ENGINEERING DESIGN PROCESS

Education Transfer Plan

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PREFACE

This document is designed as an introduction to how engineering products are designed. It is intended for use in an introductory design course in engineering with the objective of providing some hands-on experience for people interested in exploring engineering disciplines.

This document is prepared based on the experience of the author* while completing a summer fellowship at Solectron Corporation in Milpitas, California. This fellowship was coordinated by the Industry Initiatives for Science and Math Education (IISME) in 2005.

I would like to specially thank Mr. Hoshang Vaid, as my principal mentor, at Solectron Corporation whose continuous support and guidance has made my fellowship experience very productive and educational. Furthermore, I would like to extend my appreciation to the other members of the Design and Engineering department at Solectron Corporation for making my experience pleasant.

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BACKGROUND

If you take a moment to observe your surroundings, you will see examples of technological creativity. The physical objects you see, whether they are telephones, automobiles, bicycles, or electric appliances, all came into being through the creative application of technology. These everyday inventions did not miraculously appear but originated in the minds of human beings and took time to develop. Engineering is the creative process of turning abstract ideas into physical representations (products or systems). What distinguishes engineers from painters, poets, or sculptors is that engineers apply their creative energies to producing products or systems that meet human needs. This creative act is called design.

ENGINEERING DESIGN

Most engineering designs can be classified as inventions-devices or systems that are created by human effort and did not exist before or are improvements over existing devices or systems. Inventions, or designs, do not suddenly appear from nowhere. They are the result of bringing together technologies to meet human needs or to solve problems. Sometimes a design is the result of someone trying to do a task more quickly or efficiently. Design activity occurs over a period of time and requires a step-by-step methodology.

We described engineers primarily as problem solvers. What distinguishes design from other types of problem solving is the nature of both the problem and the solution. Design problems are open ended in nature, which means they have more than one correct solution. The result or solution to a design problem is a system that possesses specified properties.

Design problems are usually more vaguely defined than analysis problems. Suppose that you are asked to determine the maximum height of a snowball given an initial velocity and release height. This is an analysis problem because it has only one answer. If you change the problem statement to read, "Design a device to launch a 1-pound snowball to a height of at least 160 feet," this analysis problem becomes a design problem. The solution to the design problem is a system having specified properties (able to launch a snowball 160 feet), whereas the solution to the analysis problem consisted of the properties of a given system (the height of the snowball). The solution to a design problem is therefore open ended, since there are many possible devices that can launch a snowball to a given height. The original problem had a single solution: the maximum height of the snowball, determined from the specified initial conditions.

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Solving design problems is often an iterative process: As the solution to a design problem evolves, you find yourself continually refining the design. While implementing the solution to a design problem, you may discover that the solution you've developed is unsafe, too expensive, or will not work. You then "go back to the drawing board" and modify the solution until it meets your requirements. For example, the Wright brothers' airplane did not fly perfectly the first time. They began a program for building an airplane by first conducting tests with kites and then gliders. Before attempting powered flight, they solved the essential problems of controlling a plane's motion in rising, descending, and turning. They didn't construct a powered plane until after making more than 700 successful glider flights. Design activity is therefore cyclic or iterative in nature, whereas analysis problem solving is primarily sequential.

The solution to a design problem does not suddenly appear in a vacuum. A good solution requires a methodology or process. There are probably as many processes of design as there are engineers. Therefore, this lesson does not present a rigid "cookbook" approach to design but presents a general application of the five-step problem-solving methodology associated with the design process. The process described here is general, and you can adapt it to the particular problem you are trying to solve.

THE DESIGN PROCESS

The basic five-step process usually used in a problem-solving works for design problems as well. Since design problems are usually defined more vaguely and have a multitude of correct answers, the process may require backtracking and iteration. Solving a design problem is a contingent process and the solution is subject to unforeseen complications and changes as it develops. Until the Wright brothers actually built and tested their early gliders, they did not know the problems and difficulties they would face controlling a powered plane.

The five steps used for solving design problems are:

1. Define the problem
2. Gather pertinent information
3. Generate multiple solutions
4. Analyze and select a solution
5. Test and implement the solution

The first step in the design process is the problem definition. This definition usually contains a listing of the product or customer requirements and specially information about product functions and features among other things. In the next step, relevant information for the design of the product and its functional specifications is obtained. A survey regarding the availability of similar products in the market should be performed at

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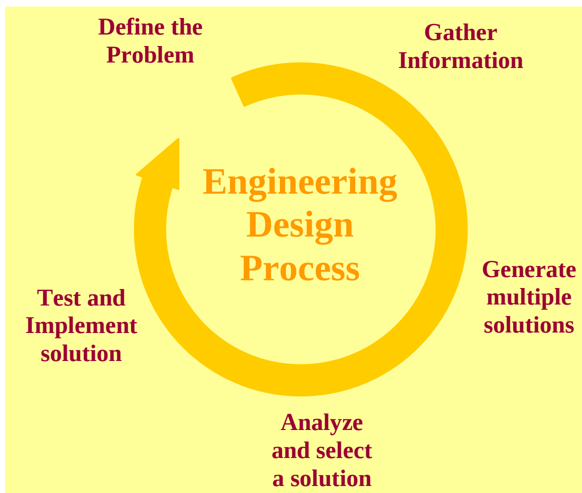
this stage. Once the details of the design are clearly identified, the design team with inputs from test, manufacturing, and marketing teams generates multiple alternatives to achieve the goals and the requirements of the design. Considering cost, safety, and other criteria for selection, the more promising alternatives are selected for further analysis. Detail design and analysis step enables a complete study of the solutions and result in identification of the final design that best fits the product requirements. Following this step, a prototype of the design is constructed and functional tests are performed to verify and possibly modify the design.

