Engineering Design Process

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Preface

Early human history shows that the design of artifacts was determined by human needs. For example, the knife was invented to protect humans from the danger of their surroundings, and Egyptians invented the wheel to facilitate traveling and transportation. The truth of the dictum ”need is the mother of invention” was is demonstrated here. The idea of design and development is what distinguishes engineering from science. Engineers throughout history have wrestled with problems of water not being where it is needed, of minerals not being close at hand, of building materials having to be moved. Ancient engineers were often called upon to devise the means for erecting great monuments, for designing defenses against enemies, and for moving people and goods across rough terrain and even rougher water. These endeavors were primarily inventive in nature and invariably approached through trial and error. However, it was not until the time of Galileo and Newton that the foundations students now learn in engineering schools were established. The Industrial Revolution brought a profileration of new machines and manufacturing techniques and provided an impetus for the growth of science and commerce on an international scale. The history of engineering abounds with stories of success triumphing over failure.

In the early 1900s, it was common in American industry for master mechanics to invent and, subsequently, for draftsmen to copy on paper what had been synthesized experimentally in the shop. Since it was less costly and more efficient to erase rather than to remake parts in the shop, the value of synthesizing on paper was soon realized. Recent trends have been to apply theory where appropriate in the process of mechanical design. But overall, it is emphasized that all of the useful ingredients - such as various aspects of art, science, engineering, practical experience and ingenuity - must be properly blended in the design process. A successful design is achieved when a logical procedure is followed to meet a specific need. This procedure, called the "design process", is similar to the scientific method with respect to its step by step routine. The design process entails the following activities, all of which must be completed

1. Idenftification of a need
2. Preoblem definition (Goals)
3. Market analysis (Search)
4. Specifications and constarins
5. Function analysis
6. Generating ideas
7. Evaluating alternatives
8. Analysis
9. Experiment
10. Marketing

Often, designs are not accomplished by an engineer simply completing the design steps in the given order. The design process holds within its structure an iterative procedure: as the engineer proceeds through the steps, new information may be discovered and new objectives may be specified, a point at which the steps may require revisiting. The more time and effort an engineer spends on articulating the problem definition and understanding the need statement, the less frequent the need for iteration.

In these notes, we try to provide the student with a reference for the course and to present the material in a systematic, easy-to-understand manner. Students are highly encouraged to submit their comments and suggestions to the authors.

Contents

Chapter 1

Introduction

Design is a creative process. Albert Einstien asserted that imagination is more important than knoweldge for knowledge is finite whereas imagination is infinite [**?**].

An engineering student during his training is crammed with a vast amount of theoretical material and information. He only realizes his helplessness when he is faced with the task of logically applying what he has learned to a specific end. So long as his work is based on familiar models or previous designs, the knowledge he possesses is perfectly adequate to enable him to find a solution on conventional lines. As soon as he or she is required to develop something already in existence to a more advanced stage, or to create something entirely new without a previous design to guide him, he will fail miserably unless he has reached a higher level of understanding. The design process was formalized to enable students in following a systematic approach in design. The most important step of the design process is identifying the customer need. Most of the time the customer provides a generic statement of need and it is to the engineer to identify the real need of the customer. Let's consider an example to illustrate the point:

We are required to design a chair that can be used by a child. Clearly all of us know how to sit on a chair, so in that perspective we know how it works. A chair is used for sitting. Unfortunately this description does not say how the chair is made. What material is used? Is the chair flexible or rigid? Does the chair rotate or fixed? What does it mean, it is to be used by a child? Is the safety the biggest concern? How much does it cost? How old is the child, etc.

Many factors in engineering design do not have a mathematical model to be based on, but the process is maintained to be logically driven in systematic sequence. In the previous example, we can use Newton's Laws of equilibrium to describe the forces generated in the chair's legs. We can also describe the deformation of the legs when a person sits down. We can even use the finite element analysis to estimate the stresses in the legs, the seat and the back. We can also describe the make and the joints used in the chair. Some of these, indeed, can be represented using mathematical models, but what mathematical model will describe the color of the chair, or what mathematical model will measure the how safe is the chair to be used by a child? It is clearly apparent that the function of the chair cannot be completely presented by a mathematical model. These functions are manipulated by reasoning. It is clear that different schemes may be needed to describe a certain design such as analytical based models that can identify the geometric presentation of the artifact, economic schemes that describe the cost of producing the artifact, verbal contents that describe the function of the artifacts and so on. So it is quite clear that in the designing process, mathematical modeling, although important, is not sufficient to design the artifact.

The design engineer must learn to think independently, to draw conclusions and to combine. There are many who believe they can acquire all this by attending lectures and reading textbooks. What they fail to realize, is that they are only accumulating one fresh item of knowledge after another. Understanding, coupled with powers of logical deduction and judgement are not a capabilities that can be conferred from outside; on the contrary, they are something purely personal and inward acquired only by diligent thinking and working with the knowledge already possessed. A basic precondition for independent designing is a lively imagination. Such imagination is required to do original work.

Through history, humans have been successfully designing artifacts to satisfy the needs of civilization. History is full of great designs and invention. Recently, design has been driven to meet an existing completion, reduce a hazard or an inconvenience or develop a new approach. Not all that engineers build has become successful, occasionally, catastrophic failures occur. A few of the well publicized disasters associated with engineering systems were:

- Chernobyle nuclear power plant.
- Challenger space shuttle.
- Boing 737 lost its cabin roof during flight in 1988.

- A skywalk of Kansas City Hyatt Regency Hotel collapsed just after the hotel was opened in 1981.
- DC-10 airplane lost an engine in flight and crashed in 1979.

Walton [8] lists the reason for failures in most engineering designs as:

1. Incorrect or overextended assumptions.
2. Poor understanding of the problem to be solved.
3. Incorrect design specifications.
4. Faulty manufacturing and assembly.
5. Error in design calculations.
6. Incomplete experimentation and inadequate data collection.
7. Errors in drawings.
8. Faulty reasoning from good assumptions.

1.1 Definition of Engineering Design

Dym [3] defines design as the systematic, intelligent generation and evaluation of specifications for artifacts whose form and function achieve stated objectives and satisfy specified constraints. A formal definition of engineering design is found in the curriculum guidelines of the Accreditation Board for Engineering and Technology (ABET). The ABET definitions states: Engineering design is the process of devising a system, component, or process to meet desired needs. It is a decision-making process (often iterative) , in which the basic sciences, mathematics, and engineering sciences are applied to convert resources optimally to meet a stated objective. Among the fundamental elements of the design process are the establishment of objectives and criteria, synthesis, analysis, construction, testing, and evaluation. The engineering design component of a curriculum must include most of the following features: development of student creativity, use of open-ended problems, development and use of modern design theory and methodology, formulation of design problem statement and specifications, production processes, concurrent engineering design, and detailed system description. Further, it is essential to include a variety of realistic constraints such as economic factors, sfatey, reliability, aesthetics, ethics and social impact.

1.2 Design Levels

As in any field of human activity there are different degrees of difficulty. In design they are adaptive designs, developed designs and new design.

1. Adaptive Design: In the great majority of instances the designer's work will be concerned with adaptation of existing designs. There are branches of manufacturing where development has practically ceased, so that there is hardly anything left for the designer to do except make minor modifications, usually in the dimensions of the product. Design activity of this kind therefore demands no special knowledge or skill and the problems presented are easily solved by a designer with ordinary technical training.

2. Development Design: Considerably more scientific training and design ability are needed for development design. The designer starts from an existing design, but the final outcome may differ quite markedly from the initial product

3. New Design: Only a small number of designs are new designs.

1.3 Design Process

To design is to create new product that turns into profit and benefits society in some way. The ability to design requires both science and art. The science can be learned through a systematic process (outlined in this chapter), experience and problem solving technique (will be mastered during your college education). The art is gained by practice and a total involvement to become proficient. The design of a device or system can be done in one of two ways

1. Evolutionary change: When a product is allowed to evolve over a period of time with only slight improvement. This is done when there is no competition. The creative capabilities of the designer are limited

2. Innovation: The rapid scientific growth and technological discoveries plus competition among companies for their slice in the market has placed a great deal of emphasis on new products which draws heavily on innovations to produce marketable ideas. Here the creative skills and analytical ability of the design engineer plays an important role.

Proficient designer controls the activities of evolution and innovation to occur simultaneously. Although more emphasis is directed toward innovation line, designer must test his ideas against prior design. One can design for the future but he must base results on what is known in the past.

In this section a brief description of the design processes is introduced. The design process is a sequence of events that help defines the stages of design and help unfold the design in a systematic manner. Different authors have attempted to draw up charts that describe the design process. Figures **??** to 1.3 show some of these attempts.

The difference in these maps is in sequence name. Careful examining of the maps lead to the identification of the same stages. Some stages are combined together in one process. In these notes we will be using the chart in figure 1.4. This chart seems more elaborate and more systematic. This chart is adapted from Cross 1994 [2]. These steps are iterative and requires a series of decisions to move the design along. More often a design oscillates back and forth between stages until it reaches an acceptable form to move to the next stage. A brief description of theses stages is given here

1.3.1 Identification the customer need

The need for a new design can be generated from several sources some of these sources are listed below.

1. Client Request: In a design company a client may submit a request for developing an artifact. It is often unlikely that the need will be expressed clearly. The client may know only the type of product that he wants, or in most cases this is the problem find a solution. An example may be in the form ”I need a safe ladder”.

2. Modification of an existing design: Quit often a client require ask for a modification of an existing artifact to make it simpler and easy to use. This may also be generated by companies to provide customers with new easy to use products. Searching the market you may notice many

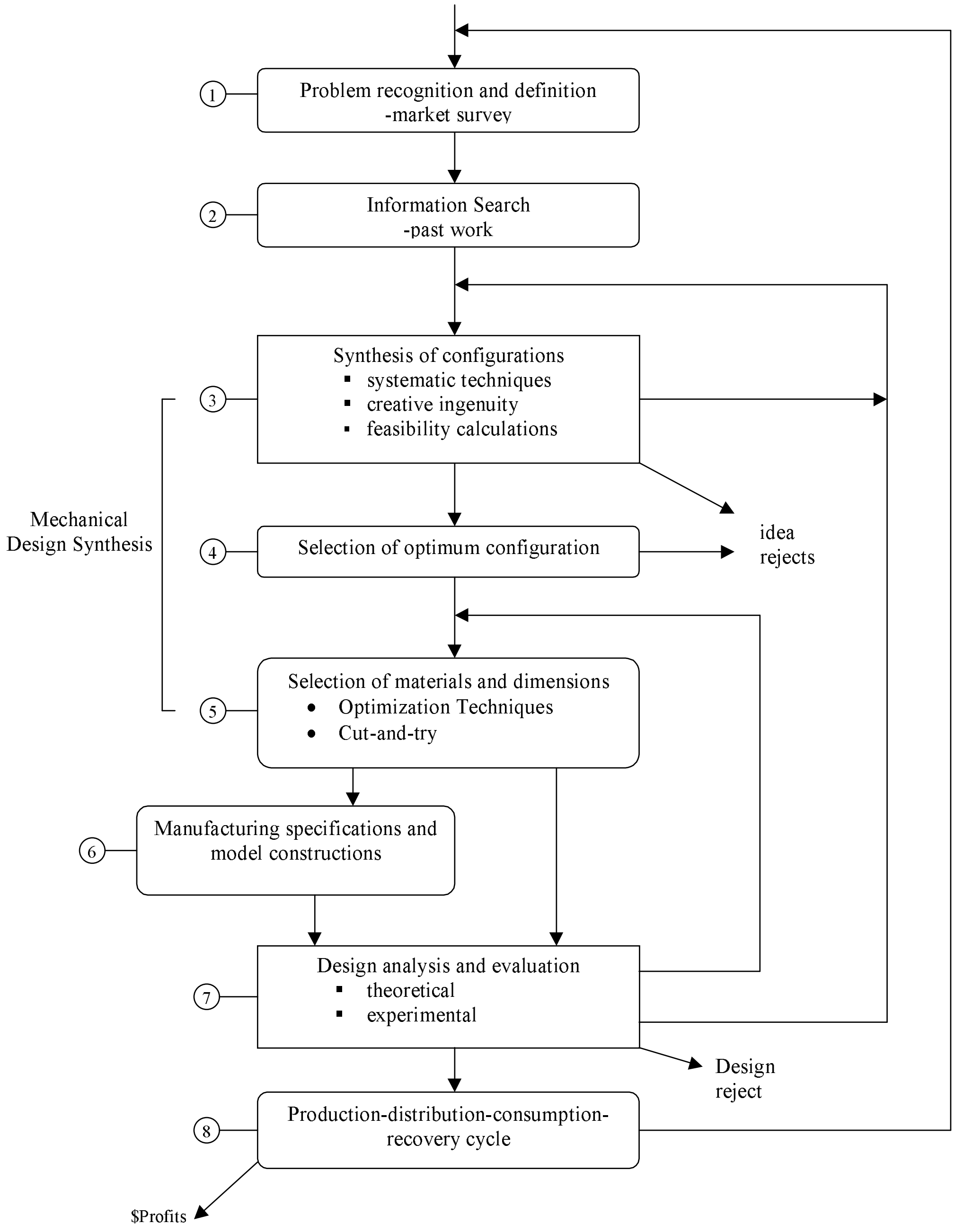

Figure 1.1: Design Process Map from Johnson (1978)[5]

