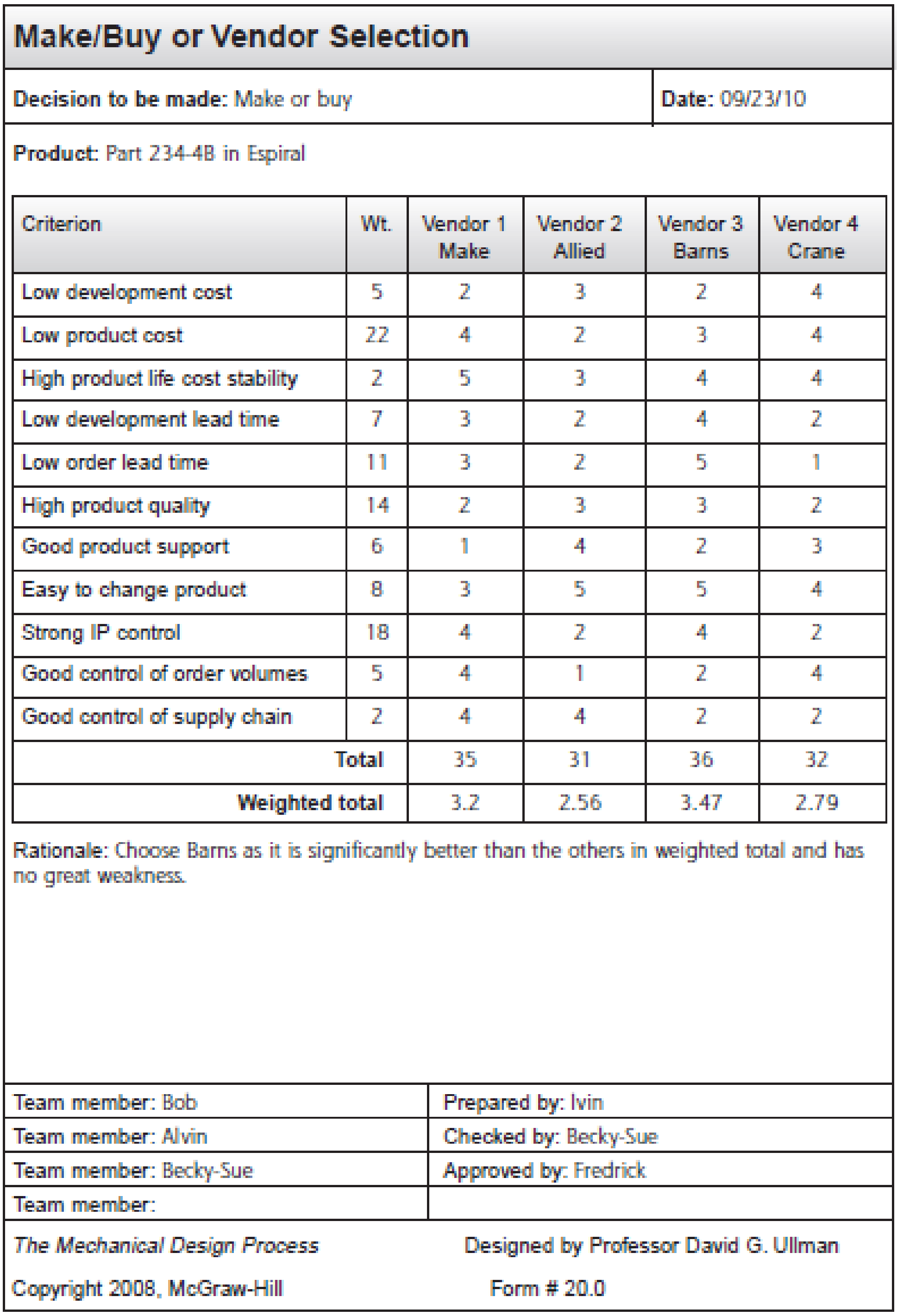
First, the *quantity of the product to be manufactured* greatly influences the selection of the manufacturing processes to be used.

9.5 VENDOR DEVELOPMENT

When specifying systems, assemblies, or components you either use what is available from vendors, or design new hardware. Mechanical designers seldom design basic mechanical components (e.g., nuts, bolts, gears, or bearings) for each new product, since these components are readily available from vendors. For example, few engineers outside of fastener manufacturing companies design new types of fasteners. Similarly, few designers outside of gear companies design gears. When such basic components are needed in a product, they are usually specified by the designer and purchased from a vendor who specializes in manufacturing them. In general, finding an already existing product that meets the needs in the product is less expensive than designing and manufacturing it, since the companies that specialize in making a specific component have many advantages over an in-house design-and-build effort:

- They have a history of designing and manufacturing the product, so they already have the expertise and machinery to produce a quality product.
- They already know what can go wrong during design and production. A new design effort requires extensive time and experience before reaching the same level of expertise.
- They specialize in the design and manufacture of the component, so they can make it in volumes high enough to keep the cost below what can be achieved through an in-house effort.

- **Low development cost**—How much is it going to cost to develop the component. If it is truly COTS, then there are no development costs. However, if work is needed to change a COTS system or part, or one needs to be developed, then these costs may be significant.
- **Low product cost**—Many decisions are based solely on this criterion. This cost is highly dependent on the volume (the number purchased), delivery costs and many other factors. These will be addressed in Chap. 11 when we discuss DFC, Design For Cost (Section 11.2).
- **High product life cost stability**—Beyond the cost, it is important to consider how the cost may change over time. Cost can be controlled better when you make a component or can be locked in by contract.
- **Low development lead time**—If this and the next criterion are important; they may dominate all the rest and force the purchase of a COTS component. COTS components need no development lead time.
- **Low order lead time**—Even COTS components have an order lead time. Sometimes it can even be longer than the time needed to make the component in house.
- **High product quality**—Sometimes quality must be traded off for cost or time. It is important to understand from the beginning, the level of quality needed to meet the engineering specifications.
- **Good product support**—To address this criterion, two questions must be answered: Who will be responsible for failures and maintenance of the component or product? And, how much support will be needed?
- **Easy to change product**—Sometimes it is necessary to change the product during its lifetime. If it is COTS then you have no control over changes. If



Make/Buy or Vendor Selection

Decision to be made: Make or buy

Date: 09/23/10

Product: Part 234-4B in Espiral

Criterion	Wt.	Vendor 1 Make	Vendor 2 Allied	Vendor 3 Barns	Vendor 4 Crane
Low development cost	5	2	3	2	4
Low product cost	22	4	2	3	4
High product life cost stability	2	5	3	4	4
Low development lead time	7	3	2	4	2
Low order lead time	11	3	2	5	1
High product quality	14	2	3	3	2
Good product support	6	1	4	2	3
Easy to change product	8	3	5	5	4
Strong IP control	18	4	2	4	2
Good control of order volumes	5	4	1	2	4
Good control of supply chain	2	4	4	2	2
Total		35	31	36	32
Weighted total		3.2	2.56	3.47	2.79

Rationale: Choose Barns as it is significantly better than the others in weighted total and has no great weakness.

Team member: Bob	Prepared by: Ivin
Team member: Alvin	Checked by: Becky-Sue
Team member: Becky-Sue	Approved by: Fredrick
Team member:	

The Mechanical Design Process Designed by Professor David G. Ullman

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Figure 9.22 Make/buy or vendor selection example.

Table 10.1 Best practices for product evaluation

- Monitoring functional change (Sec. 10.2)
- Goals of performance evaluation (Sec. 10.3)
- Trade-off management (Sec. 10.4)
- Accuracy, variation, and noise (Sec. 10.5)
- Modeling for performance evaluation (Sec. 10.6)
- Tolerance analysis (Sec. 10.7)
- Sensitivity analysis (Sec. 10.8)
- Robust design (Secs. 10.9 and 10.10)
- Design for cost (DFC) (Sec. 11.2)
- Value engineering (Sec. 11.3)
- Design for manufacture (DFM) (Sec. 11.4)
- Design for assembly (DFA) (Sec. 11.5)
- Design for reliability (DFR) (Sec. 11.6)
- Design for test and maintenance (Sec. 11.7)
- Design for the environment (Sec. 11.8)

10.2 MONITORING FUNCTIONAL CHANGE

Although the main goal of evaluation is comparing product performance with engineering targets, it is equally important to track changes made in the function of the product. Conceptual designs were developed first by functionally modeling the problem and then, on the basis of that model, developing potential concepts to fulfill these functions. This transformation from function to concept does not end the usefulness of the functional modeling tool. As the form is refined from concept to product, new functions are added.

> Evaluation always requires a clear head
> and twice the time you estimated.

clearly show what should be altered (patched) in order to make deficient products meet the requirements, and they should demonstrate the product's insensitivity to variation in the manufacturing processes, aging, and operating environment. Restated, the evaluation of product performance must support these factors:

1. Evaluation must result in *numerical measures* of the product for comparison with the engineering requirement targets developed during problem understanding. These measurements must be of sufficient accuracy and precision for the comparison to be valid.
2. Evaluation should give some indication of *which features of the product to modify*, and by how much, in order to bring the performance on target.
3. Evaluation procedures must include the influence of *variations* due to manufacturing, aging, and environmental changes. Insensitivity to these "noises" while meeting the engineering requirement targets results in a robust, quality product.

Where traditionally engineering evaluation has focused on only the first of these three points, this chapter covers all three. Much emphasis is placed on the third point, the consideration of variation because of its direct relationship with product quality.

This chapter is built around Fig. 10.2, the P-diagram. This diagram will be referenced and added to throughout this chapter. In the P-diagram, the letter "P" stands for either product or process and can represent the entire product or some system, subsystem, or process within it. The product or process being evaluated is dependent on the values of many parameters. These parameters may be physical dimensions, material properties, forces from other systems, or forces and motions from humans controlling the system. They may be the temperature of

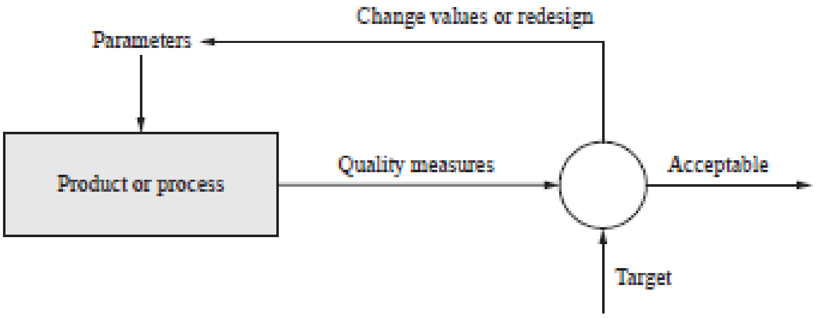


Figure 10.2 The basic P-diagram.

> Know how to control what you can, make your product insensitive to what you cannot, and be wise enough to know the difference.

the environment, the humidity, or the amount of dirt on the system. The parameters are all the factors on which the product or process depends and the values of these parameters determine the resulting performance, ease of assembly, quality, and other features of the product or process.

To evaluate the system we need to assess quality measures. These are measures that communicate quality to the customer. To evaluate the product or process these quality measures must be compared to the targets set by the engineering specifications (Chap. 6). If the quality measures compare well to the targets, then we have a quality product. If they do not, then we have to change the values of the parameters or redesign the system—changing the parameters themselves.

One addition to the P-diagram is necessary when considering dynamic function, the product or process may be responding to input signals, as is shown in Fig. 10.3. In this case, the quality measures include system performance. Examples of systems with and without input signals will be given in the chapter.

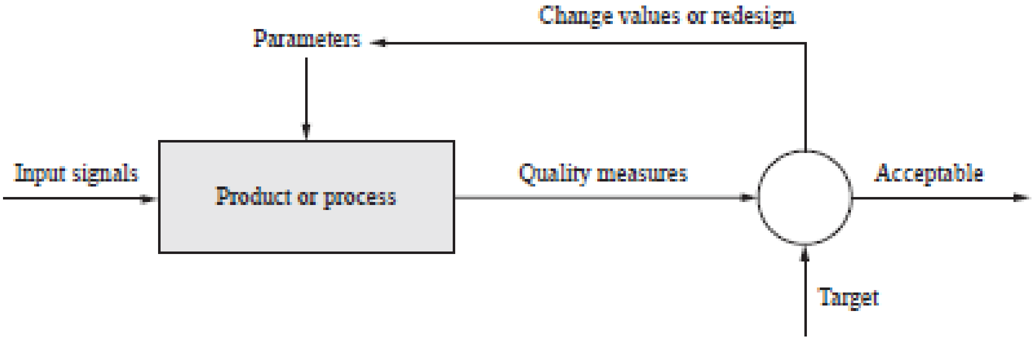


Figure 10.3 The P-diagram with input signal.