When solving a design problem, you may find at any point in the process that you need to go back to a previous step. The solution you chose may prove unworkable for any number of reasons and may require redefining the problem, collecting more information, or generating different solutions. This continuous iterative process is represented in the following Figure.



This document intends to clarify some of the details involved in implementing the design process. Therefore a description of the details involved in each step of the design process is listed below. Although the descriptions of the activities within each step may give the impression that the steps are sequential and independent from each other, the iterative nature of the application of the process should be kept in mind throughout the document.

1. DEFINE THE PROBLEM

You need to begin the solution to a design problem with a clear, unambiguous definition of the problem. Unlike an analysis problem, a design problem often begins as a vague, abstract idea in the mind of the designer. Creating a clear definition of a design problem is more difficult than, defining an analysis problem. The definition of a design problem may evolve through a series of steps or processes as you develop a more complete understanding of the problem.

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Identify and Establish the Need

Engineering design activity always occurs in response to a human need. Before you can develop a problem definition statement for a design problem, you need to recognize the need for a new product, system, or machine. Thomas Newcomen saw the need for a machine to pump the water from the bottom of coal mines in England. Recognizing this human need provided him the stimulus for designing the first steam engine in 1712. Before engineers can clearly define a design problem, they must see and understand this need.

Although engineers are generally involved in defining the problem, they may not be the ones who initially recognize the need. In private industry, market forces generally establish the need for a new design. A company's survival depends on producing a product that people will buy and can be manufactured and sold at a profit. Ultimately, consumers establish a need, because they will purchase and use a product that they perceive as meeting a need for comfort, health, recreation, transportation, shelter, and so on. Likewise, the citizens of a government decide whether they need safe drinking water, roads and highways, libraries, schools, fire protection, and so on.

The perceived need, however, may not be the real need. Before you delve into the details of producing a solution, you need to make sure you have enough information to generate a clear, unambiguous problem definition that addresses the real need. The following example illustrates the importance of understanding the need before attempting a solution.

Example: Automobile Airbag Inflation - How Not to Solve a Problem
A company that manufactures automobile airbags has a problem with an unacceptably high rate of failure in the inflation of the bag. During testing, 10 percent of the bags do not fully inflate. An engineer is assigned the job of solving the problem. At first the engineer defines the problem as a failure in the materials and construction of the inflation device. The engineer begins to solve this problem by producing a more robust inflation device. After considerable effort, the engineer discovers that improving the inflation device does not change the failure rate in the bags. Eventually, this engineer re-examines the initial definition of the problem. The company investigates the airbag inflation problem further and discovers that a high degree of variability in the tightness of folds is responsible for the failure of some bags to inflate. At the time the bags were folded and packed by people on an assembly line. With a more complete understanding of the need, the engineer redefined the problem as one of increasing the consistency in tightness of the folds in the bags. The final solution to this problem is a machine that automatically folds the bags.

Often the apparent need is not the real need. A common tendency is to begin generating a solution to an apparent problem without understanding the problem. This approach is exactly the wrong way to begin solving a problem such as this. You would be generating solutions to a problem that has never been defined.

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People have a natural tendency to attack the current solution to a problem rather than the problem itself. Attacking a current solution may eliminate inadequacies but will not produce a creative and innovative solution. For example, the engineer at the airbag company could have only looked at the current method for folding airbags-using humans on an assembly line. The engineer might have solved the problem with inconsistent tightness by modifying the assembly line procedure. However, the final solution to the problem proved to be more cost effective and reliable, in addition to producing a superior consistency in the tightness of the folds.

Develop a Problem Statement

The first step in the problem-solving process, therefore, is to formulate the problem in clear and unambiguous terms. Defining the problem is not the same as recognizing a need. The problem definition statement results from first identifying a need. The engineer at the airbag company responded to a need to reduce the number of airbag inflation failures. He made a mistake, however, in not formulating a clear definition of the problem before generating a solution. Once a need has been established, engineers define that need in terms of an engineering design problem statement. To reach a clear definition, they collect data, run experiments, and perform computations that allow that need to be expressed as part of an engineering problem-solving process.

Consider for example the statement "Design a better mousetrap." This statement is not an adequate problem definition for an engineering design problem. It expresses a vague dissatisfaction with existing mousetraps and therefore establishes a need. An engineer would take this statement of need and conduct further research to identify what was lacking in existing mousetrap designs. After further investigation the engineer may discover that existing mousetraps are inadequate because they don't provide protection from the deadly Hantavirus carried by mice. Therefore, a better mousetrap may be one that is sanitary and does not expose human beings to the Hantavirus. From this need, the problem definition is modified to read, "Design a mousetrap that allows for the sanitary disposal of the trapped mouse, minimizing human exposure to the Hantavirus."

The problem statement should specifically address the real need yet be broad enough not to preclude certain solutions. A broad definition of the problem allows you to look at a wide range of alternative solutions before you focus on a specific solution. The temptation at this point in the design process is to develop a preconceived mental "picture" of the problem solution. For example, you could define the better mousetrap problem as "Design a mousetrap that sprays the trapped mouse with disinfectant." This statement is clear and specific, but it is also too narrow. It excludes many potentially innovative solutions. If you focus on a specific picture or idea for solving the problem at this stage of the design process, you may never discover the truly innovative solutions to the problem. A problem statement should be concise and flexible enough to allow for creative solutions.