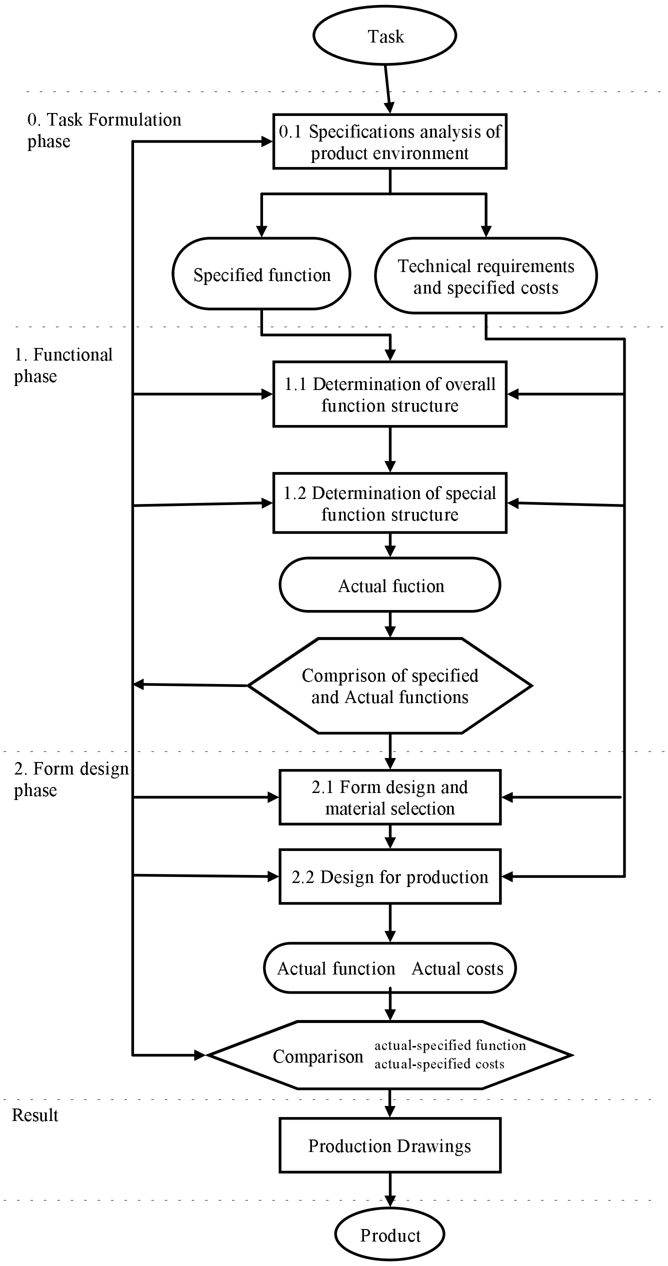

Figure 1.2: Design Process Map from Dym (1994) [3]

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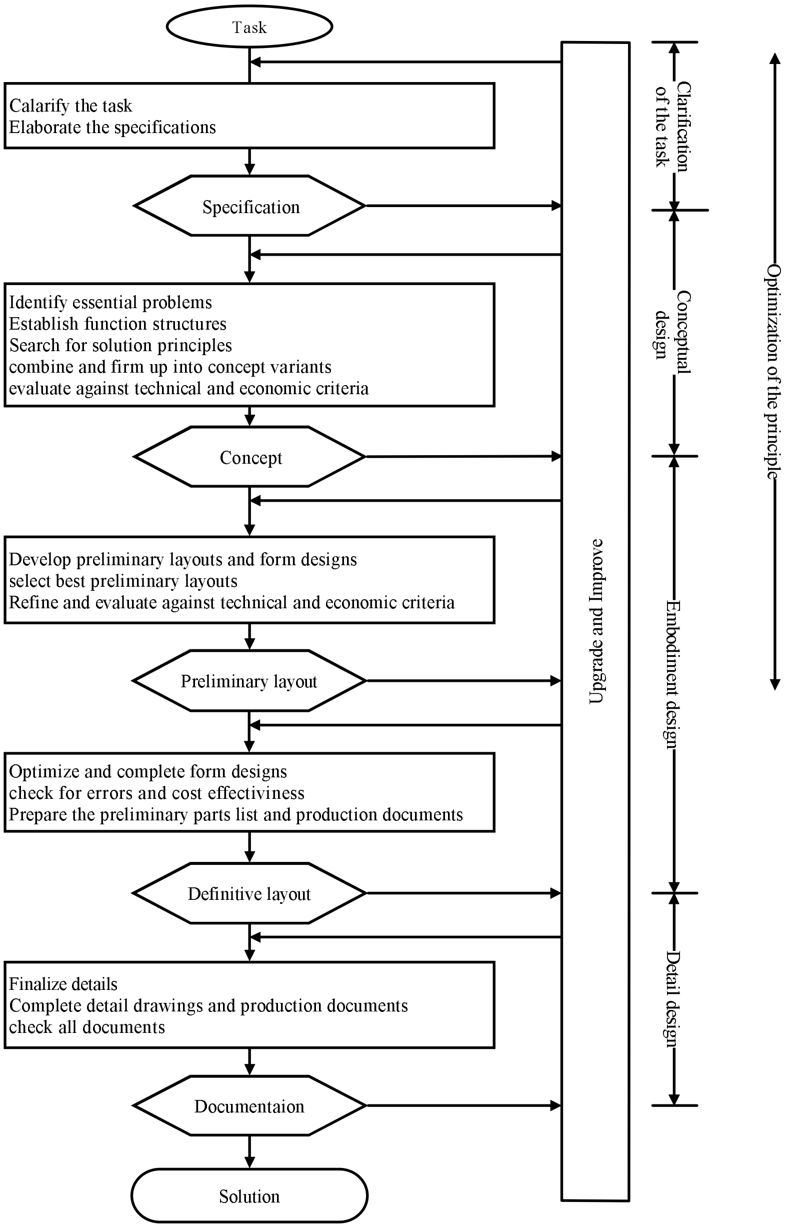

Figure 1.3: Design Process Map from Pahl and Beitz (1991) [7]

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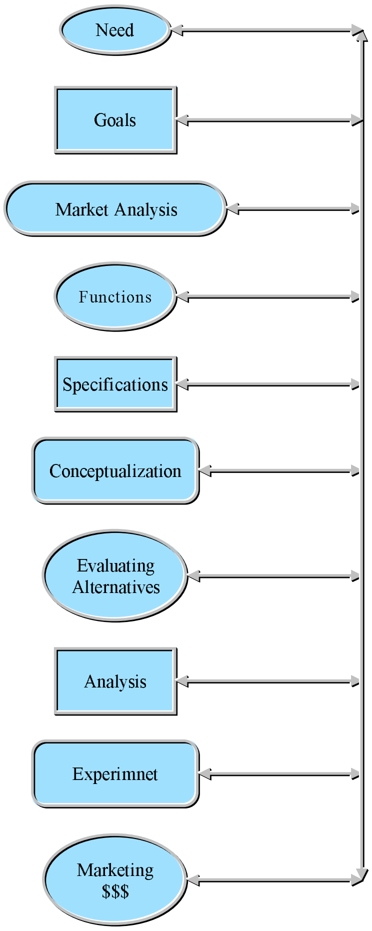


Figure 1.4: Design Process

Figure 1.4: Design Process

brand names for coffee makers what make the difference between them, may be the shape, material used, cost or special features. Lets take the papers clips as an example to demonstrate the point. Figures 1.5 to 1.8 present a demonstration of different development of paper clips. each of these new designs has its own advantages over the other clips. For example the endless filament paper clip can be used from either side of the clip. One may argue that the different designs are based on the human evolution of designs and birth of new ideas that may be true but the major driving force for the new renovation of designs is keeping the companies in business. The first patent for paper clip was filed in 1899 and the latest was filed in 1991. A hundred years of paper clip development and innovations.

3. Generation of new product: In all profit oriented industries the attention, talent and abilities of management, engineering, production, inspection, advertising, marketing, sales and servicing are focused on causing the product to return profit for the company and in turn for the stockholders. Unfortunately, sooner or later every product is pre emptied by another or degenerates into profitless price competition.

   For an industry to survive in todays world, it must continue to grow, it cannot afford to remain static. This growth, throughout history , has been heavily built on new products. New products have a characteristics life cycle pattern in sales volume and profit margins as shown in figure **??**. A product will after a period peak out when it has saturated the market and then begin to decline. It is obvious that an industry must seek out and promote a flow of new product ideas. These new products are usually protected by applying for patents.

1.3.2 Definition of Goals

In this process, the designer defines what is needed to resolve the need. It is a general statement of the wanted end product. Many of the difficulties encountered in design may be traced to poorly stated goals, or goals were hastily written and resulted in confusion or too much flexibility.

In almost all cases the client request comes in a verbal vague statement such as, I need an aluminum can crusher or a safe ladder and so on. Often designers should be careful to recognize that the customer needs are not the

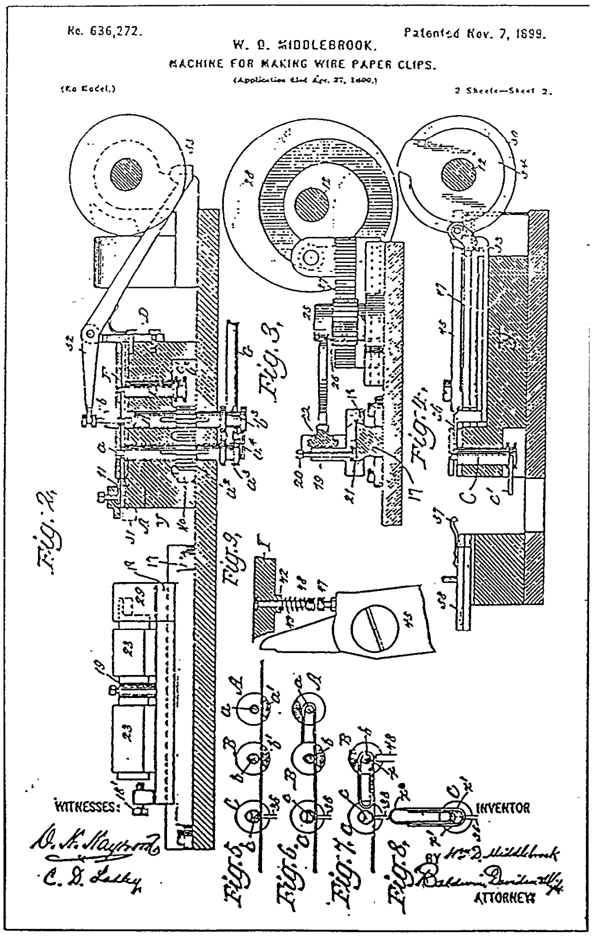


Figure 1.5: William Middelbrook's Patent for a machine for making the paper clips (1899)