10.4 TRADE-OFF MANAGEMENT

10.5 ACCURACY, VARIATION, AND NOISE

10.5.1 The Effect of Variation on Product Quality

In Table 1.1, we listed the results of a customer survey about what determines quality. Based on this survey, the most essential factors in a quality product are "works as it should," "lasts a long time," and "is easy to maintain." The first of these implies that not only does the product match its targets, but that it also stays on them regardless of variations in operating conditions or age of the product, and that all samples of the product work the same. The second quality factor says that the product's operation and looks should not vary with time. The third says that its operation should not vary or need adjustment or other attention as it ages or is used in different situations. We can reduce all of this to one statement that defines product quality:

> **A product is considered to be of high quality if its quality measures stay on target regardless of parameter variation due to manufacturing, aging, or the environment.**

"Quality measures" are those engineering requirement targets identified in the House Of Quality and result in customer satisfaction. The product quality definition is very important. In fact, designers go to great length to control some parameters so that they won't have an effect on the quality measures. For example,

- Controlling the temperature of food so it won't spoil regardless of room temperature
- Controlling the feel of power steering so the driver's steering experience stays constant regardless of road conditions
- Controlling the dimensions of a part so they will fit with other parts regardless of manufacturing, temperature, or aging

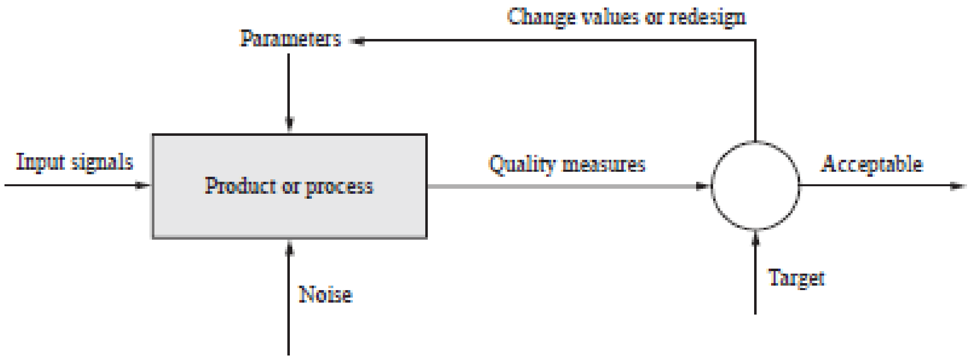


Figure 10.9 The P-diagram with noise and control parameters.

> Hand fitting parts is fun when making a prototype,
> a disaster on the assembly line.

treated as uncontrollable. Noises affecting the design parameters are generally classified as

- *Manufacturing, or unit-to-unit, variations,* including dimensional variations, variations in material and other properties, and process variations such as those in manufacturing and assembly.
- *Aging, or deterioration, effects,* including etching, corrosion, wear, and other surface effects, along with material property or shape (creep) changes over time.
- *Environmental, or external, conditions,* including all effects of the operating environment on the product. Some environmental conditions, such as temperature or humidity variations, affect the material properties; others, such as the amount of paper in the tray of a paper feeder or the amount of load on a walkway, affect the operating stresses, strains, or positions.

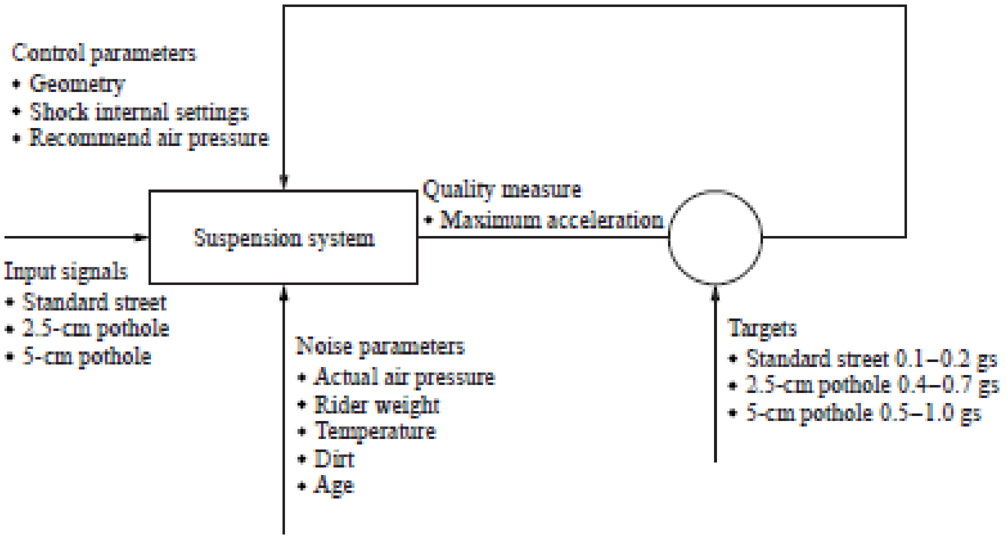


Figure 10.10 P-diagram for bicycle suspension performance.

10.6 MODELING FOR PERFORMANCE EVALUATION

10.6.1 Step 1: Identify the Output Responses (i.e., the Critical or Quality Parameters) That Need to Be Measured

Often the goal in evaluation is to see if a new idea is feasible. Even with this ill-defined goal, the important critical parameters, those that determine the performance, must be clearly identified. In developing engineering requirements and targets during the specification development phase of the design process, many parameters of interest are identified. As the product is refined, other important requirements and targets arise. Thus, throughout the development of the product, the parameters that demonstrate the performance of the product are identified and measured during product evaluation.

10.6.2 Step 2: Note the Needed Fidelity

Early in the product refinement, it may be sufficient to find only the order of magnitude of some parameters. Back-of-the-envelope calculations may be sufficient indicators of performance for relative comparisons.As the product is refined, the accuracy of the evaluation modeling must be increased to enable comparison with the target values. It is important to realize the degree of fidelity needed before beginning the evaluation. Effort spent on a finite-element model is wasted if a rough calculation using classical strength-of-materials techniques or a simple laboratory test of a piece of actual material is sufficient. Getting this wrong can lead to “paralysis by analysis”—overanalyzing to the point that progress is stifled.

10.6.3 Step 3: Identify the Input Signal, the Control Parameters and Their Limits, and Noises

It is important, before beginning to model a system, that a P-diagram is drawn and the factors affecting the output be at least initially identified and classified. Input signals are the energy, information, and materials modified by the product or process. Usually these signals are important; however, they may be secondary to the control parameters and ignored in many design situations

10.6.4 Step 4: Understand Analytical Modeling Capabilities

Generally, analytical methods are less expensive and faster to implement than physical modeling methods. However, the applicability of analytical methods depends on the level of accuracy needed and on the availability of sufficient methods. For example, a rough estimate of the stiffness of a diving board can be made using methods from strength of materials. In this analysis, the board is assumed to be a cantilever beam, made of one piece of material, of constant prismatic cross section, and with known moment of inertia. Further, the load of a diver bouncing on the end of the board is estimated to be a constant point load. With this analysis, the important dependent variables—the energy storage properties of the board, its deflection, and the maximum stress—can be estimated. Using more sophisticated and advanced strength of materials modeling techniques, the fidelity of the model is improved. For example, the taper of the diving board, the distributed nature of the diver in both time and space, and the structure of the board can be modeled. The dependent variables remain unchanged. More parameters that are independent can now be utilized in a more laborious and more accurate evaluation.

10.6.5 Step 5: Understand the Physical Modeling Capabilities

Physical models, or prototypes, are hardware representations of all or part of the final product. Most design engineers would like to see and touch physical realizations of their concepts all the way through the design process. However, time, money, equipment, and knowledge—the same resource limitations that affect analytical modeling—control the ability to develop physical models. Generally, the fact that physical models are expensive and take time to produce, controls their use.

10.6.6 Step 6: Select the Most Appropriate Modeling Method

There is nothing as satisfying in engineering as modeling a system both analytically and physically and having the results agree! However, resources rarely allow both modeling methods to be pursued. Thus, the method that yields the needed accuracy with the fewest resources must be selected.

10.6.7 Step 7: Perform the Analysis or Experiments and Verify the Results

Document that the targets have been met or that the model has given a clear indication of what parameters to alter, which direction to alter them in, and how much to alter them. In evaluating models, not only are the results as important as in scientific experimentation, but since the results of the modeling are used to patch or refine the product, the model must also give an indication of what to change and by how much. In analytical modeling, this is possible through sensitivity analysis, as will be discussed in Section 10.7. This is more difficult with physical models. Unless the model itself is designed to allow easily changed parameters, it may be difficult to learn what to do next.

For the Marin suspension system, steps 1–3 are included

10.7 TOLERANCE ANALYSIS

This section focuses on manufacturing variations and tolerances. We begin with a discussion of the relationship between tolerances and manufacturing variations.

10.7.1 The Difference Between Manufacturing Variations and Tolerance

10.7.2 General Tolerancing Considerations

10.7.4 Statistical Stack-Up Analysis

A more accurate estimate of the gap can be found statistically. Consider a stack-up problem composed of n components, each with mean length l_i and tolerance t_i (assumed symmetric about the mean), with $i = 1, \ldots, n$ (n is the number of uniaxial dimensions). If one dimension is identified as the dependent parameter (in the suspension example, the gap), then its mean dimension can be found by adding and subtracting the other mean dimensions, as in Eq. [10.1]. In general,

$$\bar{l} = \bar{l}_1 \pm \bar{l}_2 \pm \bar{l}_3 \pm \cdots \pm \bar{l}_n \qquad \textbf{[10.2]}$$

The sign on each term depends on the structure of the device. Similarly, the standard deviation is

$$s = \left(s_1^2 + s_2^2 + \cdots + s_n^2\right)^{1/2} \qquad \textbf{[10.3]}$$

where the signs are always positive. (This basic statistical relation is discussed in App. B.) Generally, "tolerance" is assumed to imply three to six standard deviations about the mean value. More recently, this has, in some high-technology industries even been as high as 9-sigma. For 3-sigma, a tolerance of 0.009 in. means that $s = 0.003$ and that 99.73% of all samples should be within tolerance (i.e., within 3σ). Since $s = t/3$, Eq. [10.3] can be rewritten as

$$t = \left(t_1^2 + t_2^2 + \cdots + t_n^2\right)^{1/2} \qquad \textbf{[10.4]}$$

For the example,

$$\bar{l}_g = \bar{l}_s - (\bar{l}_b + 2 \times \bar{l}_w) \qquad \textbf{[10.5]}$$

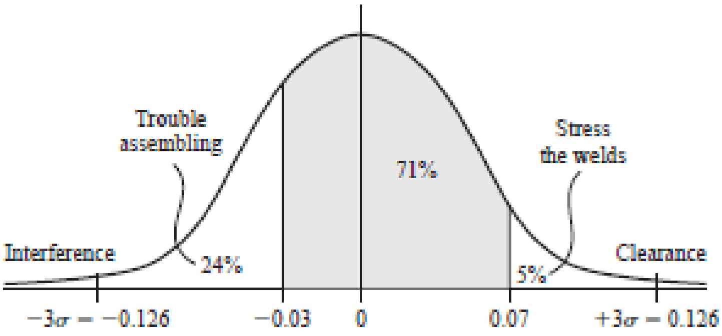


Figure 10.14 Gap distribution.

and

$$t_g = \left(t_s^2 + t_b^2 + 2 \times t_w^2\right)^{1/2} \qquad [10.6]$$

Say that we make the spacing 24.00 ± 0.10 mm, then the gap and the tolerance on it are

$$\bar{l}_g = 24 - (20 - 2 \times 2) = 0.0\,\text{mm} \qquad [10.7]$$

and

$$t_g = (0.10^2 + 0.03^2 + 2 \times 0.05^2)^{1/2} = 0.126\,\text{mm} \qquad [10.8]$$

These results show that there is, on the average, no gap and the tolerance on it is 0.126 mm. Say that the fingers can flex up to 0.07 mm inward when bolted without undue stress on the welds to compensate for any clearance. Further, say that assembly personnel can get the parts in between the fingers even if there is a 0.03-mm interference. The question then is, what percentage of the assemblies will meet these requirements?