Here is one possible problem definition statement for our better mousetrap problem:

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A Better Mousetrap: Certain rodents such as the common mouse are carriers and transmitters of an often fatal virus, the Hantavirus. Conventional mousetraps expose people to this virus as they handle the trap and dispose of the mouse. Design a mousetrap that allows a person to trap and dispose of a mouse without being exposed to any bacterial or viral agents being carried on the mouse.

Establish Criteria for Success

Criteria for success are the specifications a design solution must meet or the attributes it must possess to be considered successful. You should include criteria in the problem statement to provide direction toward the solution. At this point in the design process, the criteria are preliminary. As the design solution develops, you will most likely find that the initial criteria need to be redefined or modified. Preliminary criteria must not be too specific so they allow flexibility through the design process.

The criteria that apply to a particular design problem are based on your background knowledge and the research that you've conducted. Since each problem or project is unique, the desirable attributes, or criteria, of the solution are also unique. Some criteria are unimportant to the success of the design. The list of criteria is developed by the design team. The design team is made up of people from various engineering backgrounds that have expertise pertinent to the problem. This team may also include people from backgrounds other than engineering, such as managers, scientists, and technicians. The design team must evaluate each criterion and decide if it is applicable to the design effort. Later in the design process, value judgments must be applied to the list of criteria. Therefore, it makes little sense to include those criteria that will be of relatively low priority in the evaluation of design solutions. For example, if you were designing a critical life support system, you would not include the criterion of "must be minimum cost," because cost is not an important factor in evaluating this design.

The following is a list of preliminary criteria for a better mousetrap design. This list would be included in the problem definition statement.

- The design must be low cost.
- The design should be safe, particularly with small children.
- The design should not be detrimental to the environment.
- The design should be aesthetically pleasing.
- The design should be simple to operate, with minimum human effort.
- The design must be disposable (you don't reuse the trap).
- The design should not cause undue pain and suffering for the mouse.

2. GATHER PERTINENT INFORMATION

Before you can go further in the design process, you need to collect all the information available that relates to the problem. Novice designers will quickly skip over this step and proceed to the generation of alternative solutions. You will find, however, that effort

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spent searching for information about your problem will pay big dividends later in the design process. Gathering pertinent information can reveal facts about the problem that result in a redefinition of the problem. You may discover mistakes and false starts made by other designers. Information gathering for most design problems begins with asking the following questions. If the problem addresses a need that is new, then there are no existing solutions to the problems, so obviously some of the questions would not be asked.

- Is the problem real and its statement accurate?
- Is there really a need for a new solution or has the problem already been solved?
- What are the existing solutions to the problem?
- What is wrong with the way the problem is currently being solved?
- What is right about the way the problem is currently being solved?
- What companies manufacture the existing solution to the problem?
- What are the economic factors governing the solution?
- How much will people pay for a solution to the problem?
- What other factors are important to the problem solution (such as safety, aesthetics and environmental issues)?

Search for Information Resources

As an engineering student in the 2000s you have many more sources of information available to you than engineers did only 20 years ago. This section discusses some of the most current resources available, but because our world is witnessing an information explosion, by the time you read this many more resources will be available that are not mentioned here.

Traditional publications are still an essential source of information to engineers and scientists. However, electronic information transfer and retrieval are quickly becoming a standard source for engineers and scientists. When you begin a search for information relating to a design problem, you must be prepared to go to many different sources. The library is still the primary source of information for an engineering student. Your success as an engineer and student will be enhanced if you are able to use the library effectively. For specific help on using our library, you should consult the library staff at the college; they probably offer courses or seminars on library usage.

Some of the common resources available at a university library are discussed below:

> Scientific encyclopedias and technical handbooks. These sources are a good place to start when you are investigating an area or problem that is new to you. An encyclopedia or handbook provides a brief general overview by an authority in a particular field and includes references for more detailed information. The McGraw-Hill Encyclopedia of Science and Technology covers all scientific fields. Technical handbooks, such as the Electrical Engineers Handbook or Mark's Handbook of Mechanical Engineering, cover various fields such as chemical, civil, electrical, or mechanical engineering. The information contained in these

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handbooks is presented in a very concise form and can be good starting points for an in depth search.

Electronic catalog. Electronic catalogs give a listing of all the sources available at your library. The catalogs allow search by subject matter, author, or title. They give a brief summary of the book's content, including the title, author, publisher, copyright date, and total number of pages. The call number tells you where to locate the book in your library.

Indexes. Indexes categorize current works in various disciplines. They list the subject, title, and author of recent articles in technical and trade journals under various subject headings. Some indexes include brief abstracts of articles. Most indexes are updated monthly, so a complete search through an index may be tedious. A familiar index to scientists and engineers is the Index of Applied Science and Technology. It lists articles from 335 journals and is updated monthly. The Engineering Index is another popular index for engineers. It selects articles from approximately 2700 journals and periodic publications and includes an abstract of each article.

The Internet. There is a wealth of information on the Internet from a variety of sources. Manufacturers, professional and trade organizations, suppliers of products, and many government agencies have valuable resources on their websites. Search engines such as Google(www.google.com) and Teoma(www.teoma.com) offer tools to locate relevant information quickly and efficiently.

3. GENERATE MULTIPLE SOLUTIONS

The next step in the design process begins with creativity in generating new ideas that may solve the problem. Creativity is much more than just a systematic application of rules and theory to solve a technical problem.