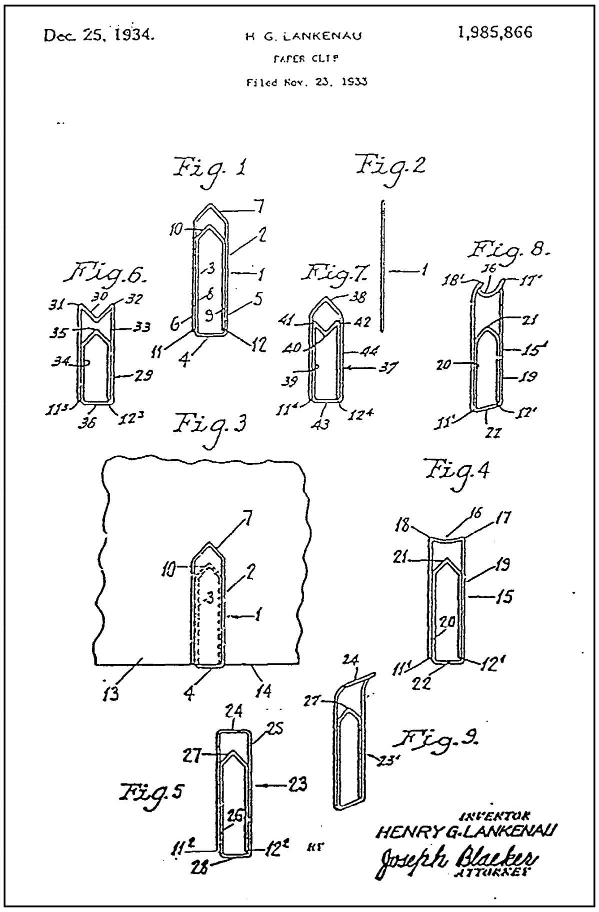
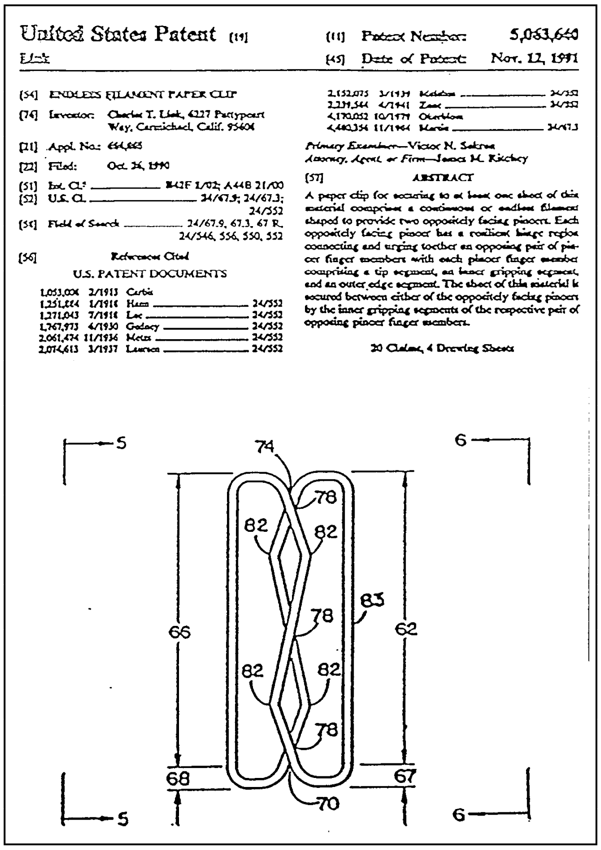


Figure 1.6: Patent for Gothic-style paper clip, issued in 1934



United States Patent [19]
Link

[11] Patent Number: 5,063,640
[45] Date of Patent: Nov. 12, 1991

[54] ENDLESS FILAMENT PAPER CLIP

[76] Inventor: Charles T. Link, 4227 Partypoint Way, Carmichael, Calif. 95608

[21] Appl. No.: 604,665

[22] Filed: Oct. 26, 1990

[51] Int. Cl.⁵ B42F 1/02; A44B 21/00
[52] U.S. Cl. 24/67.9; 24/67.3; 24/552
[58] Field of Search .... 24/67.9, 67.3, 67 R, 24/546, 556, 550, 552

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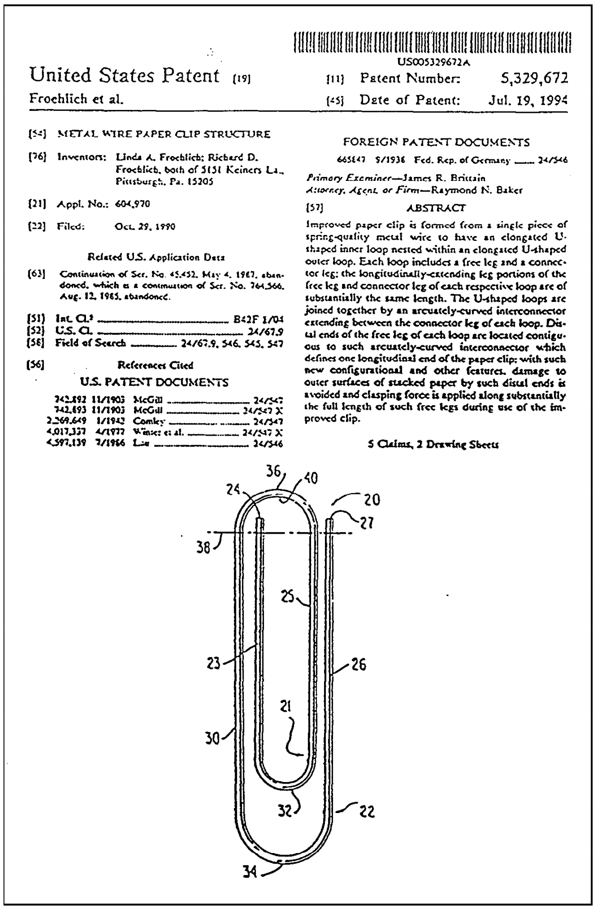
Primary Examiner—Victor N. Sakran
Attorney, Agent or Firm—James M. Ritchey

[57] ABSTRACT

A paper clip for securing to at least one sheet of thin material comprises a continuous or endless filament shaped to provide two oppositely facing pincers. Each oppositely facing pincer has a resilient hinge region connecting and urging together an opposing pair of pincer finger members with each pincer finger member comprising a tip segment, an inner gripping segment, and an outer edge segment. The sheet of thin material is secured between either of the oppositely facing pincers by the inner gripping segments of the respective pair of opposing pincer finger members.

20 Claims, 4 Drawing Sheets

Figure 1.7: Patent for an endless filament paper clip, issued to Charles T. Link (1991)



US005329672A

United States Patent [19]
Froehlich et al.

[11] Patent Number: 5,329,672
[45] Date of Patent: Jul. 19, 1994

[54] METAL WIRE PAPER CLIP STRUCTURE

[76] Inventors: Linda A. Froehlich; Richard D. Froehlich, both of 5151 Keiners La., Pittsburgh, Pa. 15205

[21] Appl. No.: 604,970

[22] Filed: Oct. 29, 1990

Related U.S. Application Data

[63] Continuation of Ser. No. 45,452, May 4, 1987, abandoned, which is a continuation of Ser. No. 764,566, Aug. 12, 1985, abandoned.

[51] Int. Cl.⁵ B42F 1/04
[52] U.S. Cl. 24/67.9
[58] Field of Search 24/67.9, 546, 545, 547

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Primary Examiner—James R. Brittain
Attorney, Agent, or Firm—Raymond N. Baker

[57] ABSTRACT

Improved paper clip is formed from a single piece of spring-quality metal wire to have an elongated U-shaped inner loop nested within an elongated U-shaped outer loop. Each loop includes a free leg and a connector leg; the longitudinally-extending leg portions of the free leg and connector leg of each respective loop are of substantially the same length. The U-shaped loops are joined together by an arcuately-curved interconnector extending between the connector leg of each loop. Distal ends of the free leg of each loop are located contiguous to such arcuately-curved interconnector which defines one longitudinal end of the paper clip; with such new configurational and other features, damage to outer surfaces of stacked paper by such distal ends is avoided and clasping force is applied along substantially the full length of such free legs during use of the improved clip.

5 Claims, 2 Drawing Sheets

Figure 1.8: Patent for for a large paper clip made of spring wire, issued to Linda and Richard Froehlich (1994)

Figure 1.9: Basic life cycle of new product

same as the product specifications. The needs should be expressed in functional terms. Also the designer needs to be aware of the fact that customers will tell you solutions, the designer needs to figure out what are his real needs and act upon that. During the customer interview you should listen carefully to what he has to say. The designer function is to clarify the design requirement from the client. To clearly define the objectives an objective tree may be constructed for clarification.

Quite often the need statement and goals are set into one process.

1.3.3 Market Analysis

Designers have to pursue an active search to locate what is already available and what they have to offer. The information gathering and recognizing the source of information is a vital task for the design engineer. Design engineers should recognize that companies hire them so they can get away from paying royalties to patent holders. The design engineers must know what is available in the market. Information sources may include the following:

1. technical and trade journals
2. abstracts
3. research reports
4. technical libraries
5. catalogue of component suppliers
6. US Patent Office
7. the Internet

The information may reveal an already available design solution and the hardware to accomplish the goal. Sometimes the goal may be altered to produce a market request product or abandoned if the product already exists in the market. The knowledge will save the designer as well as his or her client a lot of time and money. Once the designer determines what is in the market, the creativity should be put into working to generate alternatives. It should be remembered that engineering is a science of creativity and generating solutions. Therefore, one needs to look on the overall picture.

1.3.4 Establishing Functions

Recognizing the level of the problem and where it stands from the whole system is a fundamental element in the design. There is a big difference between being asked to design a car suspension system and designing a car. So it is useful to have means of considering the level where the designer is asked to work. It is also very useful if the organization is done in such a way that identifies the functions instead of the potential solutions. Let's consider an example to illustrate the idea. A blood bank approached a designer to find a solution for their frequently broken centrifuge. When the centrifuge breaks down, the blood separation unit shuts down. They have tried replacing the centrifuge, but always after few months they have the same problem. The need statement is to fix the centrifuge in such a way that it will reduce the break down time. A designer who recognizes the design process will not jump on fixing the centrifuge per-say, he will ask the following question: what is the function we try to accomplish with the centrifuge. The answer is to separate blood by enhancing the gravitational pull. Then, the function is to separate blood cells from the whole blood. This clear statement enables the designer to find alternative solutions, other than the centrifuge. Quite often the functions will be divided into sub-functions, and in all they will define the requirements of the artifact.

Another example follows here: if you were required to design a lawn mower, the function should be defined as a method for shortening the grass. The difference between two definitions of a lawn mower is that one may limit your imagination and creativity while the other may give you a wide open mind for creativity.

1.3.5 Task Specifications

This stage requires the designer to list all pertinent data and parameters that tend to control the design and guide it toward the desired goal. This stage sets the limit on the acceptable solutions. It should not be defined too narrowly because that will cause designer to eliminate acceptable solutions; however, it cannot be too broad or vague because this will leave the designer with no direction to satisfy the design goal. Let's consider the lawn mower again to set some task specifications.

1. It should be safe to operate, especially when used near children.

2. It should be easy to operate by an average person.
3. Types of power to be considered:
    - battery
    - electricity
    - 2 cycle or 4 cycle internal combustion engine
    - manual
4. The device should be easily stored in a garage.
5. Should have possibility of combining lawn tasks.
    - collecting leaves and mowing the lawn
    - shopping the leaves and fertilizing
    - shopping branches for mulch
6. The device should use available hardware and require sheet metal or fiber glass or plastic.
7. Material should be selected based on cost, manufacturablity, strength, appearance and ability to withstand varying weather conditions.
8. Device must be reliable and not require frequent maintenance.
9. Selling price should be lower than that in the market.

These are some of the task specifications.