This situation is plotted in Fig. 10.14. Assuming the tolerance calculated is 3 standard deviations, and using standard normal probability methods (App. B) the shaded area represents 71% of the assemblies. This means that 29% of the time either the assembly people will have trouble assembling the device (24%) or the welds will be overstressed (5%).

Inspecting each joint and reworking those that do not meet the specification or swapping components between joints to meet them could be used to achieve increased quality. Another way to increase the quality is to use the results of the analysis to redesign the joint. This is accomplished through sensitivity analysis.

10.8 SENSITIVITY ANALYSIS

Sensitivity analysis is a technique for evaluating the statistical relationship of control parameters (e.g., dimensions) and their tolerances in a design problem.

In this section, we explore the use of sensitivity analysis for a simple dimensional problem and then apply the method to the problem of the tank volume.

Sensitivity analysis enables the contribution of each parameter to the variation to be easily found. Rewriting Eq. [10.3] in terms of $P_i = s_i^2/s^2$,

$$1 = P_1 + P_2 + \cdots + P_n \qquad \textbf{[10.9]}$$

where P_i is the percentage contribution of the ith term to the tolerance (or variance) of the dependent variable. For the current example, these are

$$\begin{aligned} P_s &= \frac{0.10^2}{0.126^2} = 0.63 = 63\% \\ P_b &= \frac{0.03^2}{0.126^2} = 0.05 = 5\% \\ P_w &= \frac{0.05^2}{0.126^2} = 0.16 = 16\% \\ \hline \text{With two washers} \quad & \text{total} = 1.0 = 100\% \end{aligned}$$

This result clearly shows that the tolerance on the spacing has the greatest effect on the gap. For one-dimensional tolerance stack-up problems such as this, the results of the sensitivity analysis can be used for *tolerance design*. Since the spacing causes 63% of the noise in the joint, it is the most likely candidate for change.

This technique will work on all one-dimensional problems in which all the parameters are dimensions on the product. To summarize:

Step 1. Develop a relationship between the dependent dimension and those it is dependent on, as in Eq. [10.2] or [10.5]. Using each independent dimension's mean value, calculate the mean value of the dependent dimension.

Step 2. Calculate the tolerance on the dependent variable using Eq. [10.4] or work in terms of the standard deviations (Eq. [10.3]).

Step 3. If the tolerance found is not satisfactory, identify which independent dimension has the greatest effect, using Eq. [10.9], and modify it if possible. Depending on the ease (and expense), it may be necessary to choose a different dimension to modify.

Problems of two or three dimensions are similarly solved, but the equations relating the variables become complex for all but the simplest multidimensional systems.

If the variables are not related in a linear fashion, the equations already given are modified. This is best shown through the tank-volume problem introduced earlier in this chapter. The major difference is that the parameters r (the radius) and l (the length) are not linearly related to the dependent variable, V (the volume), as can be seen in Fig. 10.4. The method shown next is a generalization of the method for the linear problem. It is good for investigating any functional relationship, whether or not the parameters are dimensions.

Consider a general function

$$F = f(x_1, x_2, x_3, \ldots, x_n) \tag{10.10}$$

where F is a dependent parameter (dimension, volume, stress, or energy) and the x_i's are the control parameters (usually dimensions and material properties). Each parameter has a mean $\overline{x}_i$ and a standard deviation s_i. In this more general problem, the mean of the dependent variable is still based on the mean of the independent variables, as in Eq. [10.2]. Thus,

$$\overline{F} = f(\overline{x}_1, \overline{x}_2, \overline{x}_3, \ldots, \overline{x}_n) \tag{10.11}$$

Here, however, the standard deviation is more complex:

$$s = \left[\left(\frac{\partial F}{\partial x_1}\right)^2 s_1^2 + \cdots + \left(\frac{\partial F}{\partial x_n}\right)^2 s_n^2\right]^{1/2} \tag{10.12}$$

Note that if $\partial F/\partial x_i = 1$, as it must in a linear equation, then Eq. [10.12] reduces to Eq. [10.3]. Equation [10.12] is only an estimate based on the first terms of a Taylor series approximation of the standard deviation. It is generally sufficient for most design problems.

For the tank problem, the independent parameters are r and l. The mean value of the dependent variable V is thus given by

$$\overline{V} = 3.1416\,\overline{r}^2\,\overline{l} \tag{10.13}$$

To evaluate this, we must consider specific values of r and l. There is an infinite number of these pairs that meet the requirement that the mean volume be 4 m^3. For example, consider point A in Fig. 10.15 (which is Fig. 10.4 with added information). With $\overline{r} = 1.21$ m and $\overline{l} = 0.87$ m, from Eq. [10.13], $\overline{V} = 4$ m^3.

The tolerances on these parameters can be based on what is easy to achieve with nominal manufacturing processes. For example, take $t_r = 0.03$ m ($s_r = 0.01$) and $t_l = 0.15$ m ($s_l = 0.05$). These values are shown in the figure as an ellipse around point A. Using formula [10.12], the standard deviation on this volume is

$$s_v = \left[\left(\frac{\partial V}{\partial l}\right)^2 s_l^2 + \left(\frac{\partial V}{\partial r}\right)^2 s_r^2\right]^{1/2} \tag{10.14}$$

where

$$\frac{\partial V}{\partial r} = 6.2830rl$$

and

$$\frac{\partial V}{\partial l} = 3.1416r^2$$

For the values in this example, $\partial V/\partial r = 6.61$ and $\partial V/\partial l = 4.60$, so $s_v = 0.239$ m^3. Thus, 99.68% (three standard deviations) of all the vessels built will have volumes within 0.717 m^3 (3×0.239) of the target 4 m^3. Also, the percentage contribution of

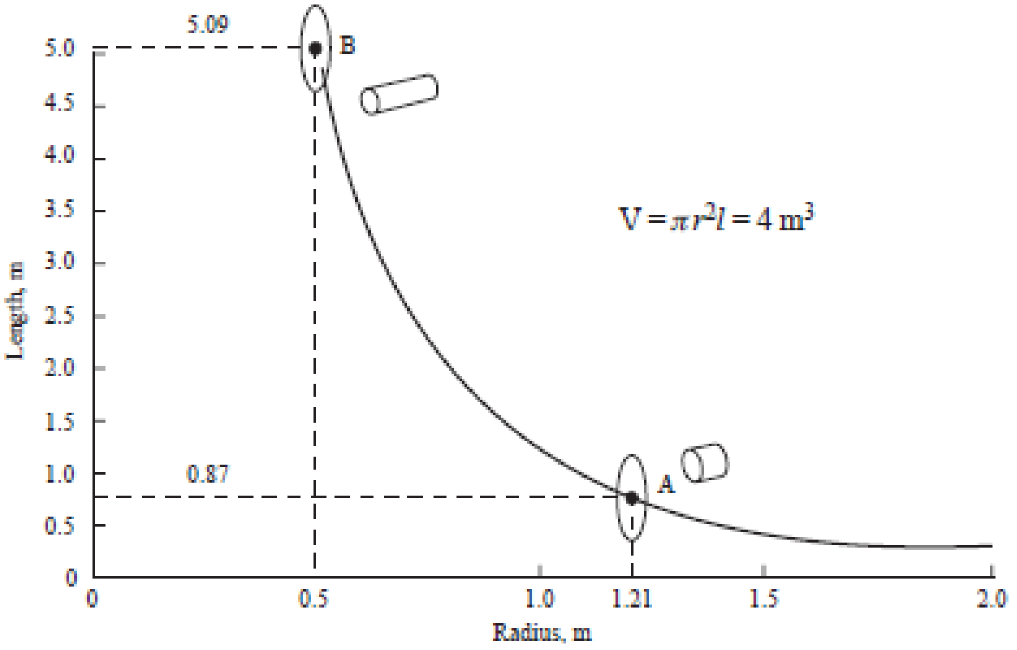


Figure 10.15 Effect of noise on the potential solutions for the tank problem.

> She who does not design a robust product
> will be cursed with unhappy customers.

each parameter can be found as in Eq. [10.9]. Here the length contributes 92.3% of the variance in volume. However, noting that the tolerance on the length is much larger than that on the radius and considering the shape of the curve in Fig. 10.14, it is evident that a longer vessel with a smaller radius might yield a smaller variance in volume. If the control parameters are taken at $r = 0.50$ m and $l = 5.09$ m (point B in Fig. 10.14), the mean volume is still 4 m^3. Now $\partial V/\partial r = 16.00$ and $\partial V/\partial l = 0.78$, so $s_v = 0.166\,\text{m}^3$, which is 31% smaller than at point A. Also, now the tolerance on r contributes 94% to the variance in the volume. Note that we achieved *the reduction in variance not by changing the tolerances on the parameters, but by changing only their nominal values.* The second design has higher quality because the volume is always closer to 4 m^3. If we can find the values of the parameters r and l that give the smallest variance on the volume, then we are employing the philosophy of robust design.

10.9 ROBUST DESIGN BY ANALYSIS

For the tank,

$$C = (2\pi rl)^2 s_r^2 + (\pi r^2)^2 s_1^2 + \lambda(\pi r^2 l - T)$$

The minimum value of the objective function can now be solved. With known standard deviations on the parameters s_r and s_l (or tolerances t_r and t_l) and a known target T, values for the parameters r and l can be found from the derivatives of the objective function with respect to the parameters and the Lagrange multiplier:

$$\frac{\partial C}{\partial r} = 0 = 2r(2\pi l)^2 s_r^2 + 4r^3\pi^2 s_l^2 + \lambda 2\pi rl$$

$$\frac{\partial C}{\partial l} = 0 = 2l(2\pi r)^2 s_r^2 + \lambda\pi r^2$$

$$\frac{\partial C}{\partial \lambda} = 0 = \pi r^2 l - 4$$

Solving simultaneously results in

$$r = 1.414 l \left(\frac{s_r}{s_l}\right) \qquad \textbf{[10.17]}$$

and

$$l = \left[\frac{2}{\pi}\left(\frac{s_l}{s_r}\right)^2\right]^{1/3} \qquad \textbf{[10.18]}$$

Thus, for any ratio of the standard deviations or the tolerances, the parameters are uniquely determined for the best (most robust) design. For the values of $s_r = 0.01$ ($t_r = 0.03$ m) and $s_l = 0.05$ ($t_l = 0.15$ m), these equations result in $r = 0.71$ m and $l = 2.52$ m. Substituting these values into Eq. [10.14], the standard deviation on the volume is $s_v = 0.138$ m^3. Comparing this to the results obtained in the sensitivity analysis, 0.239 and 0.165 m^3, the improvement in the design quality is evident.

If the radius were harder to manufacture than the length, say $s_r = 0.05$ and $s_l = 0.01$, then, using Eqs. [10.17] and [10.18], the best values for the parameters would be $r = 2.06$ m and $l = 0.29$ m. The resulting standard deviation on the volume would be 0.233 m^3.

In summary, the tolerance or standard deviation information on the dependent variables has been used to find the values of the parameters that minimize the variation of the dependent variable. In other words, the resulting configuration is as insensitive to noise as possible and is thus a robust, quality design.

If the standard deviation on the volume is not small enough, then the next step is to tighten the tolerances.

Robust design can be summarized as a three-step method:

Step 1. Establish the relationship between quality characteristics and the control parameters (for example, Eq. [10.10]). Also, define a target for the quality characteristic.

Step 2. Based on known tolerances (standard deviations) on the control variables, generate the equation for the standard deviation of the quality characteristic (for example, Eq. [10.12] or [10.14]).

Step 3. Solve the equation for the minimum standard deviation of the quality characteristic subject to this variable being kept on target. For the example given, Lagrange's technique was used; other techniques are available, and some are even included in most spreadsheet programs. There are usually other constraints on this optimization problem that limit the values of the parameters to feasible levels. For the example given, there could have been limits on the maximum and minimum values of r and l.