You start with existing solutions to the problem and then tear them apart-find out what's wrong with those solutions and focus on how to improve their weaknesses. Consciously combine new ideas, tools, and methods to produce a totally unique solution to the problem. This process is called synthesis. Casey Golden, age 13, did this when he invented the BIOtee. Casey noticed that discarded and broken wooden golf tees littered golf courses, damaging the blades and tires of lawn mowers. He decided to design a new biodegradable tee. After experimenting with different mixtures, he devised a recipe made of recycled paper fiber and food byproducts coated with a water-soluble film. When the film is broken, moisture in the ground breaks down the tee within 24 hours. As a result of his creative efforts, Casey's family started a company to manufacture BIOtees producing several million tees per year.

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Psychological research has found no correlation between intelligence and creativity. People are creative because they make a conscious effort to think and act creatively. Everybody has the potential to be creative. Creativity begins with a decision to take risks. Listed below are a few characteristics of creative people. These are not rigid rules to be followed to experience creativity. You can improve your creative ability by choosing to develop these characteristics in yourself.

- Curiosity and tolerance of the unknown. Creative people have a positive curiosity of the unknown. They are not afraid of what they don't understand.
- Openness to new experiences. Creative people have a healthy and positive attitude toward new experiences.
- Willingness to take risks. Creative people are not afraid to take risks and try new experiences or ideas, knowing that they may be misunderstood and criticized by others. They are self-confident and not afraid to fail.
- Ability to observe details and see the "whole picture." Creative people notice and observe details relating to the problem, but they also can step back and see the bigger picture.
- No fear of problems. Creative people are not afraid to tackle complex problems, and they even search for problems to solve. They seek solutions to problems with their own abilities and experience if possible. They have the attitude of "if you want something done, you'd better do it yourself."
- Ability to concentrate and focus on the problem until it's solved. Creative people can set goals and stick to them until they're reached. They focus on a problem and do not give up until the problem is solved. They have persistence and tenacity.

Solutions to engineering design problems do not magically appear. Ideas are generated when people are free to take risks and make mistakes. Brainstorming at this stage is often a team effort in which people from different disciplines are involved in generating multiple solutions to the problem.

4. ANALYZE AND SELECT A SOLUTION

Once you've conceived alternative solutions to your design problem, you need to analyze those solutions and then decide which solution is best suited for implementation. Analysis is the evaluation of the proposed designs. You apply your technical knowledge to the proposed solutions and use the results to decide which solution to carry out. You will cover design analysis in more depth when you get into upper-level engineering courses.

At this step in the design process, you must consider the results of your design analysis. This is a highly subjective step and should be made by a group of experienced people. This section introduces a systematic methodology you can use to evaluate alternative designs and assist in making a decision.

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Analysis of Design Solutions

Before deciding which design solution to implement, you need to analyze each alternative solution against the selection criteria defined in step l. You should perform several types of analysis on each design. Every design problem is unique and requires different types of analysis. The following is a list of analysis that may need to be considered; bear in mind that the importance of each varies depending on the nature of the problem and the solution.

- Functional analysis
- Industrial design/Ergonomics
- Mechanical/Strength analysis
- Electrical/Electromagnetic
- Manufacturability/Testability
- Product safety and liability
- Economic and market analysis
- Regulatory and Compliance

The following paragraphs provide details of some of these analysis types.

Functional analysis. This part determines whether the given design solution will function the way it should. Functional analysis is fundamental to the evaluation and success of all designs. A design solution that does not function properly is a failure even if it meets all other criteria. Consider for example the invention of the ballpoint pen. This common instrument was first invented and manufactured during World War II. The ballpoint pen was supposed to solve the problems of refilling and messiness inherent to the fountain pen. Unfortunately, this new design had never been evaluated for functionality. The early pens depended on gravity for the ink to flow to the roller ball. This meant that the pens only worked in a vertical upright position, and the ink flow was inconsistent: Sometimes it flowed too heavily, leaving smudgy blotches on the paper; other times the flow was too light and the markings were unreadable. The first ballpoint pens tended to leak around the ball, ruining people's clothes. An elastic ink developed in 1949, allowed the ink to flow over the ball through smooth capillary action. Not until the 1950s did the ballpoint pen finally become a practical writing instrument, thanks to proper ink and engineering. Economy, appearance, durability, and marketability of a design are unimportant if the product does not function properly.

Ergonomics. Ergonomics is the human factor in engineering. It is the study of how people interact with machines. Most products have to work with people in some manner. People occupy a space in or around the design, and they may provide a source of power or control or act as a sensor for the design. For example, people sense if an automobile air-conditioning system is maintaining a comfortable temperature inside the car. These factors form the basis for human factors, or ergonomics, of a design.

A design solution can be considered successful if the design fits the people using it. The handle of a power tool must fit the hand of everybody using it. The tool must not be too