1.3.6 Conceptualization

The process of generating alternative solutions to the stated goal in the form of concepts requires creative ability. The conceptualization starts with generating new ideas. In this stage the designer must review the market analysis and the task specifications as he or she engages in the process of innovation and creativity. This activity usually takes free hand sketches for producing a series of alternative solutions. The alternatives do not need to be worked out in detail, but are recorded as possibilities to be tested. Alternatives to perform the functions should be listed in an organized fashion. For example, to design a novel transportation system one may list the methods as:

1. Natural way
    (a) Human
        - Walk
        - Swim
    (b) Animal
        - Ride
        - Pulled in a cart
2. With Aids
    (a) Land
        - Bike
        - Skate
    (b) Water
        - Canoe
        - Tube
    (c) Air
        - Kite
    (d) Mechanical
        i. Land
            - Car
            - Train
            - Tube
        ii. Water
            - Ship
            - Sled
        iii. Air
            - Plane
            - Rocket

1.3.7 Evaluating Alternatives

Once a number of concepts have been generated in sufficient detail, a decision must be made about which one or ones will enter the next, most expensive, stages of the design process. An excellent technique to guide the designer in making the best decision regarding these alternatives is a scoring matrix, which forces a more penetrating study of each alternative against a specified criteria.

1.3.8 Analysis and Optimization

Once a concept has been chosen as a possible solution for the stated goal it must be tested against the physical laws. The manufacturability of the chosen product also needs to be checked in order to ensure its usefulness. A product may satisfy the physical laws, but if it cannot be manufactured it is a useless product. This stage is put in iterative sequencing with the conceptualization. Often analysis requires a concept to be altered or redefined, then reanalyzed so that the design is constantly shifted between analysis and concept. Analysis starts with estimation, and is followed by order of magnitude calculation. Estimation is an educated guess based on experience. Order of magnitude analysis is a rough calculation of the specified problem. The order of magnitude doesn't provide an exact solution but it gives the order in which the solution should be expected.

1.3.9 Experiment

The experiment stage in engineering design requires that a piece of hardware is constructed and tested to verify the concept and analysis of the design as to its work ability, durability and performance characteristics. Here the design on paper is transformed into a physical reality. Three techniques of construction are available to the designer:

1. Mock-up : The mock-up is generally constructed to scale from plastics, wood, cardboard and so-forth. The mock-up is often used to check clearance, assembly technique, manufacturing considerations and appearance. It is the least expensive technique, provides the least amount of information, and is quick and relatively easy to build.

2. Model: This is a representation of the physical system through a mathematical similitude. Four types of models are used to predict behavior of the real system:

   - A true model is an exact geometric reproduction of the real system, built to scale and satisfying all restrictions imposed in the design parameters.
   - An adequate model is so constructed to test specific characteristics of the design
   - A distorted model purposely violates one or more design conditions. This violation is often required when it is difficult to satisfy the specified conditions.
   - Dissimilar models bear no apparent resemblance to the real system, but through appropriate analogies give accurate information on behavioral characteristics.

3. prototype: This is the most expensive experimental technique and the one producing the greatest amount of useful information. The prototype is the constructed, full-scale working physical system. Here the designer sees his or her idea come to life, and learns about such things as appropriate construction techniques, assembly procedures, work ability, durability and performance under actual environmental conditions.

As a general rule, when entering the experimental stage of the design process, one should first deal with the mock-up, then the model and finally the prototype (after the mock-up and model have proven the real worth of the design), in order to allow beneficial interaction with concept and analysis.

1.3.10 Marketing

This stage requires specific information that defines the device, system, or process. Here the designer is required to put his or her thoughts regarding the design on paper for the purpose of communication with others. Communication is involved in selling the idea to management or the client, directing the shop on how to construct the design and serving management in the initial stages of commercialization. The description should take the form of one of the following:

1. A report containing the following: a detailed description of the device, how it satisfies the need and how it works, a detailed assembly drawing, specifications for construction, a list of standard parts, a cost break down and any other information that will ensure that the design will be understood and constructed exactly as the designer intended.

2. A flyer containing a list of the special features that the design can provide, advertisements, promotional literature, market testing and so forth.

1.4 Professionalism and Ethics

Professionalism is a way of life. A professional person is one who engages in an activity that requires a specialized and comprehensive education and is motivated by a strong desire to serve humanity. The work of engineers generally affects the day-to-day life of all humans. Developing a professional frame of mind begins with your engineering education.

The American Society of Mechanical Engineers (ASME) requires ethical practice by each of its members and has adopted the following Code of Ethics of Engineers as referenced in the ASME Constitution, Article C2.1.1.

Engineers uphold and advance the integrity, honor and dignity of the engineering profession by:

I. Using their knowledge and skill for the enhancement of human welfare;

II. Being honest and impartial, and serving with fidelity the public, their employers and clients; and

III. Striving to increase the competence and prestige of the engineering profession.

The Fundamental Canons

1. Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.

2. Engineers shall perform services only in the areas of their competence.

3. Engineers shall continue their professional development throughout their careers and shall provide opportunities for the professional and ethical development of those engineers under their supervision.

4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest or the appearance of conflicts of interest.

5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.

6. Engineers shall associate only with reputable persons or organizations.

7. Engineers shall issue public statements only in an objective and truthful manner.

The ASME criteria for interpretation of the Canons are guidelines and represent the objectives toward which members of the engineering profession should strive. They are principles which an engineer can reference in specific situations. In addition, they provide interpretive guidance to the ASME Board on Professional Practice and Ethics on the Code of Ethics of Engineers.

1. Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties.
    (a) Engineers shall recognize that the lives, safety, health and welfare of the general public are dependent upon engineering judgments, decisions and practices incorporated into structures, machines, products, processes and devices.
    (b) Engineers shall not approve or seal plans and/or specifications that are not of a design safe to the public health and welfare and in conformity with accepted engineering standards.
    (c) Whenever the Engineers' professional judgments are over ruled under circumstances where the safety, health, and welfare of the public are endangered, the Engineers shall inform their clients and/or employers of the possible consequences.
        i. Engineers shall endeavor to provide data such as published standards, test codes, and quality control procedures that will enable the users to understand safe use during life expectancy

        associated with the designs, products, or systems for which they are responsible.
        ii. Engineers shall conduct reviews of the safety and reliability of the designs, products, or systems for which they are responsible before giving their approval to the plans for the design.
        iii. Whenever Engineers observe conditions, directly related to their employment, which they believe will endanger public safety or health, they shall inform the proper authority of the situation.
    (d) If engineers have knowledge of or reason to believe that another person or firm may be in violation of any of the provisions of these Canons, they shall present such information to the proper authority in writing and shall cooperate with the proper authority in furnishing such further information or assistance as may be required.

2. Engineers shall perform services only in areas of their competence.

    (a) Engineers shall undertake to perform engineering assignments only when qualified by education and/or experience in the specific technical field of engineering involved.
    (b) Engineers may accept an assignment requiring education and/or experience outside of their own fields of competence, but their services shall be restricted to other phases of the project in which they are qualified. All other phases of such project shall be performed by qualified associates, consultants, or employees.

3. Engineers shall continue their professional development throughout their careers, and should provide opportunities for the professional and ethical development of those engineers under their supervision.

4. Engineers shall act in professional matters for each employer or client as faithful agents or trustees, and shall avoid conflicts of interest or the appearance of conflicts of interest.

    (a) Engineers shall avoid all known conflicts of interest with their employers or clients and shall promptly inform their employers or clients of any business association, interests, or circumstances which could influence their judgment or the quality of their services.

(b) Engineers shall not undertake any assignments which would knowingly create a potential conflict of interest between themselves and their clients or their employers.

(c) Engineers shall not accept compensation, financial or otherwise, from more than one party for services on the same project, or for services pertaining to the same project, unless the circumstances are fully disclosed to, and agreed to, by all interested parties.

(d) Engineers shall not solicit or accept financial or other valuable considerations, for specifying products or material or equipment suppliers, without disclosure to their clients or employers.

(e) Engineers shall not solicit or accept gratuities, directly or indirectly, from contractors, their agents, or other parties dealing with their clients or employers in connection with work for which they are responsible. Where official public policy or employers' policies tolerate acceptance of modest gratuities or gifts, engineers shall avoid a conflict of interest by complying with appropriate policies and shall avoid the appearance of a conflict of interest.

(f) When in public service as members, advisors, or employees of a governmental body or department, Engineers shall not participate in considerations or actions with respect to services provided by them or their organization(s) in private or product engineering practice.

(g) Engineers shall not solicit an engineering contract from a governmental body or other entity on which a principal, officer, or employee of their organization serves as a member without disclosing their relationship and removing themselves from any activity of the body which concerns their organization.

(h) Engineers working on codes, standards or governmental sanctioned rules and specifications shall exercise careful judgment in their determinations to ensure a balanced viewpoint, and avoid a conflict of interest.

(i) When, as a result of their studies, Engineers believe a project(s) will not be successful, they shall so advise their employer or client.

   (j) Engineers shall treat information coming to them in the course of their assignments as confidential, and shall not use such information as a means of making personal profit, if such action is adverse to the interests of their clients, their employers or the public.
      i. They will not disclose confidential information concerning the business affairs or technical processes of any present or former employer or client or bidder under evaluation, without his consent, unless required by law or court order.
      ii. They shall not reveal confidential information or finding of any commission or board of which they are members unless required by law or court order
      iii. Designs supplied to Engineers by clients shall not be duplicated by the Engineers for others without the express permission of the client(s).
   (k) Engineers shall act with fairness and justice to all parties when administering a construction (or other) contract.
   (l) Before undertaking work for others in which Engineers may make improvements, plans, designs, inventions, or other records which may justify seeking copyrights, patents, or proprietary rights, Engineers shall enter into positive agreements regarding the rights of respective parties.
   (m) Engineers shall admit their own errors when proven wrong and refrain from distorting or altering the facts to justify their mistakes or decisions.
   (n) Engineers shall not accept professional employment or assignments outside of their regular work without the knowledge of their employers.
   (o) Engineers shall not attempt to attract an employee from other employers or from the market place with false or misleading representations.

5. Engineers shall build their professional reputation on the merit of their services and shall not compete unfairly with others.

   (a) Engineers shall negotiate contracts for professional services on the basis of demonstrated competence and qualifications for the type of professional service required.

   (b) Engineers shall not request, propose, or accept professional commissions on a contingent basis if, under the circumstances, their professional judgments may be compromised.
   (c) Engineers shall not falsify or permit misrepresentation of their, or their associates', academic or professional qualifications. They shall not misrepresent or exaggerate their degrees of responsibility in or for the subject matter of prior assignments. Brochures or other presentations used to solicit personal employment shall not misrepresent pertinent facts concerning employers, employees, associates, joint venturers, or their accomplishments.
   (d) Engineers shall prepare articles for the lay or technical press which are only factual. Technical Communications for publication (theses, articles, papers, reports,etc.) which are based on research involving more than one individual (including students and supervising faculty, industrial supervisor/researcher or other co-workers) must recognize all significant contributors. Plagiarism, the act of substantially using another's ideas or written materials without due credit, is unethical. (See Appendix.)
   (e) Engineers shall not maliciously or falsely, directly or indirectly, injure the professional reputation, prospects, practice or employment of another engineer, nor shall they indiscriminately criticize another's work.
   (f) Engineers shall not use the equipment, supplies, laboratory or office facilities of their employers to carry on outside private practice without consent.

6. Engineers shall associate only with reputable persons or organizations.
   (a) Engineers shall not knowingly associate with or permit the use of their names or firm names in business ventures by any person or firm which they know, or have reason to believe, is engaging in business or professional practices of a fraudulent or dishonest nature.
   (b) Engineers shall not use association with non-engineers, corporations, or partnerships to disguise unethical acts.

7. Engineers shall issue public statements only in an objective and truthful manner.

   (a) Engineers shall endeavor to extend public knowledge, and to prevent misunderstandings of the achievements of engineering.
   (b) Engineers shall be completely objective and truthful in all professional reports, statements or testimony. They shall include all relevant and pertinent information in such reports, statements or testimony.
   (c) Engineers, when serving as expert or technical witnesses before any court, commission, or other tribunal, shall express an engineering opinion only when it is founded on their adequate knowledge of the facts in issue, their background of technical competence in the subject matter, and their belief in the accuracy and propriety of their testimony.
   (d) Engineers shall issue no statements, criticisms, or arguments on engineering matters which are inspired or paid for by an interested party, or parties; unless, they preface their comments by identifying themselves, by disclosing the identities of the party or parties on whose behalf they are speaking, and by revealing the existence of any financial interest they may have in matters under discussion.
   (e) Engineers shall be truthful in explaining their work and merit, and shall avoid any act tending to promote their own interest at the expense of the integrity and honor of the profession or another individual.