There are some limitations on the method developed here. First, it is only good for design problems that can be represented by an equation. In systems in which the relationships between the variables cannot be represented by equations, experimental methods must be used (Section 10.10). Second, Eq. [10.15] does not allow for the inclusion of constraints in the problem. If the radius, for example, had to be less than 1.0 m because of space limitations, Eq. [10.15] would need additional terms to include this constraint.

10.10 ROBUST DESIGN THROUGH TESTING

It is often impossible to analytically evaluate a proposed design because no mathematical models of the system exist or the fidelity of those that do are too low. In many cases, even when analysis is possible, the analytical model of the system may not allow determination of the effect of the noise on a proposed design. In either case, it is necessary to design and build a physical model for experimental testing. In Chap. 8, physical models were used to verify the concept; now they are needed to refine the product. The material in this section is an introduction to Taguchi's experimental method for the robust design of products. Like many other topics, this subject has entire books devoted to it (see Section 10.12, Sources); however, this material is sufficient to make us appreciate the strength of the method and its complexity and enable us to apply it to the design of the tank as a simple example. We will assume that we do not know the formula $V = \pi r^2 l$ and only know $V = f(r, l)$. To experimentally find dimensions for radius and length, we could begin by building a tank with some best-guess dimensions and then measuring the volume. Then, if the volume was too high, we could build new models, one with a smaller radius and another with a shorter length, and then measure the volumes. Based on these new measurements, we could try to estimate the dependence of the volume on each of the dimensions and iterate (i.e., patch) our way to the target volume. This is the way most experiments are run. This "random walk" toward a solution may require many models, so it is not very efficient. Additionally, the solution found could be anywhere on the curve shown in Figs. 10.4 and 10.15; there is no guarantee that the final design will be the most robust. The following steps can overcome these drawbacks.

10.10.1 Step 1: Identify Signals, Noise, Control, and Quality Factors (i.e., Independent Parameters)

Referring back to the P-diagram in Fig. 10.9, it is necessary to list all the dependent and independent parameters related by the product or system. Then it is necessary to decide which of these are critical to the evaluation of the product. Sometimes this is not easy, and critical parameters or noises may be overlooked. This may not become evident until data are taken and the results are found to have wide distribution, implying that the model is not complete or the experiments have been poorly done. It is essential to take care here to understand the system.

The P-diagram for the tank (Fig. 10.16) shows that the designer has control over the length and radius and that there are many noises that affect the volume of liquid held. The function of the tank is to "hold liquid," and its performance is measured by how accurately the tank can be held to the target value of 4 m^3. The noises include the manufacturing variations on the radius and length, and the aging and environmental effects not considered here.

10.10.2 Step 2: For Each Quality Measure (i.e., Output Response) to Be Evaluated, Recall or Determine Its Target Value and the Nature of the Quality Loss Function

During the development of the QFD, target values were determined and the shape of the loss function (see Table 10.2) was identified. If this information has not been previously generated for the parameter being measured, do this before the experiment is developed.

Loss is proportional to the Mean Square Deviation, MSD, the average amount the output response is off the target. This amount is also often referred to as the Signal-to-Noise ratio, or S/N ratio. Generally the S/N ratio is $-10 \log(\text{MSD})$. The minus is included so that the maximum S/N ratio is the minimum quality loss, the 10 is used to get the units to decibels, and the logarithm is used to compress the values.

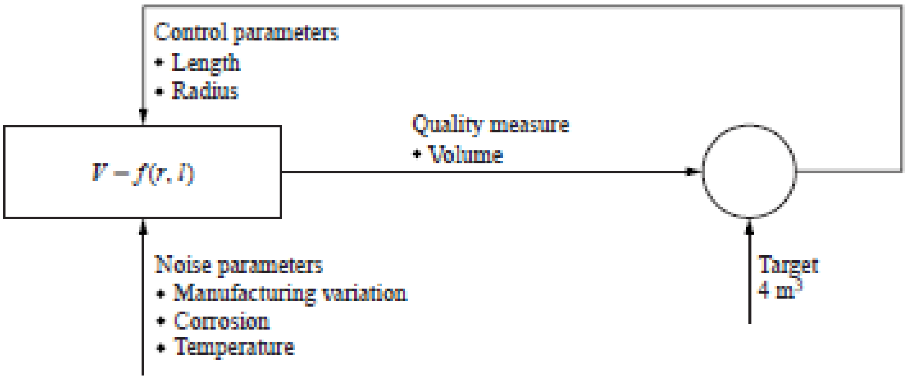


Figure 10.16 P-diagram for tank problem.

Table 10.2 Formulas for means and S/N ratios

Quality loss function	Mean square deviation (MSD)	S/N ratio
Smaller-is-better	$\frac{1}{n}\sum_{i=1}^{n} y_i^2$	$-10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right)$
Larger-is-better	$\frac{1}{n}\sum_{i=1}^{n}\left(\frac{1}{y_i^2}\right)$	$-10\log\left(\frac{1}{n}\sum_{i=1}^{n}\frac{1}{y_i^2}\right)$
Nominal-is-best	$\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2+(\bar{y}-m)^2$ m = target value	$-10\log\frac{1}{n}\sum_{i=1}^{n}(y_i-\bar{y})^2$

The MSD and S/N for the three most common types of targets identified in Section 6.8 are shown in Table 10.2. For the smaller-is-better target, the larger the value of the output, y, the larger the MSD and the smaller the S/N ratio. In other words, larger values of y are noise, so the signal is weaker relative to that noise. For the larger-is-better case, smaller values of y are seen as noise.

The nominal-is-best target is more complex; there are many ways to calculate the S/N ratio. The most common is shown here. As shown in Table 10.2, the mean square deviation is simply the sum of the variation about the mean and the accuracy about the target. Generally, only the sum of the variation is used in calculating the S/N ratio, as shown in the table.

For the tank problem, 4 m^3 is a nominal-is-best target.

Parameter design is based on maximizing the S/N ratio and then tuning the parameters to bring the design on target. In other words, the goal is to find the conditions that make the product insensitive to noise and then use parameters that do not affect the S/N ratio to bring the quality functions to the desired value. The use of this philosophy will become clear in the example problem.

10.10.3 Step 3: Design the Experiment

The goal is to design an experiment that forces what ever can happen, to happen. It is not sufficient to design a simple experiment in which the model is patched and patched until it works once. This does not lead to a robust design. Instead, the experiment should be designed so that the results give a clear understanding of the effects on the output response of changing control parameters and an understanding of the effects of noise. An ideal experiment will show how to adjust the control parameter to meet the target and show which one to choose so that the resulting system is insensitive to noise.

The physical model of the product or system must be designed so that these can be achieved:

- Control factors can be changed to represent the options available. This may mean designing a number of different physical devices or designing one with

10.10.4 Step 4: Take and Reduce Data

The measured volumes of the tank are shown in Table 10.4 along with the calculated values of the mean and nominal-is-best S/N ratio. Mean values and S/N ratios are calculated for repetitions of each set of control and noise conditions. Two of the mean values are fairly close to the target of 4 m^3. This was the result of luck in choosing the starting values for r and l. In fact, this result raises the question of which one is best, because they have vastly different values for radius and length.

10.10.5 Step 5: Analyze the Results, and Select New Test Conditions If Needed

The first set of experiments may not yield satisfactory results. The goal is to maximize the S/N ratio and then bring the mean value on target. For analytical problems, we can find the true maximum (Section 10.9); here we can only estimate when we reach that point.

10.11 SUMMARY

- Product evaluation should be focused on comparison with the engineering requirements and also on the evolution of the function of the product.
- Products should be refined to the degree that their performance can be represented as numerical values in order to be compared with the engineering requirements.
- P-diagrams are useful for identifying and representing the input signals, control parameters, noises, and output response.
- Physical and analytical models allow for comparison with the engineering requirements.
- Concern must be shown for both the accuracy and the variation of the model.
- Parameters are stochastic, not deterministic. They are subject to three types of noises: the effects of aging, of environment change, and of manufacturing variation.
- Robust design takes noise into account during the determination of the parameters that represent the product. Robust design implies minimizing the variation of the critical parameters.
- Tolerance stacking can be evaluated both by the additive method and by statistical means.
- Both analytical and experiment methods exist for finding the most robust design.

11.2.1 Determining the Cost of a Product

The total cost of a product to the customer (i.e., the list price) and its constituent parts are shown in Fig. 11.1. All costs can be lumped into two broad categories,

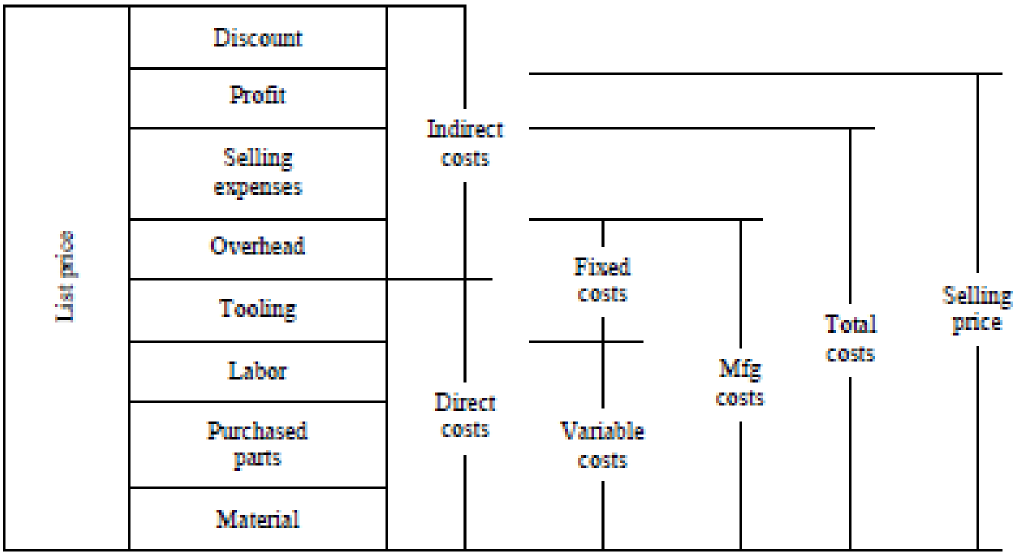


Figure 11.1 Product cost breakdown

11.2.3 The Cost of Machined Components

Machined components are manufactured by removing portions of the material not wanted. Thus, the costs for machining are primarily dependent on the cost and shape of the stock material, the amount and shape of the material that needs to be removed, and how accurately it must be removed. These three areas can be further decomposed into seven significant control factors that determine the cost of a machined component:

1. **From what material is the component to be machined?** The material affects the cost in three ways: the cost of the raw material, the value of the scrap produced, and the ease with which the material can be machined. The first two are direct material costs, and the last affects the amount of labor, the amount of time, and the choice of machines that are used manufacturing the component.