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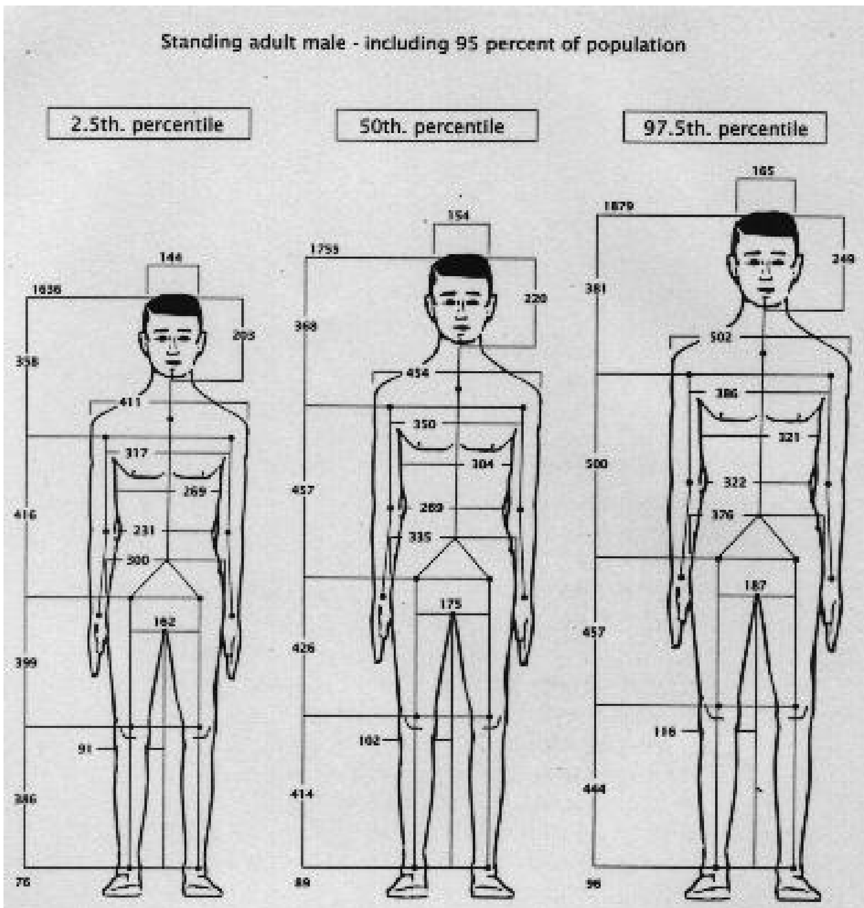
heavy or cumbersome to be manipulated by all sizes of people using the tool. The geometric properties of people-their weight, height, reach, circumference, and so on-are called anthropometric data. The difficulty in designing for ergonomics is the abundance of anthropometric data. The military has collected and evaluated the distribution of human beings and published this information in military standard tables. A successful design needs to be evaluated and analyzed against the distribution of geometry of the people using it. The following Figure shows the geometry of typical adult males and females for the general population in millimeters. Since people come in different sizes and shapes, such data are used by design engineers to assure that their design fits the user. A good design will be adjustable enough to fit 95 percent of the people who will use it.



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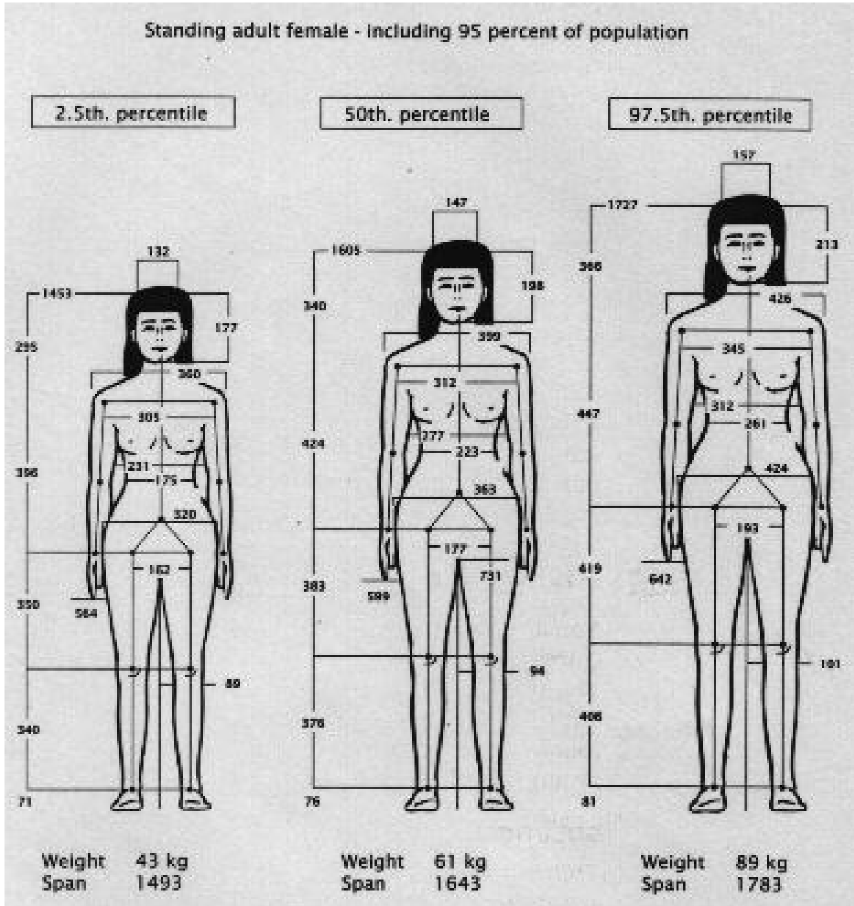

Product Safety and Liability. The primary consideration for safety in product design is to assure that the use of the design does not cause injury to humans. Safety and product liability issues, however, can also extend beyond human injury to include property damage and environmental damage from the use of your design. Engineers must also consider the issues of safety in design because of liability arising from the use of an unsafe product. Liability refers to the manufacturer of a machine or product being liable, or financially responsible, for any injury or damage resulting from the use of an unsafe product.

The only way to assure that your design will not cause injury or loss is to design safety into the product. You can design a safe product in three ways. The first method is to design safety directly into the product. Ask yourself, "Is there any probability of injury during the normal use and during failure of your design?" For example, modern downhill ski bindings use a spring-loaded brake that brakes the ski automatically when the ski disengages from the skier's boot. Older ski bindings used an elastic cable attached to the skier's ankle, but this had a tendency to disconnect during a severe fall.