8. Engineers accepting membership in The American Society of Mechanical Engineers by this action agree to abide by this Society Policy on Ethics and procedures for its implementation.

1.5 Problems

1.5.1 Team Activities

1. List the steps in the design process.
2. Define each step in the design process.
3. What is the difference between customer statement and problem definition?

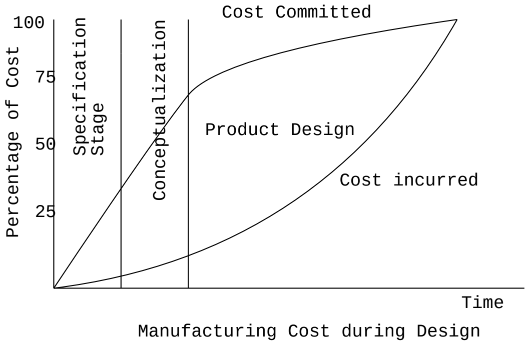


Figure 1.10: Manufacturing Cost

4. What is the difference between the specification step and defining the problem step in the design process?

5. What is function analysis and how is it different from the definition of the problem?

6. List three factors that market analysis achieves.

7. Why does the function analysis proceed the conceptualization step?

8. Give examples of a mock-up.

9. Tell why you think schedualing is important.

1.5.2 Individual Activities

1. The figure (1.10 below shows the percent of cost committed and incurred as a function of time during the design of a product. The committed cost is the amount of money allocated for the manufacturing of the product while the incurred cost is the amount of money spent on the design.

   (a) Explain your findings from the figure.

   (b) Discuss why it is more important to spend time and money on the early stages of design than on the late stages of design.

2. Describe in detail the various types of design.

3. List several common sources of Engineering failures.

4. Explain the difference between Engineering Design and Engineering Design Process.

5. Identify several commonalities and differences between figures 1.1, 1.2, 1.3 and 1.4 in your text.

6. List four factors that may be used to determine quality, and discuss the following statment in light of your listing, ”Quality cannot be built into a product unless it is designed into it.”

7. Consider the following two statements:

    - What size SAE grade 5 bolt should be used to fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N?
    - Design a joint to fasten together two pieces of 1045 sheet steel, each 4 mm thick and 6 cm wide, which are lapped over each other and loaded with 100 N.

    (a) Explain the difference between the two statements.

    (b) Similarly change a problem from one of your engineering science/physics classes into a design problem.

8. Explain the engineering design process to a student in high school.

9. Define professionalism.

10. Read through the ASME code of ethics and list three findings.

Chapter 2

Prerequisites

Before beginning the discussion on the process, it is important to state some of the prerequisites that should be in mind during the design process. The word prerequisites was chosen to reveal what the designer needs to keep in mind during the design process. The prerequisites include: scheduling, material selection, human factors, and safety issues.

2.1 Scheduling

Development of a new product, following the design process, is always limited by the time available for the entire process. Over the years, several procedures have been proposed to manage and plan for an artifact. Many projects have failed because of the lack of detail. Historically, engineering projects were typically created by one engineer, working alone. The designer, the drafter and the planner were the same person. In recent years, however, with the advancement of products and the technology products require, teams of engineers and technical helpers work beside each other to accomplish a project. In the following, we will discuss some existing techniques for scheduling.

2.1.1 Gantt Chart

This chart was introduced by Henry L. Gantt and Frederick Taylor in the early 1900's to aid the management of projects. The Gantt chart has taken the form of a bar chart. The steps to establish a Gantt chart are as follows:

1. List all events or milestones of the project in an ordered list.

2. Estimate the time required to establish each event.
3. List the starting time and end time for each event.
4. Represent the information in a bar chart.

An example of the Gantt chart is shown in figure2.1.

2.1.2 CPM/PERT

The critical path method(CPM) and the program evaluation and review technique(PERT,) which were originally developed during the same time period, are the two most widely used approaches. PERT was developed under the guidance of the U.S. Navy Special Projects Office by a team that included members from the Lockheed Missile Systems Division and the consulting firm Booz, Allen and Hamilton. The technique was developed to monitor the effort of 250 main contractors and 9,000 subcontractors who were concerned with the Polaris missile project. CPM was the result of the efforts of the Integrated Engineering Control Group of E.I. duPont de Nemours & Company, and it was developed to monitor activities related to design and construction. A survey of manufacturing companies in the United States revealed that CPM/PERT is used over 65% of the time, among all other methods. A CPM/PERT project generally has the following characteristics:

1. There are clearly defined activities or jobs whose accomplishment results in project completion.
2. Once started, the activity or job continues without interruption.
3. The activities or tasks are independent, which means they may be started, stopped, and performed individually in a prescribed sequence.
4. The activities or jobs are ordered and they follow each other in a specified manner.

Even though the CPM and PERT techniques were developed independently, the basic theory and symbology in both techniques are essentially the same.

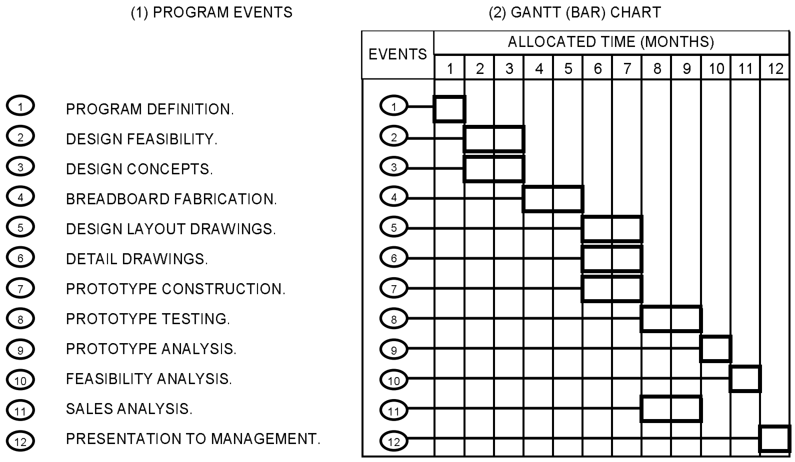


Figure 2.1: Gantt Chart

2.1.3 Definitions

Several symbols, terms and definitions are used in developing the CPM/PERT networks, and they are:

1. Event (node): This represents a point in time in the life of a project. An event can be the beginning or the end of an activity. A circle is used to represent an event. Generally, each network event is identified with a number.

2. Activity: This is an effort needed to carry out a certain portion of the project. An activity consumes money, labor, time and materials and is denoted by a continuous arrow [⟶]. The direction of progress on the project is indicated by the arrowhead. Furthermore, an activity both begins and ends at a circle.

3. Dummy activity: This is an imaginary activity that takes zero time and no resources to perform. Its purpose is to show appropriate relationships between activities. A dotted arrow is used to represent such an activity.

4. Network paths: These are the paths used (or needed) for reaching the project termination point, or the event from the project starting point or event.

5. Critical path: This is the longest path with respect to time duration through the PERT/CPM network. In other words, the critical path creates the largest sum of activity duration of all individual network paths.

6. Earliest event time (EET): This is the earliest time at which an event occurs, providing all proceeding activities are accomplished within their estimated times.

7. Latest event time (LET): This is the latest time at which an event could be reached without delaying the predicted project completion date.

8. Total float: This is the latest time of an event, minus the earliest time of the preceding event, and the duration time of the in-between activity.

2.1.4 Network Development

Steps involved in constructing a CPM network are as follows:

1. Break down the design into individual activities and identify each activity.
2. Estimate the time required for each activity.
3. Determine the activity sequence.
4. Construct the CPM network, using the defined symbols.
5. Determine the critical path of the network.

Similarly, the steps involved in developing a PERT network are:

1. Break down the design into individual activities and identify each activity.
2. Determine the activity sequence.
3. Construct the PERT network, using the defined symbols.
4. Obtain the expected time to perform each activity, using the following formula:

   $$T_e = \frac{x + 4y + z}{6}$$

   where
   T_e is the expected time for the activity
   x is the optimistic time estimate for the activity
   y is the most likely time estimate for the activity
   z is the pessimistic time estimate for the activity

5. Determine the network critical path.
6. Compute the variance associated with the estimated expected time of T_e of each activity using the following formula:

   $$S^2 = \left(\frac{z - x}{6}\right)^2$$

w	Probability
-3	0.0013
-2.5	0.006
-2	0.023
-1.5	0.067
-1	.159
-0.5	0.309
0	.5
0.5	0.69
1	0.84
1.5	0.933
2	0.977
2.5	0.994
3	0.999

7. Obtain the probability of accomplishing the design project on the stated date using the following formula:

$$w = \frac{T - T_L}{[\sum S_{cr}^2]^{\frac{1}{2}}}$$

where
S_{cr}^2 is the variance of activities on the critical path
T_L is the last activity's earliest expected completion time, as calculated through the network.
T is the design project due date, expressed in time units. Table 7 presents the probabilities for selective values of w.

Example

A mechanical design project was broken down into a number of major jobs or activities, as shown in table 2.1. A CPM network was developed using the data given in the table, and the critical path of the network was determined, along with the expected project duration time period.

Using the defined symbols and the data given in table 2.1, the CPM network shown in figure 2.2.

The paths originated at event 1 and terminated at 11 are as follows:

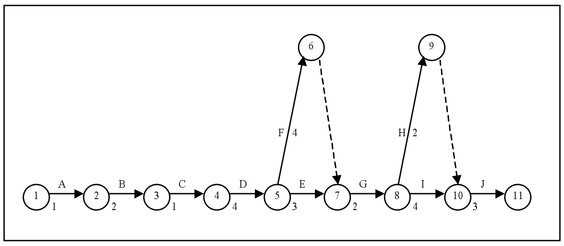


Figure 2.2: CPM Chart

Activity Description	Activity identification	Immediate Predecessor activity or activities	Activity Duration week or weeks
formation	A	–	1
search and idea generation	B	A	2
evaluation	C	B	1
and evaluation	D	C	4
manufacture	E	D	3
procurement	F	D	4
assembly	G	E,F	2
	H	G	2
estimation	I	G	4
and presentation	J	H,I,3	

Table 2.1: Design Project

1. A-B-C-D-E-G-I-J time=20
2. A-B-C-D-F-G-I-J time=21
3. A-B-C-D-E-G-H-J time =18
4. A-B-C-D-F-G-H-J time=19

These results indicate that the longest path is (A-B-C-D-F-G-I-J), and the predicted time for the design project is 21 weeks.

2.2 Material Selection

The design, even of the simplest element, requires the selection of a suitable material and a decision regarding the methods of manufacturing which are to be used in producing the element. These two factors are closely related, and the choice will affect the shape, appearance, cost and so on. It may also determine the difference between a commercial success and a commercial failure. As the design becomes more complex and involves more elements, the selection of suitable materials and methods of production becomes more difficult. The design engineer must be sufficiently familiar with the characteristics and properties of the materials, and the way in which they can be shaped to ensure that his or her decisions are well made.