2. **What type of machine is used to manufacture the component?** The type of machine—lathe, horizontal mill, vertical mill, and so on—used in manufacture affects the cost of the component. For each type, there is not only the cost of the machine time itself but also the cost of the tools and fixtures needed.
3. **What are the major dimensions of the component?** This factor helps determine what size of machines of each type will be required to manufacture the component. Each machine in a manufacturing facility has a different cost for use, depending on the initial cost of the machine and its age.
4. **How many machined surfaces are there, and how much material is to be removed?** Just knowing the number of surfaces and the material removal ratio (the ratio of the final component volume to the initial volume) can aid in giving a good estimate for time required to machine the part. Estimates that are more accurate require knowing exactly what machining operations will be used to make each cut.
5. **How many components are made?** The number of components in a batch has a great effect on the cost. For one piece, fixturing is minimal, though long setup and alignment times are required. For a few pieces, simple fixtures are made. For a high volume, the manufacturing process is automated, with extensive fixturing and numerically controlled machining.
6. **What tolerance and surface finishes are required?** The tighter the tolerance and surface finish requirements, the more time and equipment are needed in manufacture.
7. **What is the labor rate for machinists?**

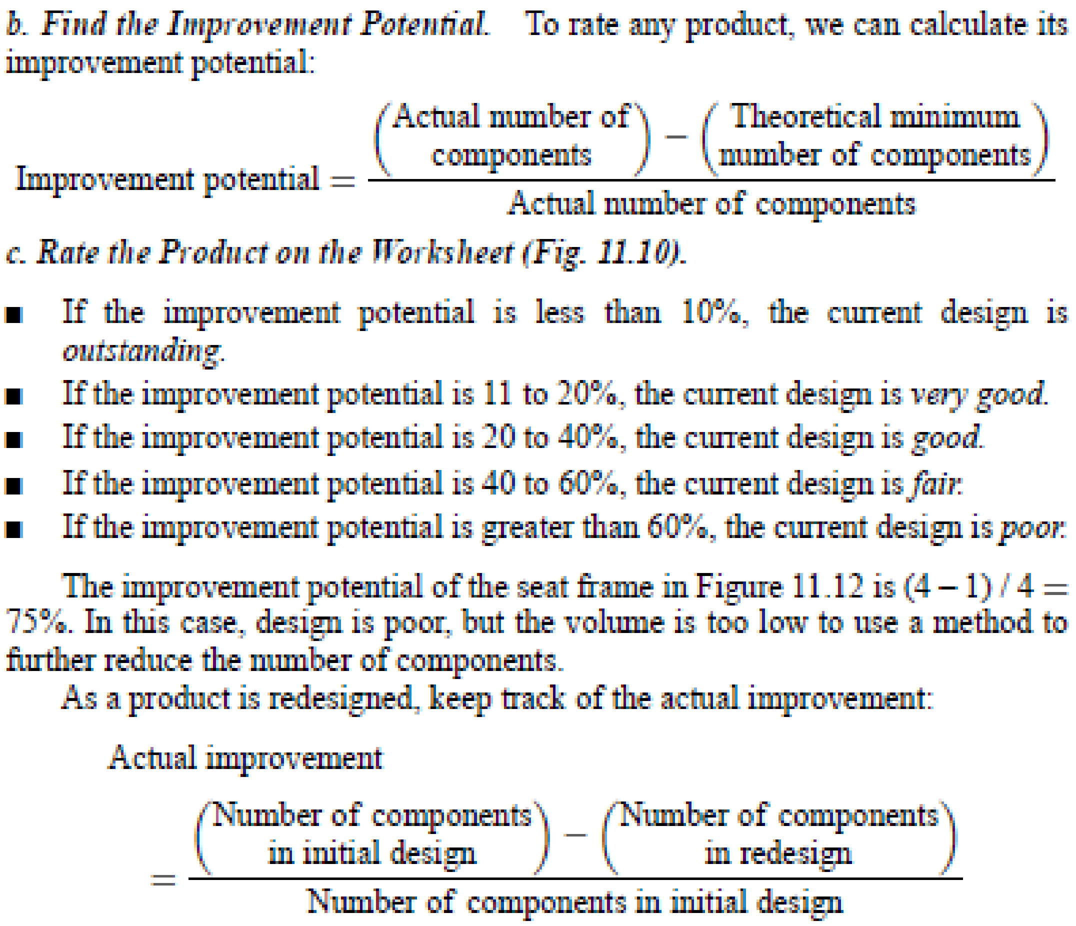
As an example of how these seven factors affect the cost of machined components, consider the component in Fig. 11.6.[1] For this component the seven significant factors affecting cost are

1. The material is 1020 low-carbon steel.
2. The major manufacturing machine is a lathe. Two additional machines need to be used to mill the flat surfaces and drill the hole.
3. The major dimensions are a 57.15-mm diameter and a 100-mm length. The initial raw material must be larger than these dimensions.
4. There are three turned surfaces and seven other surfaces to be made. The final component is approximately 32% the volume of the original.
5. The number of components to be made is discussed in the next paragraph.
6. The tolerance varies over the different surfaces of the component. On most surfaces, it is nominal, but on the diameters, it is a fit tolerance. The surface finish, .8 μm (32 μin.), is considered intermediate.
7. The labor rate used is $35 per hour; this includes overhead and fringe benefits.

11.4 DFM—DESIGN FOR MANUFACTURE

11.5 DFA—DESIGN-FOR-ASSEMBLY EVALUATION

11.5.1 Evaluation of the Overall Assembly



b. Find the Improvement Potential. To rate any product, we can calculate its improvement potential:

$$\text{Improvement potential} = \frac{\begin{pmatrix}\text{Actual number of}\\ \text{components}\end{pmatrix} - \begin{pmatrix}\text{Theoretical minimum}\\ \text{number of components}\end{pmatrix}}{\text{Actual number of components}}$$

c. Rate the Product on the Worksheet (Fig. 11.10).

- If the improvement potential is less than 10%, the current design is *outstanding*.
- If the improvement potential is 11 to 20%, the current design is *very good*.
- If the improvement potential is 20 to 40%, the current design is *good*.
- If the improvement potential is 40 to 60%, the current design is *fair*.
- If the improvement potential is greater than 60%, the current design is *poor*.

The improvement potential of the seat frame in Figure 11.12 is (4 – 1) / 4 = 75%. In this case, design is poor, but the volume is too low to use a method to further reduce the number of components.

As a product is redesigned, keep track of the actual improvement:

$$\text{Actual improvement} = \frac{\begin{pmatrix}\text{Number of components}\\ \text{in initial design}\end{pmatrix} - \begin{pmatrix}\text{Number of components}\\ \text{in redesign}\end{pmatrix}}{\text{Number of components in initial design}}$$

11.5.2 Evaluation of Component Retrieval

11.5.3 Evaluation of Component Handling

11.5.4 Evaluation of Component Mating

11.6 DFR—DESIGN FOR RELIABILITY

11.6.1 Failure Modes and Effects Analysis

11.6.1 Failure Modes and Effects Analysis

The Failure Modes and Effects Analysis, FMEA, technique presented here can be used throughout the product development process and refined as the product is refined. The method aids in identifying where redundancy may be needed and in diagnosing failures after they have occurred. FMEA follows these five steps, and can be developed in a simple table, as shown in Figure 11.32:

Step 1: Identify the Function Affected. For each function identified in the evolution of the product, ask, "What if this function fails to occur?" If functional development has paralleled form development, this step is easy; the functions are already identified. However, if detailed functional information is not available, this step can be accomplished by listing all the functions of each component or assembly. For products being redesigned, the functions of a component or assembly are found by examining the connections or component interfaces and identifying the flow of energy, information, or materials through them. Additional considerations come from extending the basic question to read, "What if this function fails to occur at the right time?" "What if this function fails to occur in the right sequence?" or "What if this function fails to occur completely?"

Step 2: Identify Failure Modes. For each function, there can be many different failures. The failure mode is a description of the way a failure occurs. It is what is observed, what can be detected when the function fails to occur.

Step 3: Identify the Effect of Failure. What are the consequences on other parts of the system of each failure identified in step 1? In other words, if this failure occurs, what else might happen? These effects may be hard to identify in systems in which the functions are not independent. Many catastrophes result when one system's benign failure overloads another system in an unexpected manner, creating an extreme hazard. If functions have been kept independent, the consequences of each failure should be traceable.

Step 4: Identify the Failure Causes or Errors. List the changes or the design or manufacturing errors that can cause the failure. Organize them into three groups: design errors (D), manufacturing errors (M), and operational changes (O).

Step 5: Identify the Corrective Action. Corrective action requires three parts, what action is recommended, who is responsible, and what was actually done. For each design error listed in step 3, note what redesign action should be taken to ensure that the error does not occur. The same is true for each potential manufacturing error. For each operational change, use the information generated to establish a clear way for the failure mode to be detected. This is important, as it is the basis for the diagnosis of problems when they do occur. For operational changes it may also be important to redesign the device so that the failure mode has a reduced effect on the function. This may include the addition of other devices (for example, fuses or filters) to protect the function under consideration; however, the failure potential of these added devices should also be considered. The use of redundant systems is another way to protect against failures. But redundancy might add other failure modes as well as increase costs.

FMEA is best used as a bottom-up tool. This means focusing on a detailed

11.6.2 FTA—Fault Tree Analysis

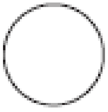
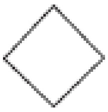
Fault Tree Analysis (FTA) can help in finding failure modes. FTA evolved in the 1960s during the development of the Minuteman Missile System and has gained in use ever since. The goal of this method is to graphically develop a tree of all the faults that could happen to cause a system failure, and the logical relationships among these faults. Further, there are analytical methods to compute probabilities of faults, but we will only give a basic, usable introduction to the method here.

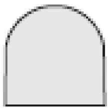
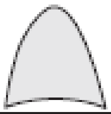
Fault Trees are built from symbols that signify events and logic. The most basic of these are listed in Table 11.2 and used in an example Fault Tree for the MER (Fig 11.33). This Fault Tree is a partial analysis for the event "Loss of Rover Mobility." The full Fault Tree had hundreds of events identified. Fault Trees are built from the top down, beginning with an undesired event (loss of Rover mobility) taken as the root ("top event"). The steps for building a Fault Tree are

Step 1: Identify the top event. There should be only one top event.

Step 2: Identify the events (i.e., faults) that can possibly occur to cause the top event. Ask the question "What can go wrong?" repeatedly until all the events that

Table 11.2 Basic Fault Tree symbols

Event block	FTA symbol	Description
Event		An event, something that happens to something and causes a function to fail.
Basic Event		A basic initiating fault or a failure event.
Undeveloped Event		An event that is not further developed.

Logical operation	FTA symbol	Description
AND		The output event occurs if all input events occur.
OR		The output event occurs if at least one of the input events occurs.