Inherent safety is impossible to design into some products, such as rotating machinery and vehicles. In such cases you use the second method of designing for safety: You include adequate protection for users of the product. Protection devices include safety

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shields placed around moving and rotating parts, crash protective structures used in vehicles, and "kill" switches that automatically turn a machine off (or on) if there is potential for human injury. For example, new lawnmowers generally include a protective shield covering the grass outlet and include a kill switch that turns the motor off when the operator releases the handle.

The third method used in considering safety is the use of warning labels describing inherent dangers in the product. Although this method does not implement safety in design, it is primarily used as a way to shift the responsibility to the consumer for having ignored the safety guidelines in using the product. In most cases, however, a warning label will not protect you from liability. Protective shields or other devices must be included in the design.

A product liability suit may be the result of a personal injury due to the operation of a particular product. The manufacturer and designer of a device can be found liable to compensate a worker for losses incurred during the operation or use of their product. During a product liability trial, the plaintiff attempts to show that the designer and manufacturer of a product are negligent in allowing the product to be put on the market. The plaintiff's attorney may bring charges of negligence against the designer.

To protect themselves in a product liability trial, engineers must use state-of-the-art design procedures during the design process. They must keep records of all calculations and methods used during the design process. Safety considerations must be included in the criteria for all design solutions. The designer must also foresee other ways people could use the product. If a person uses a shop vacuum to remove a gasoline spill, is the designer responsible when the vacuum catches fire? The courts can decide that a design is poor if the engineer did not foresee improper use of the product. It is imperative that you evaluate all of your alternative solutions against safety considerations. Reject or modify any unsafe elements of your design at this stage in the design process.

Economic and Market Analysis. The net result or purpose of most engineering designs is to produce a product that generates a profit for the company. Obviously, each alternative design has to be evaluated against criteria such as sales features, potential market, cost of manufacturing, advertising, and so on. Large companies often conduct marketing surveys to obtain a measure of what the public will buy. These surveys may be conducted by telephone interviews with randomly selected people, or they may be personal interviews conducted with potential users of a product. Our society is based on economics and competition. Many good ideas never get into production because the manufacturing costs exceed what people will pay for the product. Market analysis involves applying principles of probability and statistics to determine if the response of a selected group of people represents the opinion of society as a whole. Even with a good marketing survey, manufacturers never know for certain if a new product will sell.

Mechanical/Strength Analysis. Engineering analysis of a preliminary design often include the analysis of its mechanical features. The engineer conducts mechanical analysis to answer questions such as, "Will the device or structure support the maximum

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loads that it will be subjected to?" You must also determine the effect of shocks and repetitive or dynamic loading over the life of the product. Many systems generate heat, so you need to determine if the design can dissipate all of the heat being generated during normal operation. Thermal analysis is an area important to the design of electronic equipment. Many pieces of electronic equipment fail prematurely due to inadequate heat transfer. For example, the early releases of Intel's Pentium microprocessor could not operate at their rated speed due to overheating. The production of this microcircuit was delayed while engineers figured out ways to dissipate the excess heat.

You need to perform strength calculations to determine whether the design alternative will be able to support the specified mechanical loads. As a mechanical system is subjected to applied loads, it will deform or deflect.

Many products contain several subsystems and, quite often, the evaluation is done on each of the subsystems rather than the complete product itself.

The Decision Process

After analyzing your alternative solutions, you need to decide and document which design solution is the best. You will refine and develop the best solution in more detail during the later stages of the design process. At this stage, to evaluate each solution objectively against the stated design criteria or requirements, you need a quantitative basis for judging and evaluating each design alternative. One widely used method to formalize the decision-making process is the decision matrix. The decision matrix is a mathematical tool you can use to derive a number that specifies and justifies the best decision.

The first step in creating a decision matrix is for the design team to rank, in order of importance, the desirable attributes or criteria for the design solution. These attributes can include factors such as safety, manufacturing considerations, the ease of fabrication and assembly, cost, portability, compliance with government regulations, etc. You then assign to each attribute or criteria a value factor related to the relative importance of that attribute. For example, suppose you decide that safety is twice as important to the success of your design as cost. You would assign a value factor of 20 for safety and a value factor of 10 for cost. You assign value factors on a basis of 0 to 100, representing relative importance of each criterion to the decision.

Next you evaluate each design alternative against the stated criteria. A rating factor is assigned to each solution, based on how well that solution satisfies the given criterion. The rating factor is on a scale of 0 to 10, with 10 representing a solution that satisfies the given criterion the best. To make an accurate evaluation, you need as much information as possible. Unfortunately, engineers seldom have enough information to make a "perfect" evaluation. If you have done the analysis phase of the design process properly, those results can provide a basis for evaluation. Computer models and prototypes can also yield valuable information to assist in the decision phase. In most cases you must use

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engineering judgment, and the decision is subjective. The following example illustrates the use of a decision matrix in deciding the best alternative design for a can crusher.