2.2.1 Material Classifications and Properties

The various types of materials that may be used in a product design are classified as:

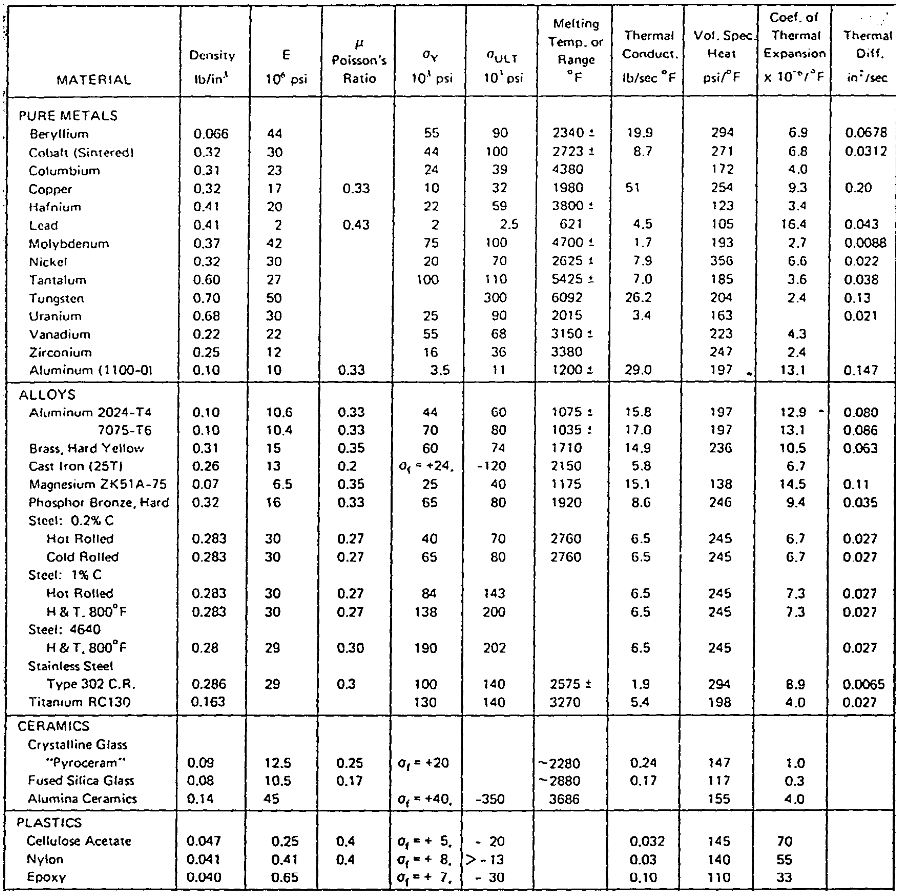
1. Metals: This important materials classification can be further divided into two; ferrous and nonferrous alloys. Ferrous alloys are based on iron, which has mechanical properties. Nonferrous alloys are based on materials other than iron, such as copper, tin, aluminum and lead.

2. Ceramics and glass: These are the result of the combination of metallic and nonmetallic elements. They are good insulators, brittle, thermally stable, and more wear resistant compared to metals. They are also harder and lower in thermal expansion than most metals.

3. Woods and organics: These are obtained from trees and plants. Their major advantage is that they are a renewable resource. However, some of their drawbacks include that they absorb water, require special treatment to prevent rotting and are more flammable.

4. Polymers or plastics: These materials change viscosity with variation in temperature; therefore they are easy to mold into a given shape. There are several benefits of polymers: they are good insulators; they are resistant to chemicals and water; they have a smooth surface finish; and they are available in many colors, which eliminates the need for painting. There are several drawbacks to polymers, however: they are low in strength, they deteriorate in ultraviolet light, and have excessive creep at all temperatures.

The properties of material can be divided into six categories: mechanical, thermal, chemical, and fabrication. Mechanical properties include: fatigue, strength, wear, hardness and plasticity. Thermal properties include: absorptivity, fire resistance and expansion coefficience. Physical properties are: permeability, viscosity, crystal structure, and porosity. Chemical properties include: corrosion, oxidation and hydraulic permeability. Four important electrical properties are: hysteresis, conductivity, coercive force and dielectric constant. There are several fabrication properties, some of which are: weldability, castability, and heat treatability. Partial list of selected material proprties is shown in figure 2.3.



MATERIAL	Density lb/in^3	E 10^6 psi	μ Poisson's Ratio	σ_Y 10^3 psi	σ_{ULT} 10^3 psi	Melting Temp. or Range °F	Thermal Conduct. lb/sec °F	Vol. Spec. Heat psi/°F	Coef. of Thermal Expansion x 10^{-6}/°F	Thermal Diff. in^2/sec
PURE METALS										
Beryllium	0.066	44		55	90	2340 ±	19.9	294	6.9	0.0678
Cobalt (Sintered)	0.32	30		44	100	2723 ±	8.7	271	6.8	0.0312
Columbium	0.31	23		24	39	4380		172	4.0	
Copper	0.32	17	0.33	10	32	1980	51	254	9.3	0.20
Hafnium	0.41	20		22	59	3800 ±		123	3.4	
Lead	0.41	2	0.43	2	2.5	621	4.5	105	16.4	0.043
Molybdenum	0.37	42		75	100	4700 ±	1.7	193	2.7	0.0088
Nickel	0.32	30		20	70	2625 ±	7.9	356	6.6	0.022
Tantalum	0.60	27		100	110	5425 ±	7.0	185	3.6	0.038
Tungsten	0.70	50			300	6092	26.2	204	2.4	0.13
Uranium	0.68	30		25	90	2015	3.4	163		0.021
Vanadium	0.22	22		55	68	3150 ±		223	4.3	
Zirconium	0.25	12		16	36	3380		247	2.4	
Aluminum (1100-0)	0.10	10	0.33	3.5	11	1200 ±	29.0	197	13.1	0.147
ALLOYS										
Aluminum 2024-T4	0.10	10.6	0.33	44	60	1075 ±	15.8	197	12.9	0.080
7075-T6	0.10	10.4	0.33	70	80	1035 ±	17.0	197	13.1	0.086
Brass, Hard Yellow	0.31	15	0.35	60	74	1710	14.9	236	10.5	0.063
Cast Iron (25T)	0.26	13	0.2	$\sigma_f = +24.$	-120	2150	5.8		6.7	
Magnesium ZK51A-75	0.07	6.5	0.35	25	40	1175	15.1	138	14.5	0.11
Phosphor Bronze, Hard	0.32	16	0.33	65	80	1920	8.6	246	9.4	0.035
Steel: 0.2% C										
Hot Rolled	0.283	30	0.27	40	70	2760	6.5	245	6.7	0.027
Cold Rolled	0.283	30	0.27	65	80	2760	6.5	245	6.7	0.027
Steel: 1% C										
Hot Rolled	0.283	30	0.27	84	143		6.5	245	7.3	0.027
H & T, 800°F	0.283	30	0.27	138	200		6.5	245	7.3	0.027
Steel: 4640										
H & T, 800°F	0.28	29	0.30	190	202		6.5	245		0.027
Stainless Steel										
Type 302 C.R.	0.286	29	0.3	100	140	2575 ±	1.9	294	8.9	0.0065
Titanium RC130	0.163			130	140	3270	5.4	198	4.0	0.027
CERAMICS										
Crystalline Glass										
"Pyroceram"	0.09	12.5	0.25	$\sigma_f = +20$		~2280	0.24	147	1.0	
Fused Silica Glass	0.08	10.5	0.17			~2880	0.17	117	0.3	
Alumina Ceramics	0.14	45		$\sigma_f = +40.$	-350	3686		155	4.0	
PLASTICS										
Cellulose Acetate	0.047	0.25	0.4	$\sigma_f = + 5.$	- 20		0.032	145	70	
Nylon	0.041	0.41	0.4	$\sigma_f = + 8.$	> - 13		0.03	140	55	
Epoxy	0.040	0.65		$\sigma_f = + 7.$	- 30		0.10	110	33	

Figure 2.3: Material Properties

2.2.2 Material Selection Process

Several systematic approaches have been developed for selecting materials, one of these is listed here:

1. Perform a material requirements analysis: This step is concerned with determining environmental and service conditions under which the product will have to operate.
2. List the suitable material: This step calls for filtering through the available material and obtaining several suitable candidates.
3. Choose the most suitable material: This step involves analysis of the material listed, with respect to such factors as cost, performance, availability and fabrication ability, then selecting the most suitable material.
4. Obtain the necessary test data: this step calls for determining the important properties of the selected material, experimentally under real life operational conditions.
5. Product specification fulfillment: The selected material must satisfy the stated specifications.
6. Cost: This important factor plays a dominant role in the marketing of the end product.
7. Material availability: The selected material must be available at a reasonable cost.
8. Material Joining approach: Under real life conditions, it may be impractical to produce an element using a single piece of material. This may call for manufacturing the components with different pieces of material joined together to form a single unit.
9. Fabrication: Engineering products usually require some level of fabrication, and different fabrication techniques are available. Factors affecting the fabrication method selected include: time constraints, material type, product application, cost, and quantity to be manufactured.
10. Technical issues: Technical factors are mainly concerned with the material mechanical properties. Examples include: strength compared to anticipated load, safety factors, temperature variation and potential loading changes.

2.2.3 Primary Manufacturing Methods

The primary manufacturing methods which are used to convert a material into the basic shape required are:

1. Casting: Casting is a widely used first step in the manufacturing process. During casting, an item takes on its initial usable shape. In the casting process, a solid is melted down and heated to a desirable temperature level. The molten material is then poured into a mold made in the required shape. The cast items may range in size and weight from a fraction of an inch to several yards. Typical examples include: a zipper's individual teeth, and the stern frames of ships.

2. Forging: Forging, which is among the most important methods of manufacturing items of high performance uses, involves changing the shape of the piece of material by exerting force on that piece. The methods of applying pressure include: the mechanical press, hydrolic press and drop hammer. Products such as cranckshafts, wrenches and connecting rods are the result of forging. The material to be forged may be hot or cold.

3. Machining: Machining involves removing unwanted material from a block of material according to given specifications, such as size, shape, and finish, to produce a final product. There are many machining processes such as milling, boring, grinding and drilling.

4. Welding: Welding is a versatile production process which is used for combining items produced by some other means of manufacturing. Welding is the process of permanently joining two materials through coalescence, which involves a combination of pressure and surface conditions.

2.3 Human Factors

The science that considers humans and their reactions to familiar, as well as strange environments, is known by several terms. Some include human engineering, human performance and ergonomics. Adapting a human to fit a given environment is almost impossible, so methods for adapting the environment to suit the human must be devised. Human behavior is critical to the success of an engineering system. Therefore, it is important to take typical human behaviors into consideration during the design phase. Examples of typical human behaviors include:

1. Humans are often reluctant to admit errors.
2. Humans usually perform tasks while thinking about other things.
3. People frequently misread or overlook instructions and labels.
4. People often respond irrationally in emergency situations.
5. A significant percentage of people become complacent after successfully handling dangerous items over a long period of time.
6. Most people fail to recheck outlined procedures for errors.
7. People are generally poor estimators of speed, clearance, or distance. They frequently overestimate short distance and underestimate large distance.
8. People are generally too impatient to take the time needed to observe.
9. People are often reluctant to admit that they cannot see objects well, due either to poor eyesight or to inadequate illumination. They generally use their hands for examining or testing.

Every time people dial telephones, drive cars, study oscilloscopes, computers or form parts on a lathe, they have joined their sensing, decision-making, and muscular powers into an engineering system. Figure 2.4 shows the coupling of components that are necessary to consider a human as an integral part of an efficient human-machine system.

2.3.1 Human Sensory Capabilities

Human sensory capabilities include:

1. Sight: Human eyes see differently from different angles or positions. For example, looking straight ahead, the eyes can perceive all colors. However, with an increase in the viewing angle, human perception begins to decrease. The limits of color vision are given in table 1: Also, at night or in the dark, small-sized orange, blue, green and yellow lights are impossible to distinguish from a distance.