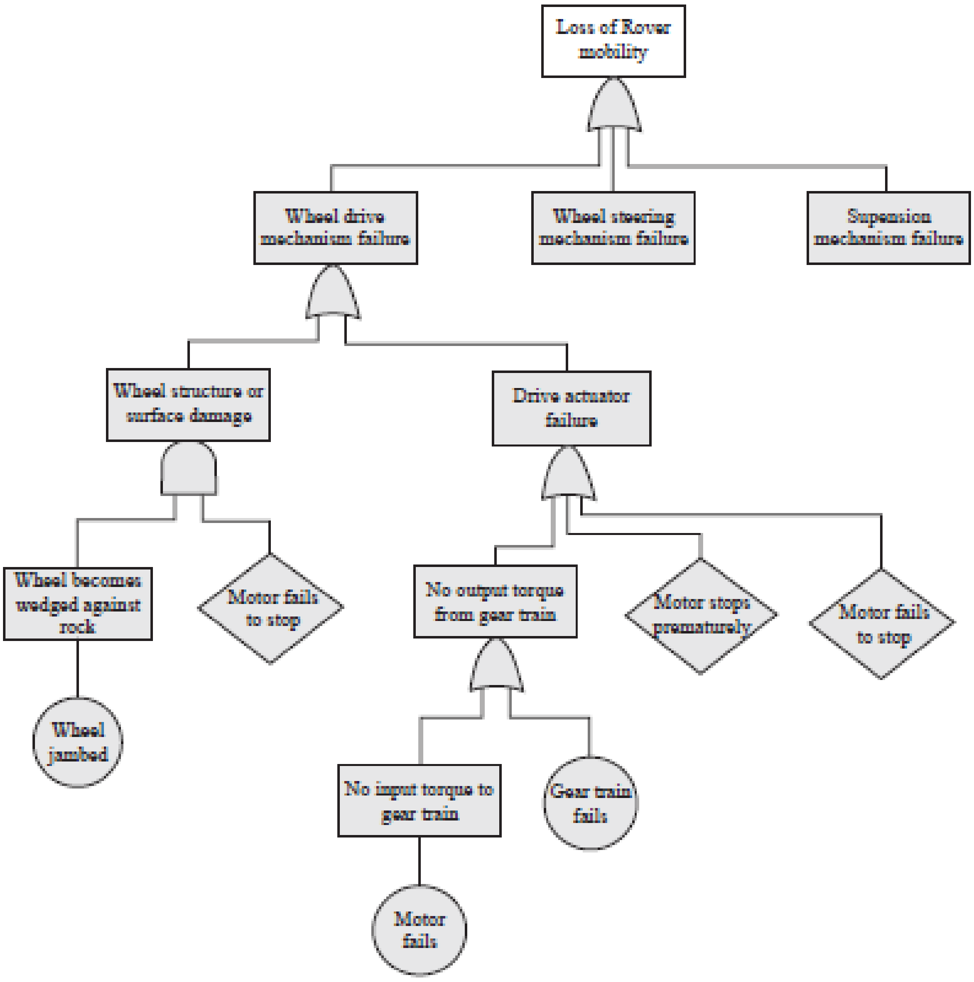
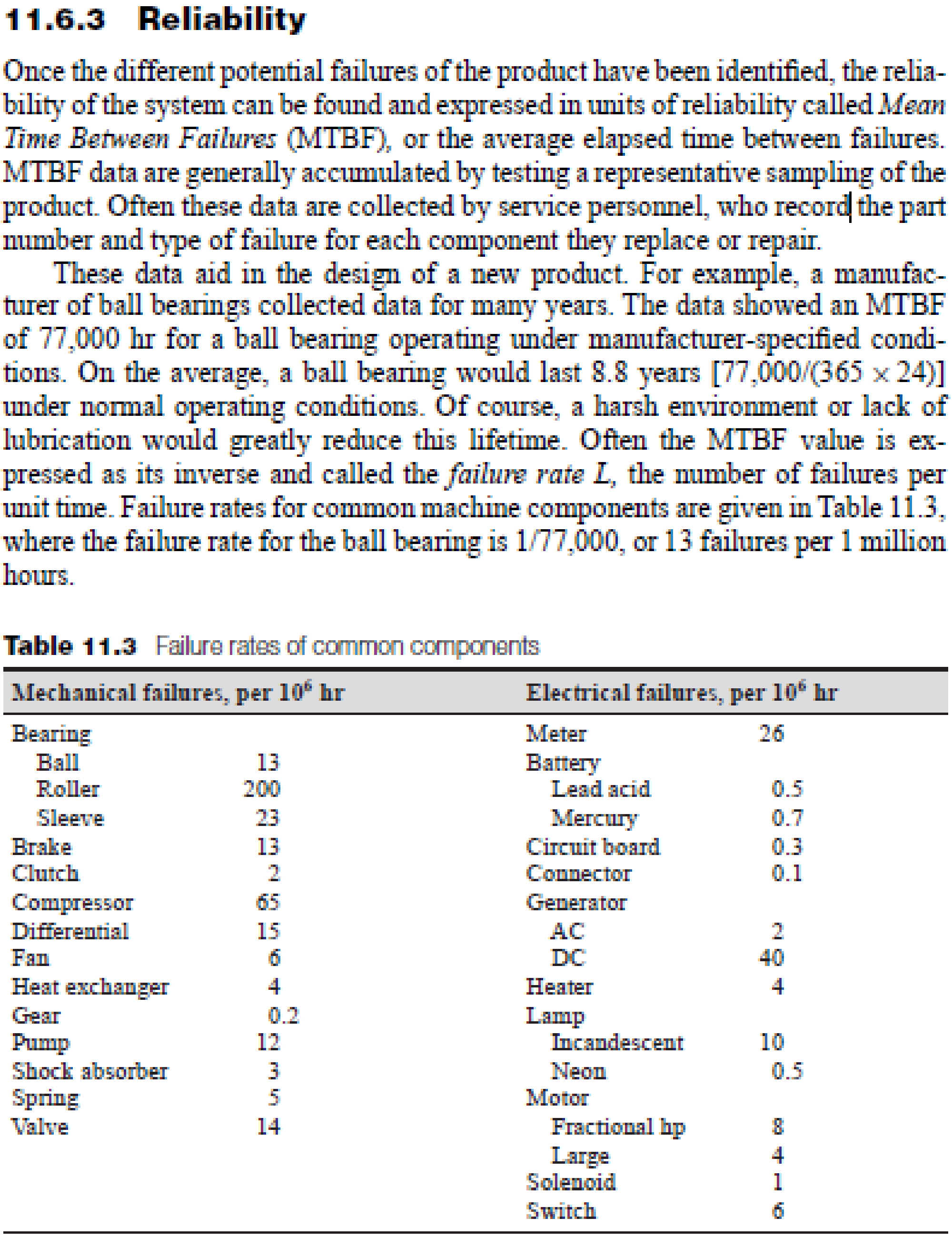


Figure 11.33 Partial Fault Tree for MER Mobility



11.6.3 Reliability

Once the different potential failures of the product have been identified, the reliability of the system can be found and expressed in units of reliability called *Mean Time Between Failures* (MTBF), or the average elapsed time between failures. MTBF data are generally accumulated by testing a representative sampling of the product. Often these data are collected by service personnel, who record the part number and type of failure for each component they replace or repair.

These data aid in the design of a new product. For example, a manufacturer of ball bearings collected data for many years. The data showed an MTBF of 77,000 hr for a ball bearing operating under manufacturer-specified conditions. On the average, a ball bearing would last 8.8 years [77,000/(365 × 24)] under normal operating conditions. Of course, a harsh environment or lack of lubrication would greatly reduce this lifetime. Often the MTBF value is expressed as its inverse and called the *failure rate L*, the number of failures per unit time. Failure rates for common machine components are given in Table 11.3, where the failure rate for the ball bearing is 1/77,000, or 13 failures per 1 million hours.

Table 11.3 Failure rates of common components

Mechanical failures, per 10^6 hr		**Electrical failures, per 10^6 hr**	
Bearing		Meter	26
Ball	13	Battery	
Roller	200	Lead acid	0.5
Sleeve	23	Mercury	0.7
Brake	13	Circuit board	0.3
Clutch	2	Connector	0.1
Compressor	65	Generator	
Differential	15	AC	2
Fan	6	DC	40
Heat exchanger	4	Heater	4
Gear	0.2	Lamp	
Pump	12	Incandescent	10
Shock absorber	3	Neon	0.5
Spring	5	Motor	
Valve	14	Fractional hp	8
		Large	4
		Solenoid	1
		Switch	6

11.7 DFT AND DFM—DESIGN FOR TEST AND MAINTENANCE

11.8 DFE—DESIGN FOR THE ENVIRONMENT

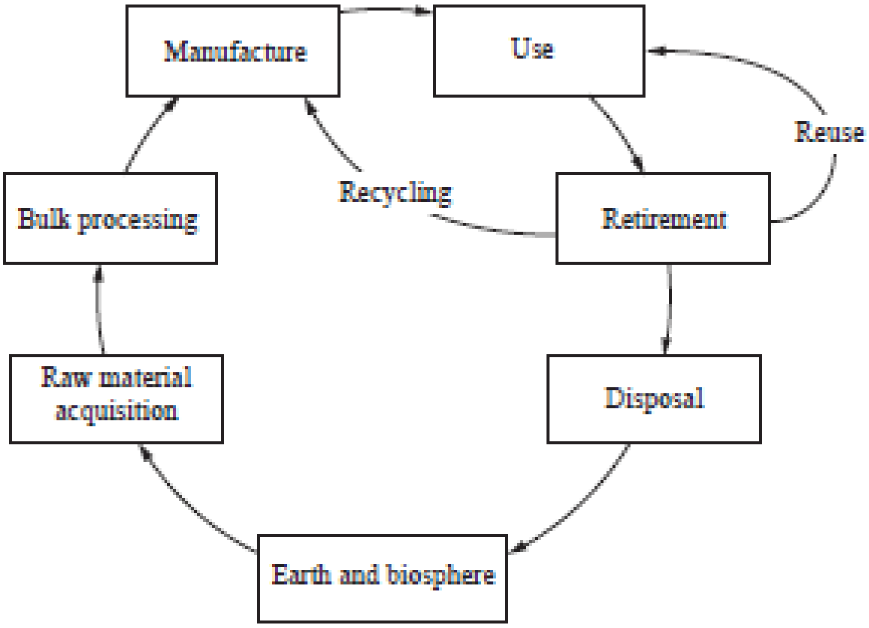


Figure 11.34 Green design life cycle.

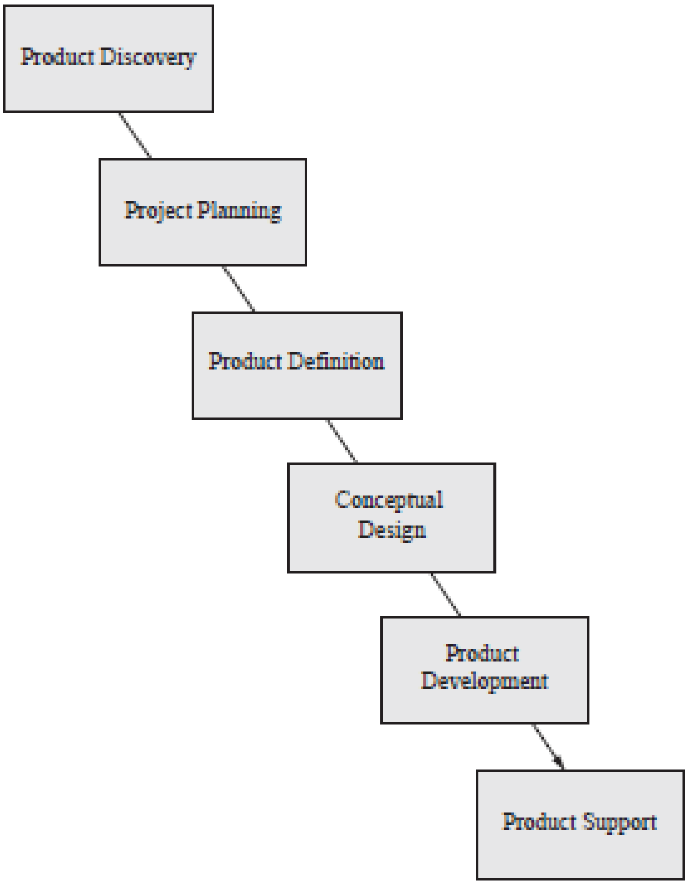


Figure 12.1 The mechanical design process.

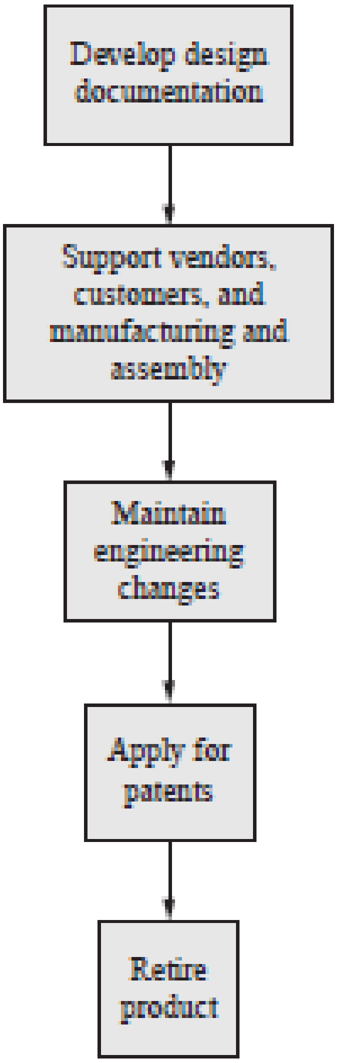


Figure 12.2
Product support details.

12.2 DESIGN DOCUMENTATION AND COMMUNICATION

In the previous chapters, many design best practices were introduced to aid in the development of a product. The documentation generated by these techniques, along with the personal notebooks of the design team members and the drawings and bill of materials, constitute a record of a product's evolution. Additionally, summaries of the progress for design reviews also exist. All of this information constitutes a complete record of the design process. Most companies archive this information for use as a history of the evolution of the product, or in patent disputes or liability litigation.

Beyond the information generated during the process, there is still much to be done to communicate with those downstream in the product's life. This section briefly describes the types of additional documents that need to be developed and communicated.

12.2.1 Quality Assurance and Quality Control

Even if quality has been a major concern during the design process, there is still a need for Quality Control (QC) inspections. Incoming raw materials and manufactured components and assemblies should be inspected for conformance to the design documentation. The industrial engineers on the design team usually have the responsibility to develop the QC procedures that address the questions, What is to be measured? How will it be measured? How often will it be measured?

Quality Assurance (QA) documentation must be developed if the product is regulated by government standards. For example, medical products are controlled by the Food and Drug Administration (FDA), and manufacturers of medical devices must keep a detailed file of quality assurance information on the types of materials and processes used in their products. FDA inspectors can come on site without prior notification and ask to see this file.