Example: Aluminum Can Crusher
Students are being asked to design a simple device to crush aluminum cans. A student design team proposes four solutions to the problem. They develop six criteria that are important to a successful design. The student team agrees that the most important criteria (or desirable attributes) of the design and assigned weights are

- Safety: 30 percent (30 points)
- Ease of use: 20 percent (20 points)
- Portability: 20 percent (20 points)
- Durability and strength:10 percent (10 points)
- Use of standard parts:10 percent (10 points)
- Cost:10 percent (10 points)

This team also proposes four alternative solutions to this problem, which are illustrated in the following Figure. They are

1. A spring-loaded crusher
2. A foot-operated device
3. A gravity-powered dead weight crusher
4. An arm-powered lever arm crusher

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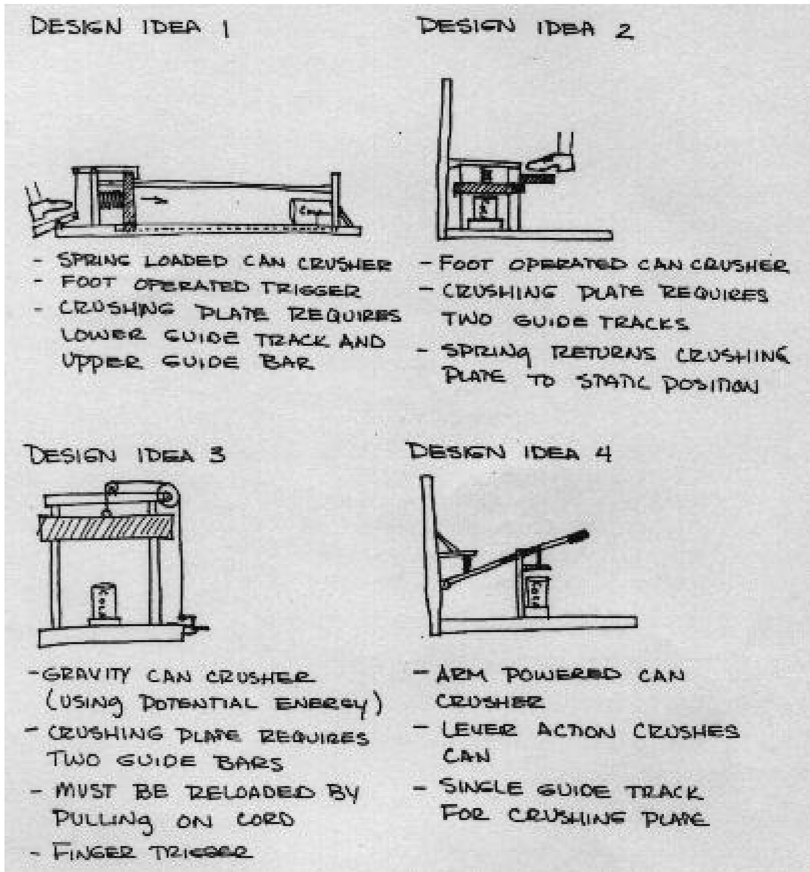

After analyzing each solution against the six criteria, the team evaluates each design alternative. After assigning a rating factor to each design alternative for each of the specified criteria, the team multiplies the rating factor by the value factor. The product of the value and rating factors is then summed down the column for each design alternative. The total sum at the bottom of each column determines the best design alternative. The results of this decision matrix are illustrated in the following Table.

Table Decision matrix for evaluating alternative can crusher designs

Criteria	Weight(%)	Design 1	Design 2	Design 3	Design 4
Safety	30	2	9	2	9
R x Weight		60	270	60	270
Ease of Use	20	8	9	6	9
R x Weight		160	180	120	180
Portability	20	5	3	2	8
R x Weight		100	60	40	160
Durability	10	8	8	6	8
R x Weight		80	80	60	80
Standard Parts	10	7	7	8	8
R x Weight		70	70	80	80
Cost	10	6	5	7	8
R x Weight		60	50	70	80
Total	100	530	710	430	850

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Although rating each design against the six stated criteria is subjective, the rating factor for each design alternative is assigned according to the consensus of the design team. The results of an analysis are used to evaluate and rate each design. The rating factor R is assigned according to the following scale:

- Excellent 9-10
- Good 7-8
- Fair 5-6
- Poor 3-4
- Unsatisfactory 0-2

Design 4 was chosen the best design largely due to the rating assigned for safety, criterion l. The team felt that the chances of human injury were negligible for this design. Since safety is the most important factor (30% of the total weight), the high safety rating for design 4 gives it the highest overall score (9 x 30, or 270).

5. TEST AND IMPLEMENT THE SOLUTION

The final phase of the design process is implementation, which refers to the testing, construction, and manufacturing of the solution to the design problem. You must consider several methods of implementation, such as prototyping and concurrent engineering, as well as distinct activities that occur during implementation, such as documenting the design solution and applying for patents.

Prototyping. The first stage of testing and implementation of a new product, called prototyping, consists of building a prototype of the product-the first fully operational production of the complete design solution. A prototype is not fully tested and may not work or operate as intended. The purpose of the prototype is to test the design solution under real conditions. For example, a new aircraft design would first be tested as a scale model in a wind tunnel. Wind tunnel tests would generate information to be used in constructing a full-size prototype of the aircraft. Test pilots then fly the prototype extensively under real conditions. Only after testing under all expected and unusual operating conditions are the prototypes brought into full production.

Concurrent Engineering. Traditional design practices are primarily serial or sequential: Each step in the process is completed in order or sequence only after the previous steps have been completed. The implementation of the design occurs after a prototype or model is created from engineering drawings. A machinist working from the engineering drawings generated by a drafter, or an engineer, makes the prototype. Only after creating a prototype of the design would the engineer discover that a hole was too small, parts didn't mate properly, or a handgrip was misplaced. The part would have to be redesigned and the process completed until a satisfactory solution was reached.

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In the competitive manufacturing climate of the 1990s, the serial practice of design proved inadequate. In a matter of months, a manufacturer may find that factors such as markets, material prices and technology, and government regulations and tax laws may have changed. This competitive environment required a company to design high-quality products faster, better, and less expensively than their competitors. One solution to the traditional design paradigm was concurrent engineering.