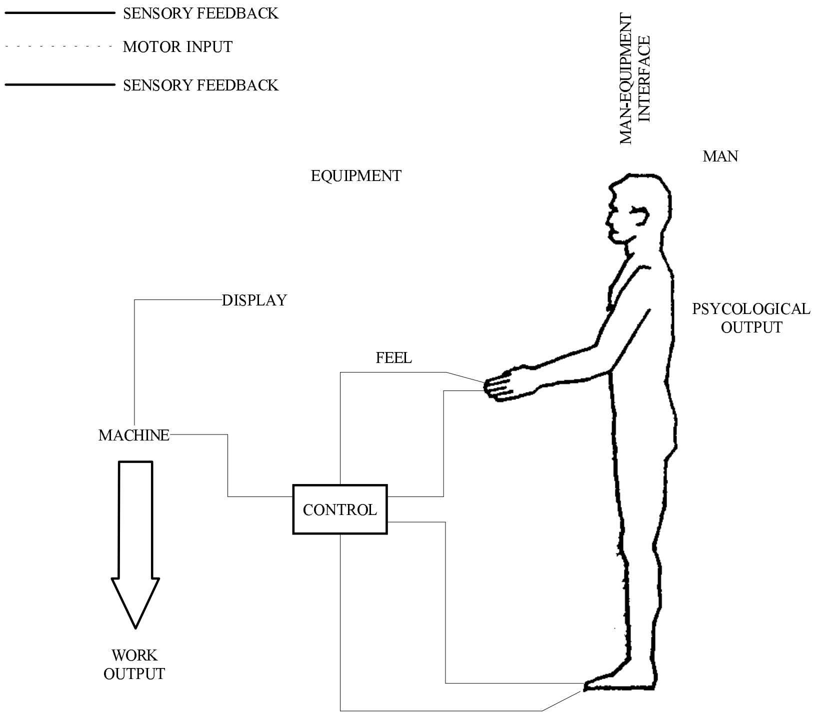


Figure 2.4: Man-machine System

Situation	Green	Blue	Yellow	White	Green-Red	Red
Vertical	40^o	80^o	95^o	130^o	–	45^o
Horizontal	–	100^o	120^o	180^o	60^o	–

2. Noise: The performance quality of a task requiring intense concentration can be affected by noise. It is an established fact that noise contributes to peoples' feelings, such as irritability, boredom, and well being. A noise level of 90 DB (decibels) is considered harmless, while above 100 DB is unsafe. Levels in excess of 130 dB are considered unpleasant and may actually become harmful.

3. Touch: Touch adds to, or may even replace, the information transmitted to the brain by eyes and ears. For example, it is possible to distinguish knob shapes with touch alone. This ability could be valuable if, for instance, the power goes out and there is no light.

4. Vibration and motion: It is now an accepted fact that poor performance of physical and mental tasks by equipment operators could be partially or fully attributed to vibrations. For example, eye strain, headaches and motion sickness could result from low frequency, large amplitude vibrations. Useful guidelines for the effects of vibration and motion are as follows:

   (a) Eliminate vibrations with an amplitude greater than 0.08 millimeter.

   (b) Use such devices as shock absorbers and springs wherever possible.

   (c) Use damping materials or cushioned seats to reduce vibration wherever possible.

   (d) Since seated humans are most affected by vertical vibration, use this information to reduce vertical vibrations.

   (e) The resonant frequency of the human vertical trunk, in the seated position, is between 3 and 4 cycles per second. Therefore, avoid any seating that would result in or would transmit vibration of 3 to 4 cycles per.

2.3.2 Anthropometric Data

Anthropomorhy is the science that deals with the dimensions of the human body. These are divided into statistical groups known as percentiles. If 100 men are lined up from smallest to largest in any given respect, they would be classified from the 1 percentile to the 100 percentile. The 2.5 percentile means that designs based on this series of dimensions would allow up to 2.5% of the population to use the system and the remaining 97.5% would be excluded. Figure 2.5 shows the dimensions of a standing adult male.

2.4 Safety Considerations

One very important consideration in engineering design maintains that the resulting product be safe for humans. In recent years, the liability decisions made by the courts further increased the importance of safety. According to the National Safety Council, over 105,000 Americans were accidently killed and over 10 million suffered a disabling injury in 1980 which translated into $83.2 billion. Therefore safety is hardly new, it has been important for thousands of years. There are many safety functions used during the design process,including:

1. Developing accident prevention requirements for the basic design.
2. Participating in the design reviews.
3. Performing hazard analyses during the product design cycle.

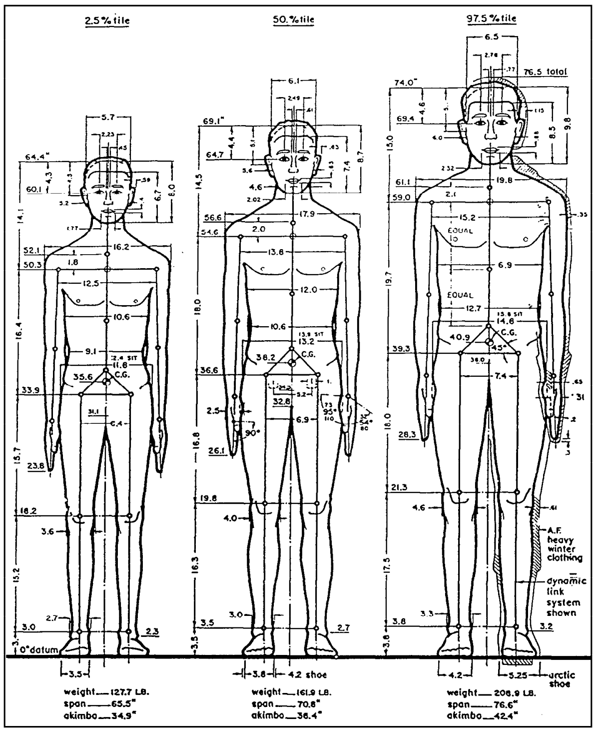
2.4.1 Safety Analysis Techniques

The two techniques, failure modes and effect analysis (FMEA) and fault trees, which are used for design stage reliability analysis can also be applied for saftey analyses.

Failure modes and effect analysis (FMEA)

This method was originally developed for use in the design and development of flight control systems. The method can also be used to evaluate design at the initia stage from the point of view of safety. Basically, the technique calls for listing the potential failure modes of each part, as well as the effects on the parts, and on humans. The technique may be broken down into seven steps:

1. Defining system boundaries and requirements.
2. Listing all items.



© "The Measure of Man" by Henry Dreyfuss, Whitney Library of Design, New York, N.Y. 1959, 1960.

Figure 2.5: Standing adult male

3. Identifying each component and its associated failure modes.
4. Assigning an occurrence probability or failure rate to each failure mode.
5. Listing the effects of each failure mode on concerned items and people.
6. Entering remarks for each possible failure mode.
7. Reviewing and initiating appropriate corrective measures.

Fault trees

This technique uses various symbols. It starts by identifying an undesirable event, called the top event, and then successively asking the question ”How could this event occur?” This process continues until the fault events do not require further development. If occurrence data are known for the basic or primary fault event, the occurrence measure for the top event can be calculated.

2.5 Technical Writing and Presentation

In the engineering and scientific professions, communication skills are as important as in other fields. Following the development of an innovative design and a cost estimate that predicts large profit, the designer must be able to communicate the findings to other people. An old adage reminds us that a tree falling in a forest doesn't make a sound unless there is someone to listen. Similarly, the best technical design in the world might never become implemented unless the designer can communicate the design to the proper people, in the right way.

The quality of a report generally provides an image in the reader's mind that, in large measure, determines the reader's impression of the quality of work. Of course, an excellent job of report writing cannot disguise a sloppy investigation, but many excellent design studies have not received proper attention and credit because the work was reported in a careless manner. A formal technical report is usually written at the end of a project. Generally, it is a complete, stand-alone document which is aimed at persons who have widely diverse backgrounds. Therefore, much more detail is required. The outline of a typical formal report consists of:

1. Cover page: Should have
    - title of the report
    - name of author(s)
    - address
2. Summary: summarizes the work, and should also include a short conclusion.
3. Table of contents.
4. List of figures and list of tables that includes the corresponding page number.
5. Introduction: Background of the work (market analysis) to acquaint the reader with the problems with and purposes of carrying on the work.
6. Design Process: Details of the procedure followed in the design process.
7. Discussion: This section should contain the comprehensive explanation of the results. The discussion could be divided into several subsections, such as:
    - technical analysis (force requirement, speed, etc.)
    - details of the build up of the artifact
    - equipment used
    - assembly and setup procedures
    - experimental setups and results
    - details of the final results
8. Conclusions: This section states in as concise a form as possible the conclusions that can be drawn from the study.
9. References: This section lists all the documents to which the writers referred. The information on each document must be complete and must follow the same format throughout.
10. Appendices: This includes material deemed beyond the scope of the main body of the report. The appendix section may be divided into as many subsections as necessary.

2.5.1 Steps in Writing a Report

The five operations involved in the writing of a high-quality report are best remembered with the acronym POWER:

1. **P**: Plan the writing
2. **O**: Outline the report
3. **W**: Write
4. **E**: Edit
5. **R**: Rewrite

Good writers usually produce good reports. Some of the attributes of good writing:

1. Write as objectively as possible. DO not become emotionally involved or attached to a problem or a solution.
2. Be reasonably methodical.
3. Record whatever is learned, and keep in mind that whatever work is performed must eventually be documented.
4. Always strive for clarity in writing, and keep in mind that the written material should be simple and straightforward.
5. Deliver the written material on time.

There are also certain qualities associated with good reports, such as:

1. Delivered on the due date.
2. Effectively answers readers' questions as they arise.
3. Gives a good impression at the first sight.
4. Reads coherently.
5. Contains an effective summary and conclusion.
6. Is written clearly and concisely, and avoids vague or superfluous phrases.
7. Provides pertinent information.

2.5.2 Illustration Guidelines

Visual elements, such as figures, charts, graphs, etc., in technical reports have specific purposes and convey specific information. Visuals are used to explain, illustrate, demonstrate, verify or support written material. Visuals are only valuable if their presentation is effective. The general guidelines for preparing effective visuals (illustrations) are as follows:

1. Reference all illustrations in the text.
2. Reference the data source.
3. Carefully plan the placement of illustrations.
4. Specify all units of measure and the scale used in the drawing.
5. Label each illustration with an identifying caption and title. Include figure source, if it was obtained from another document.
6. Spell words out rather than using abbreviations.
7. When a document has five or more figures, include a list of figures at the beginning of the report.
8. Avoid putting too much on an illustration.

2.5.3 Mechanics of Writing

The following suggestions are presented as a guide to writing in order to help writers aviod some of the most common mistakes:

- Paragraph structure: Each paragraph should begin with a topic sentence that provides an overall understanding of the paragraph. Since each paragraph should have a single theme or conclusion, the topic sentence states that theme or conclusion.

- Sentence length: Sentences should be kept as short as possible so that their structure is simple and readable. Long sentences require complex construction, provide an abundance of opportunity for grammatical errors, take considerable writing time, and slow the reader down. Long sentences are often the result of putting together two independent thoughts that could be stated better in separate sentences.

- Pronouns: There is no room for any ambiguity between a pronoun and the noun for which it is used. Novices commonly use ”it”, ”this”, ”that”, etc., where it would be better to use one of several nouns. It may be clear to the writer, but is often ambiguous to the reader. In general, personal pronouns (I, you, he, she, my, mine, our, us)are not used in reports.
- Spelling and punctuation: Errors in these basic elements of writing are inexcusable in the final draft of the report.
- Tense: use the following rules when choosing the tense of the verb when writing:
  - Past tense: Use to describe work done when you were building or designing, or in general when referring to past events.
  - Present tense: Use in reference to items and ideas in the report itself.
  - Future tense: Use in making predictions from the data or results that will be applicable in the future.

2.6 Presentation Style

Unlike advertising executives, engineers are ill-equipped to sell their ideas. Second hand information represented by the company officials may not answer all of the client’s questions. In this write-up and during the semester, students will be given the opportunity to be trained in technical presentations. Also, in this write-up, the techniques of oral presentations will be briefly discussed.

2.6.1 Objective

Every presentation should have an objective. The speaker’s main objective is to deliver the message(objective) to the audience. The objectives may vary from one talk to another. To identify the real objective, one needs to ask the following question: ”If everything goes perfectly, what do I intend to achieve?” One also should realize who the audience is, and what their educational level may be. Time, in most cases, is limited. It is of utmost importance to keep within the scheduled time during question/answer sessions.

To accomplish this, detailed planning is required. Different tools can be used in the presentation such as, slides, models, transparencies, audio-visual, and the Web. Make sure to account for the time needed to shift, if more than one medium is used. One easy way to evaluate the effectiveness of a presentation while on a team, is to practice through role playing. One person can play the role of the speaker, and the rest of the team can act as the audience, and possibly even play the devil's advocate. This way, the team gains valuable experience before attempting the actual presentation.

2.6.2 Oral Presentation - Obstacles

To sell your ideas to others, you should first be convinced that your ideas will accomplish the task. Oral presentation requires a high degree of creativity. Recall that humans resist changes, although they announce that they embrace it. Humans like familiar methods. Changes require additional efforts which humans, in general, resist. Some typical reactions one may hear include:

- We tried before.
- It is a too radical change.
- We have never done that before.
- Get back to reality.
- We have always done it this way.
- I don't like the idea.