12.2.2 Manufacturing Instructions

A good drawing should have all the information needed to manufacture a component. Nonetheless, each plant has a certain set of manufacturing equipment, jigs and fixtures, and processes to make each component. Industrial engineers have the major responsibility for developing these manufacturing instructions. In very small companies, those with no industrial engineers, manufacturing instructions may become the responsibility of the product designers.

12.2.3 Assembly, Installation, Operating, and Maintenance Instructions

We have all purchased products, opened the box, and seen that there was "some assembly required." Then, on reading the directions, found that they were unintelligible. Similarly, most software user manuals are impossible to decipher. In smaller organizations, engineers often get to write assembly, installation, operating, and maintenance instructions. In larger organizations, engineers may work with professional writers to create these documents. Either way, it is important to understand what is required to develop a good set of instructions.

For many products, *assembly instructions* are part of the total design package. These instructions spell out, step by step, how to assemble the product. This is necessary whether the assembly is done by hand or by machine. The generation of assembly instructions, while tedious, can be enlightening in that the assembly itself is refined, the assembly sequence (Section 11.5) is refined, and jigs and fixtures for holding the assembly are developed. *Installation instructions* include instructions for unpacking the items and making the necessary connections for power, support, and environmental control. Instructions for initial start-up and testing may also be included. For many systems, these are major parts of the final product package. *Operation instructions* include instructions on how to operate the device over the normal range of activity. Various modes—start-up, standby, emergency operation, and shutdown—may be described. Instructions on how to determine when the equipment is failing may also be included. Finally, all products need maintenance. *Maintenance instructions* may be included with operating instructions. Maintenance can range from something as simplistic as cleaning the surface of the product to total disassembly and inspection.

Although writing instructions may not seem like a task suited for an "engineer," writing them can help you understand your product in a unique way. It forces you to assume the role of assembler, installer, operator, and maintainer. In fact, writing instructions is helpful to understanding your product if you begin to write them early in the design process.

Some guidelines for writing instructions are

1. Read as many similar instruction manuals as you can. Many companies post their manuals online, or you can obtain one by calling a company's headquarters and requesting a copy.
2. Organize instructions into sections to make it easy to find answers. Do not write in the order you developed the product, write in the order in which it will be assembled, installed, operated, or maintained. A good way to understand the difference is to walk through assembling, installing, operating, or maintaining the product while pretending you have no knowledge beyond that which you assume the readers of the instructions to have.
3. Recruit members of the user community not familiar with the product to test your instruction manuals. It is best if you hand them the instructions and then watch them assemble, install, operate, or maintain the product using what

you wrote. It is important not to say anything while observing. It is amazing to witness how much you have assumed. You need to observe whether or not the instructions are easy to follow, or if searching, rereading, and interpreting are required? Instructions should consist of short paragraphs explaining the process, plus accompanying numbered or bulleted lists, figures, photographs, or screenshots, and steps for users to follow. Text instructions embedded in long paragraphs are extremely difficult to follow.

4. Make instructions activity centered. Explain the most basic activities and how to accomplish them. Make the explanations short and simple and do not explain every knob and button and menu item.
5. Put legal warnings in an Appendix. When instructions are needed, they are needed right away, and having to work one's way through pages of legal warnings only increases the anxiety level and decreases the pleasure of the product. Moreover, people skip these anyway, so they are ineffective. Consult with a lawyer to make sure you include the right wording to protect your company and employees from potential liability. This is especially important if you have to write instructions for products that may be potentially dangerous.
6. Hire an excellent technical writer. The instruction writers should be a part of the design team. Ideally, instructions are written first, to help understand the voice of the customer.

12.3 SUPPORT

Although not usually thought of as part of the design process, support for downstream activities often takes a sizable portion of engineering time. It has been estimated that about 20 to 30% of all engineering time is spent supporting existing products. Support includes maintaining vendor relationships, interfacing with customers, supporting manufacturing and assembly, and maintaining changes (see Section 12.4).

12.3.1 Vendor Relationships

Very few products are made solely in house. In fact, many companies make no components themselves and only specify, assemble, sell, or distribute what others make. Others only specify and make nothing themselves. Thus, for most companies, relationships with their vendors are crucial. Prior to 1980, many large companies had thousands of vendors, each chosen for its low bid to make a component or assembly. These companies realized, however, that this was a poor way to do business, because the cheapest components were not always of the highest quality even if they met the specifications. Additionally, managing thousands of vendors proved very expensive and difficult.

Guidelines that can help you build and maintain good vendor relationships include:

1. Know your goals and your vendor's goals. Building a strong vendor relationship means more than cutting product or service costs. It is about improving value provided to the business, reducing the time to deliver solutions, reducing staff effort, and much more. Define the goals and objectives of your department/company and work only with vendors who are aligned with your goals. Vendor's goals may include building a center of excellence, entering new markets, gaining market share within a product line, developing industry verticals, and so on. It is very important for your relationship to understand the vendor's goals and determine how your organization fits into this strategy. When the vendor's goals are aligned with your goals, the relationship will be more successful since you are both working toward the same end results.
2. Define clear relationship guidelines. Meeting with a vendor only when there is a problem with a product is a problem relationship from the beginning. Both organizations lose from this relationship. Clearly defining a regular vendor meeting structure with a defined agenda is the key for both organizations to understand the goals, needs, wants, and actionable items of the other. Both parties must clearly understand each others obligations, who is responsible, and the expected outcomes. Clearly defining this up front is a key success factor.
3. Involve vendors early. When dealing with vendors, you cannot afford delays and extensive alterations. Treat them as your customers early in the product development process, include them on teams, and enlist their expertise as you design the product.
4. Establish relationships. It is important to have vendor partners who understand that the relationship should be win-win for both parties. If you do a lot of business with a particular vendor, he or she will reward you for your loyalty by offering discounts and incentives to you. They will even go out of their way to help you by speeding up the shipment process if you need to quickly ship some orders, for example, or receive a back order. There should be a single point of contact in both organizations and they should get to know each other.
5. Treat vendors with respect. The Golden Rule of any relationship is, "Treat others as you want to be treated, with respect and integrity." Treat your vendors like your customers, and they in turn will treat you like a customer. All successful relationships are built on mutual trust. Only work with vendors that have a good reputation, ones that keep their word. Likewise, be honest and forthcoming in your communications to vendors.
6. Communicate. Put everything in writing—responsibilities, expected sales volume, payment, mode of payment, and so on. Anything you think may cause misunderstanding and strained vendor relationships later must be put

down in writing beforehand. When in doubt, talk it out. What works for interpersonal relationships also serves as a reliable rule of thumb for fostering healthy relationships with your vendors. Poor communication will reduce your relationship to, "It is not in the contract" instead of the response "How can we help you."

7. Stay professional. Things go wrong in life. When they go wrong in a relationship, the smartest thing to do is to deal with the problem calmly and factually, in order to avoid ruining the relationship.

12.3.2 Customer Relationships

Although many companies isolate their engineers from their customers, others make an effort to close the loop with direct feedback from customers to engineers. Most companies have a product service department that handles day-to-day customer communication and filters information reaching the engineers. This is both necessary and a problem as interruptions slow the development of new products, but some direct contact improves the product developer's understanding of how the products are being used, their good features, and their bad features.

Other companies, especially those that produce low-volume products, have the engineers work directly with customers. Using methods like quality function deployment keep that communication positive and useful.

12.3.3 Manufacturing and Assembly Relationships

In Chap. 1, the over-the-wall design method showed information flowing from design to production and not back again. Most modern companies try to maintain communication between the two groups so that problems in manufacturing and assembly, those that can lead to changes, are minimized. Methods already discussed like concern for the product life cycle, DFM, DFA, and PLM all help break the over-the-wall way of doing business. For example, quoting from a Neon design manager at Chrysler, "It used to be that the engineers handed off the project to the assembly plant 28 weeks before volume production began . . . now workers began meeting with engineers on the Neon 186 weeks before Job One." At various stages of Neon development, busloads of engineers traveled en masse to meet with manufacturing and assembly workers to ready the car for production. These meetings focused on designing the product to be easy to manufacture and assemble. This transformation is significant for a company of Chrysler's size.

12.4 ENGINEERING CHANGES

Although this book encourages change early in the design process, change may still occur after the product is released to production (see Fig. 1.5). Changes are caused by

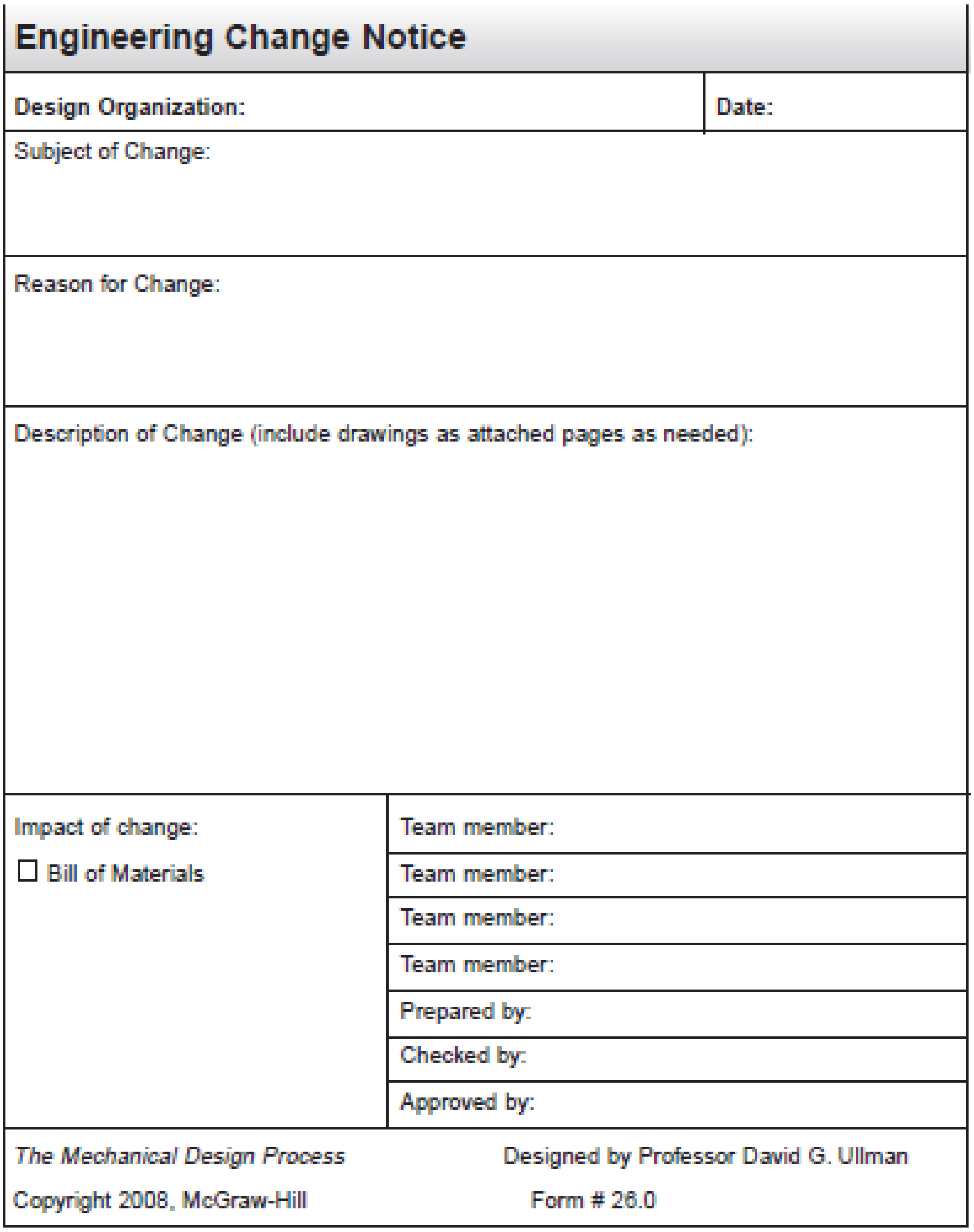
- Correction of a design error that doesn't become evident until testing and modeling, or customer use reveals it.

- A change in the customers' requirements necessitating the redesign of part of the product.
- A change in material or manufacturing method. This can be caused by a lack of material availability, a change in vendor, or to compensate for a design error.