Concurrent engineering is the ability to implement parallel design and analysis in which safety, manufacturability, serviceability, marketability, and compliance issues are considered early on and during the process. Concurrent engineering is however possible through the application of modern computer-aided design (CAD), analysis, and manufacturing software. A designer starts with an idea of a new product in which the above factors are considered and uses the CAD software to create a preliminary design. With the appropriate software, the preliminary design can also be analyzed for functionality as the design is being created. Using the results of this analysis, the designer then makes any necessary modifications and reanalyzes the computer model. An engineer designing a bicycle frame, for example, would use concurrent engineering to minimize the weight and maximize the supported loads in a new frame design. The engineer would first create a design and model the physical behavior of the frame on the computer before actually manufacturing the frame.

The next stage in concurrent engineering is called rapid prototyping or sometimes called "art to part." Here the three-dimensional computer model of the finished design is used with computer-aided manufacturing (CAM) software to drive appropriate machinery to physically create the part. The entire design cycle therefore becomes nearly paperless. Engineers can go from design to prototype in a matter of days, instead of weeks or months as with earlier serial design practices. Since design is an iterative process, concurrent engineering significantly shortens the time between iterations. A product can therefore get to market much quicker, at a lower cost, and with a higher quality.

Documentation. One of the most important activities in design is documenting your work, clearly communicating the solution to your design problem so someone else can understand what you have created. Usually this consists of a design or technical report.

Communicating the solution to a design problem through language, both written and oral, is a vital part of the implementation phase. Many people you will be communicating with do not have technical training and competence. They may be the general public, government officials, or business leaders. Successful engineers must possess more than just technical skills. The ability to communicate and sell a design solution to others is also a critical skill.

You can use graphs, charts, and other visual materials to summarize the solution process and present your work to others. Multimedia techniques, including Power Point presentations, slides, sounds, videos, and computer-generated animations, are often used to clearly communicate the solution to a design problem.

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Applying for Patents. If you develop an original and novel solution to a design problem, part of the implementation phase may include applying for a patent on your solution. A patent will not protect you from someone else copying your solution, but it does give you specific rights to make and sell your design for a specified period. A patent is an agreement made between you-the designer or inventor-and the U.S. government. Through a patent document you agree to make public all the details and technology of your invention. You agree to provide an invention disclosure, which provides enough details to allow anyone to build a working model of your invention. Most large libraries now have files of issued patents, which are available for anyone to see. These can be a good source of ideas for engineering design solutions. In return for making your invention or design solution public, the U.S. Patent Office grants you the exclusive right to your invention for a specified period of time.

Pursuing a patent is not a trivial process and may take a long time, costing hundreds or even thousands of dollars. Before considering a patent you should have a general understanding of patent requirements and what can be patented. Ideas by themselves cannot be patented. To obtain a patent, you must prove that your idea can be applied to produce a "new and useful process, machine, manufacture, or composition of matter, or any new and useful improvement thereof." These categories include just about everything made by people and the processes for making them.

Most engineering design problems fall into the patentable categories of utility patents or design patents. All mechanical and electrical devices fall into the category of utility patent, which is granted for 20 years. At the end of the patent period, your protection expires, and anyone can copy, manufacture, and sell your invention without giving you credit or payment. A design patent is granted to protect the styling or ornamental features of a design. A design patent is only granted for the appearance of an item, not for how it works or is made. For example, if you invent a telephone that looks like a shoe, you might apply for a design patent. The design patent would be granted on the appearance of the phone, not on the electronic and mechanical workings of the phone. Design patents are granted for 3-1/2, 7, or 14 years, depending on the patent fee paid. The fees range from $200 to $600.

Patents are only granted to the inventor of a device. However, the inventor can assign the rights to the patent to another party. If you develop an invention while working as an engineer for a company, you will probably be required to assign the patent rights to that invention to your employer.

Once a patent is granted, there is no guarantee that someone else will not try to copy the invention. The U.S. Patent Office does not enforce patent rights. It is the responsibility of the patent holder or a patent attorney to police the patent and make sure no one else copies it while it is in effect. Since a patent makes all information about your design public, some people choose not to pursue a patent, but rather keep the details of the invention secret. If no one else learns how the invention works, you will have protection until another inventor figures it out. For example, the formulas for Coca-Cola and Silly

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Putty have never been patented, and the secrets are only known to selected company officials.

To apply for a patent, you need to prepare and include the following items:

> A written document clearly describing your invention and stating that you are the original inventor. Enough information must be provided so that someone else can make your invention from the information you provide. You must also make claims about your invention which describe the features which distinguish it from already patentable material.
>
> Engineering drawings that follow the format documented in Guide for Patent Draftsmen, which is available from the U.S. Patent Office.
>
> The filing fee. This is a basic fee of at least $ 150 that must accompany the patent application. If the patent is granted, you will be charged an additional patent issue fee. The total charges for obtaining a patent can be hundreds of dollars.

A patent is granted only after an extensive review process of the U.S. Patent Office. The office will first search the nearly 5 million existing patents to determine whether your design has been previously patented or infringes on an existing patent. This process can take several years and be very expensive. Many inventors employ patent attorneys or agents to conduct a preliminary patent search. Most large libraries have records of all the patents filed with the U.S. Patent Office. This information is also available on a CD-ROM database at many libraries. You can look at this database and read the patent applications filed under the same product category as yours. This will give you a good idea on how an application is written and might help you improve your own design. Before spending more time and money pursuing a patent, it is a good idea to find out if someone else has already patented your invention.

Testing and Verification. Testing and verification are important parts of the design process. At all steps in the process, you may find that your potential solution is flawed and have to back up to a previous step to get a workable solution. Without proper testing at all stages in the process, you may find yourself making costly mistakes later.

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