To make a change in an approved configuration, an *Engineering Change Notice* (ECN), also called an *Engineering Change Order* (ECO), is required. An ECN is an alteration to an approved set of final documents and thus needs approval itself. As shown in the example in Fig. 12.3, an ECN must contain at least this information:

- Identification of what needs to be changed. This should include the part number and name of the component and reference to the drawings that show the component in detail or assembly.
- Reason(s) for the change.
- Description of the change. This includes a drawing of the component before and after the change. Generally, these drawings are only of the detail affected by the change.
- List of documents and departments affected by the change. The most important part of making a change is to see that all pertinent groups are notified and all documents updated.
- Approval of the change. As with the detail and assembly drawings, the changes must be approved by management.
- Instruction about when to introduce the change—immediately (scrapping current inventory), during the next production run, or at some other milestone.

12.5 PATENT APPLICATIONS



Engineering Change Notice

Design Organization:

Date:

Subject of Change:

Reason for Change:

Description of Change (include drawings as attached pages as needed):

Impact of change:

☐ Bill of Materials

Team member:

Team member:

Team member:

Team member:

Prepared by:

Checked by:

Approved by:

The Mechanical Design Process

Designed by Professor David G. Ullman

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Form # 26.0

Figure 12.3 Engineering change notice.

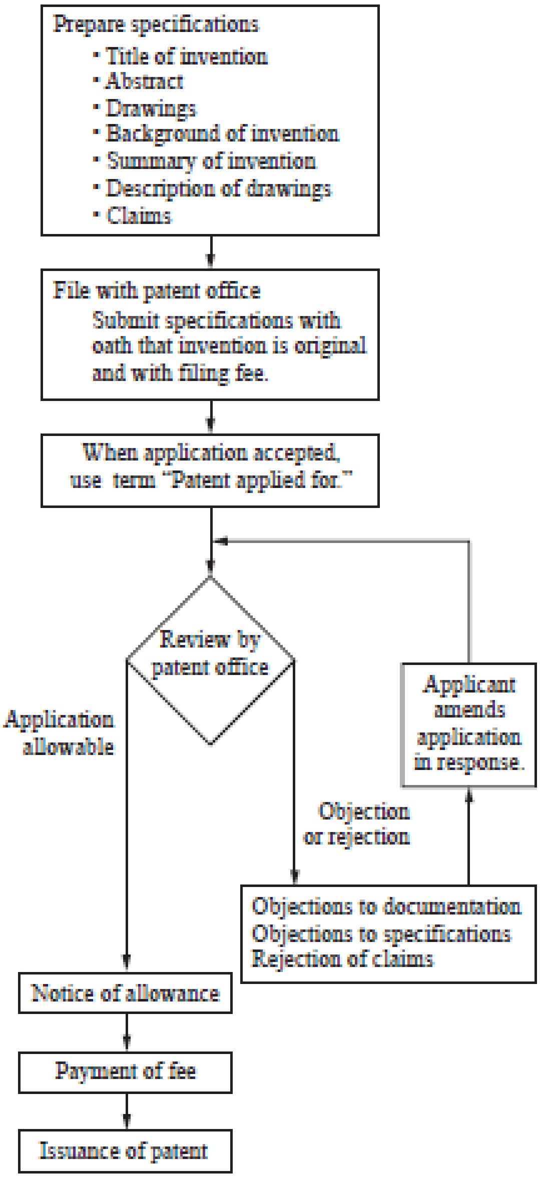
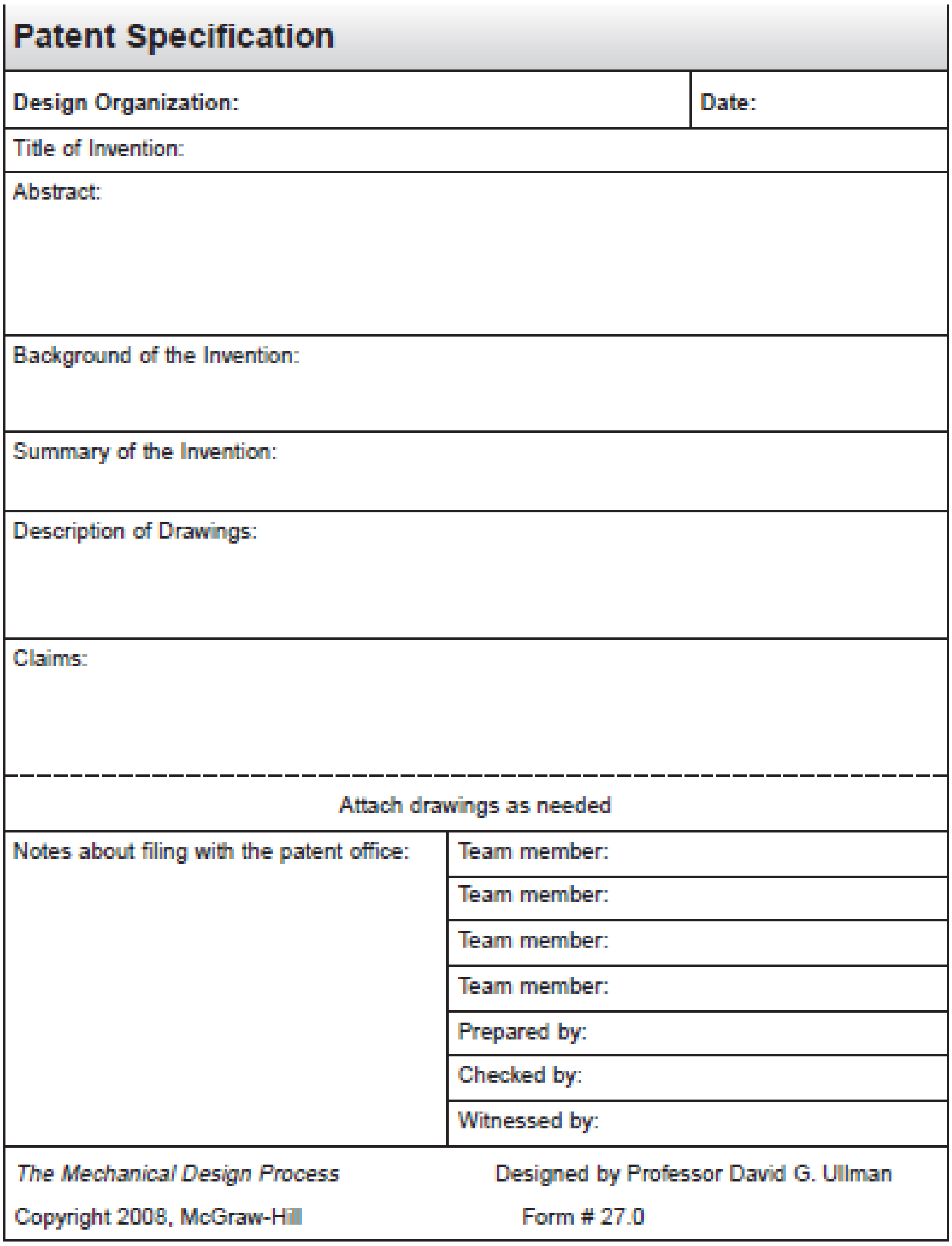


Figure 12.4 Patent application procedure.



Patent Specification

Design Organization:
Date:
Title of Invention:
Abstract:
Background of the Invention:
Summary of the Invention:
Description of Drawings:
Claims:

Attach drawings as needed

Notes about filing with the patent office:
Team member:
Team member:
Team member:
Team member:
Prepared by:
Checked by:
Witnessed by:

The Mechanical Design Process Designed by Professor David G. Ullman
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Figure 12.5 Patent Specification.

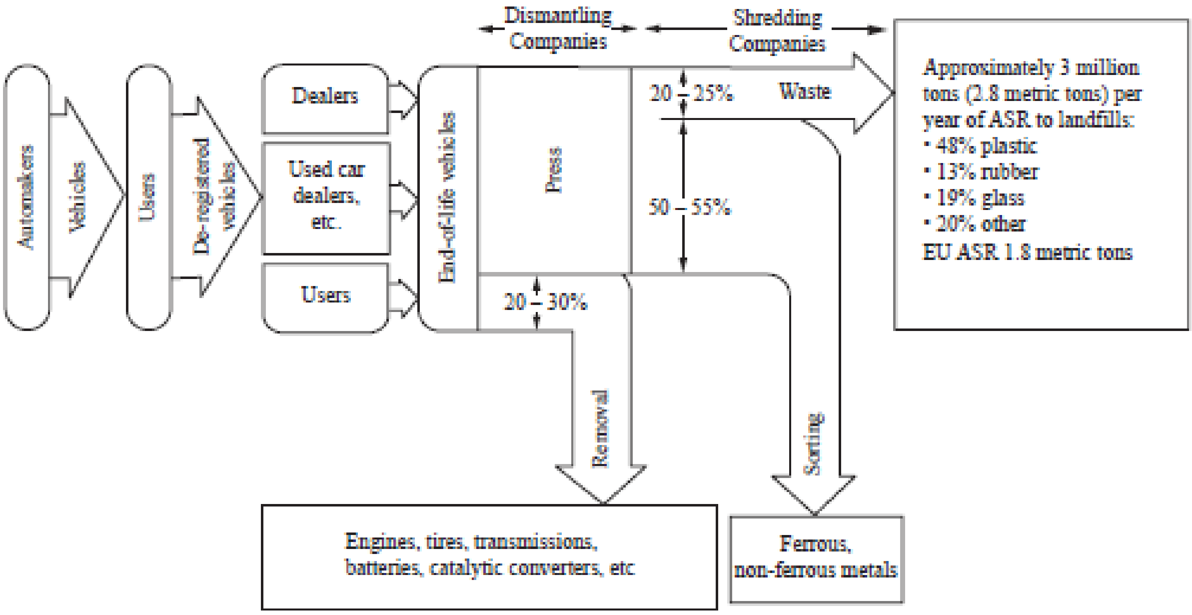
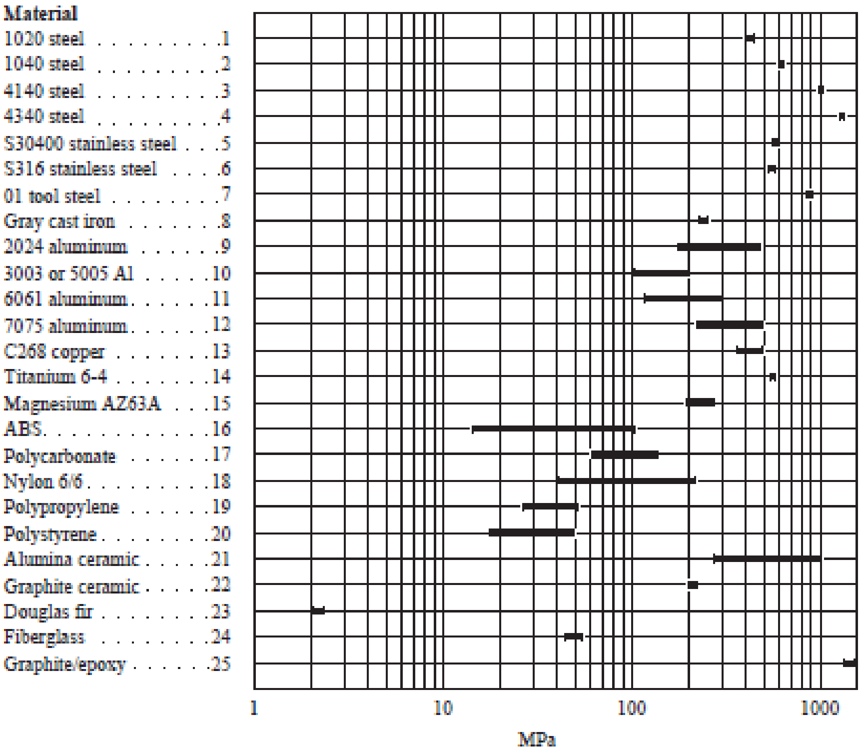


Figure 12.6 The life cycle of a vehicle emphasizing ELVs.



Note: Longitudinal value for graphite/epoxy.
1 MPa = 144.7 psi.

Figure A.1 Tensile strength.