The speaker needs to keep in mind that:

- Only 70% of the spoken word is actually received and understood. Complete understanding can come through repetition and redundancy in speech.
- People mostly understand three dimensional objects. Two dimensional projections need to be transmitted with added details.
- Usually people perceive problems from their own perspectives.
- Convey ideas so that they may be interpreted with the least expenditure of energy.

2.6.3 Oral Presentation Dos and Donts

1. Know your audience thoroughly. Deliver an extempore- prepared talk.
2. Never read from notes, a sheet or directly from an overhead projector.
3. Bring the audience up to the speed, in the first few moments.
4. Stay within the time allotted.
5. Include relevant humorous stories, anecdotes or jokes (Only if you are good at it).
6. Avoid using specialized technical jargon. Explain the terms if you feel the audience may not know.
7. Understand your message clearly. The entire goal is to clearly communicate the message.
8. Practice-practice-practice! You may like to memorize the introduction and concluding remarks.
9. The dry run is a dress rehearsal. Use it to iron out problems in delivery,organization and timing.
10. Avoid mannerisms: speak confidently but not aggressively.
11. Maintain eye-to-eye contact with some audience members, and keep shifting that contact through the talk.
12. Never talk to the board or to empty space.
13. Present the material in a clever fashion, but not in a cheap and senstional fashion. Be genuinely sincere and professional.
14. A logical presentation is much more critical in an oral one than it is in a written one.

2.6.4 Oral Presentation Techniques

1. Visual aids (sketches, graphs, drawings, photos, models, slides,transperencies, the Web) often convey information more efficiently and effectively. Visual aids permit the use of both the hearing and seeing senses, and they help the speaker.

2. Limit slides (Viewgraphes) to not more than one per minute.

3. Each slide should contain one idea.

4. The first slide should show the title of your talk and names.

5. The second slide should give a brief outline of the talk.

6. The last slide should summarize the message you just delivered.

7. If you need to show a slide more than once use a second copy.

8. Avoid leaving a slide on the screen if you have finished discussion on the topic.

9. Never read directly from the slide. Spoken words should complement the slides. Prepare notes for each slide and use them during practice.

10. Use graphs to explain variations. Clearly label the axis, data, and title. Acknowledge the source.

11. Every graph should have a message (idea). Color should enhance the communication, not distract from it.

12. Audiences respond to well organized information. That means:
    - (a) Efficient presentation.
    - (b) All assumptions clearly stated and justified.
    - (c) Source of information and facts are clearly outlined.

13. Begin with the presentation of the problem and conclusion/recommendation (primary goal).

14. Finish ahead and be prepared for the question/answer session.

2.6.5 Question/Answer session

The question/answer session is very important. It shows the enthusiasm of the audience and usually reveals interest and attention. In the Q/A session you should:

1. Allow the questioner to complete the question, before answering.
2. Avoid being argumentative.
3. Do not let the questioner feel that the question is stupid.
4. Adjourn the meeting, if the questions slack off.
5. Thank the audience one final time after the Q/A session.

2.7 Problems

2.7.1 Team Activities

Scheduling

1. Painting a two story house was broken down into a number of major jobs or activities as shown in the table 2.2 below:

Activity	Identification	Predecessor	Duration
Contract signed	A	–	2
Purchase of material	B	A	2
Ladder&staging in site	C	A	2
Preparation of surface	D	C,B	5
Base Coat Complete	E	D	6
Base Coat Inspected	F	E	2
Trim Coat Complete	G	E	5
Trim Coat Inspected	H	G,F	2
Final Inspection	I	H	2
Removal of staging	J	H	2
Final Clean up	K	I,J	2

Table 2.2: Team problem 1

   (a) Develop a CPM network.
   (b) Determine the critical path of the network.
   (c) Determine the expected project duration time period.

2. Assume that the optimistic, most likely and pessimistic activity times are as given in table 2.3 Team problem 2.

	Pessimistic	Most likely	Optimistic	Expected time	Variance
	3	2	1		
	3	2	1		
	3	2	1		
	7	5	3		
	9	6	4		
	3	2	1		
	7	5	4		
	3	2	1		
	3	2	1		
	3	2	1		
	3	2	1		

Table 2.3: Team problem 2

   (a) Fill up the table.
   (b) Find the probability of finishing up the job in 32 weeks.

3. You should work on this activity during the lab hours.
   (a) Develop a CPM network and determine the critical path for the events defined in the Gantt chart in figure 2.1.
   (b) Develop a Gantt chart for the events defined in the table 2.1.
   (c) For the events defined in table 2.4 below:
      i. Fill up the table.
      ii. Draw the PERT network.
      iii. Find the probability of finishing the task on time if the design due date is after 95 days.

   Material selction

4. In two opposite columns, list five uses of metals that are not appropriate for plastics and five uses of plastics not appropriate for metals.
5. From the table of mechanical properties of selected materials, list the differences between pure metals and metal alloys.
6. Based on the table, compare between Metals-Alloys/Ceramics/Plastics in terms of weight, strength, stiffness, and thermal expansion.
7. What is the difference between forging, casting and welding?
8. Choose the captain of your team to measure and record his anthropomorphic dimensions on the chart shown 2.6. In what percentile would you classify your captain?

2.7.2 Indvidual Activities

1. Define the following terms:
   (a) CPM
   (b) Gantt chart
   (c) PERT
2. Discuss four major classifications of material.
3. List the classifications of manufacturing processes.
4. Describe the following:
   (a) casting
   (b) forging
   (c) welding
5. Assume that an engineering course term project is broken down into a number of major jobs or activities, as shown in table 2.5 below.
   (a) Draw a Gantt Chart.
   (b) Develop a CPM network.
   (c) Determine the critical path of the network.

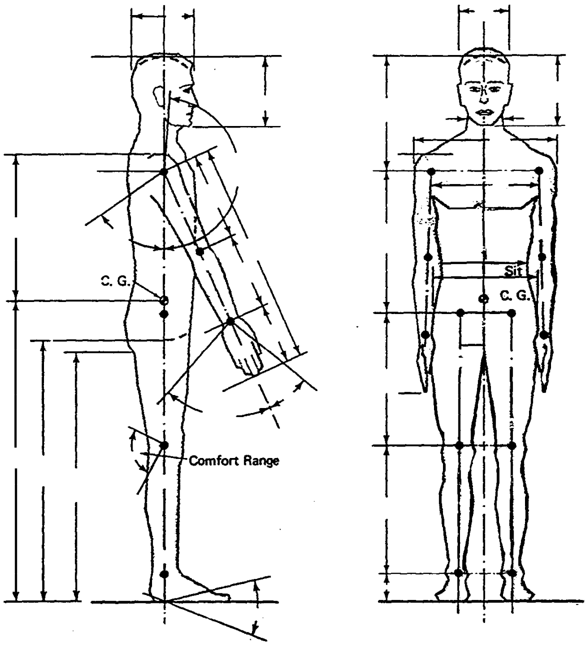


Figure 2.6: anthropometric chart

   (d) Determine the project duration time period.

6. Assume that, for example,the optimistic, most likely, and pessimistic activity times are as in table 2.6 below. Calculate each activity's expected time and variance, and the probability of accomplishing the design project in 32.5 weeks. In addition, calculate each event's earliest and latest event times.

7. Describe the following terms:

   - Ergonomics
   - Human error
   - Human reliability
   - Human engineering*Hint: Search in the library for more information.*

8. Consider that you have been assigned the task of designing the environment for an industrial worker who must be seated at a control console for four continuous hours each day. The worker monitors and controls plant and laboratory temperature and humidity. Describe (list) the types of environment that would be considered ideal for this operator.

9. Design an optimum display of controls, indicators and utility items listed below in the proposed dash layout, paying particular attention to human engineering principles. Where present dials and indicators are ineffective, redesign the display of information for effecient use by the human operator. Ask yourself the following questions about the information to be conveyed: Which is the most important? Least important? Which is the most often used? Least often used? What information must the indicator convey to the operator? Does it provide this information? Does it over-inform? Under-inform? What medium does it use? Most indicators are used visually and eyes are often overburdened in their functional useage. This would be critical in a high speed car. Could the same information be obtained by other means, such as light, sound, or touch?

	Indicators	Utility Items
	Speedometer	Glove Compartment
	Odometer	Radio
	Fuel	Cigarette Lighter
	Engine Temperature	Ventilation
signals	Battary	Rear view mirror
	Oil Prussure	
(starter)	High-beam Lights	

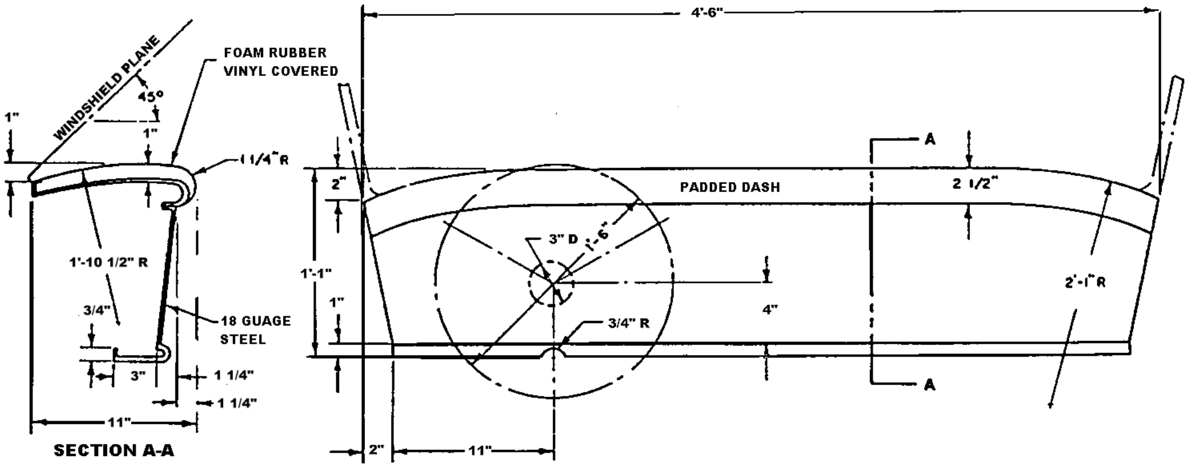


Figure 2.7: Proposed dash design layout

10. What is meant by each of the following terms:
    (a) elastic limit
    (b) yield point
    (c) ultimate strength
    (d) stiffness

11. What is the major requirement of a material if minimum deflection is required? Give an example.

12. What is meant by ductility? Suggest a method to measure ductility.

	Predecessor	Optimistic	Most likely	Pessimistic	Expected	Variance
	1	3	5	8		
	1	4	6	9		
	3	3	4	5		
	2	2	3	4		
	5	3	4	5		
	1	8	12	14		
	4	14	18	21		
	7	5	10	14		
	7	5	10	14		
	7	5	10	14		
	7	5	10	14		
	7	5	10	14		
	12	4	6	10		
	11	4	6	10		
	10	4	6	10		
	9	4	6	10		
	8	4	6	10		
	13	10	12	18		
	6	16	18	24		
	14	7	10	15		
	14	10	15	22		
	17	5	9	9		
	18	4	6	8		
	16	6	8	12		
	15	3	8	12		
	19	3	4	5		

Table 2.4: Team problem 3

Activity Description	Activity Identification	Immediate Predecessor activity	Activity Duration (days)
Literature Collection	A	-	7
Literature review	B	A	4
Outline Preparation	C	B	1
Analysis	D	B	10
Report writing	E	C	5
Typing	F	E	3
Revision	G	E	4
Final Draft	H	G	2

Table 2.5: Term Project

Pessimistic	Most likely	Optimistic	Expected time	Variance
4	2	1	2.16	0.25
3	2	1	2	0.11
4	2	1	2.16	0.25
8	5	3	5.16	0.7
5	4	2	3.83	0.25
7	4	3	4.33	0.44
5	3	2	3.17	0.25
5	3	2	3.17	0.25
9	6	3	6	1
7	4	2	4.17	0.69

Table 2.6: Activity Time estimates (weeks)

Chapter 3

Needs and Goals

3.1 Problem Definition: Need Statement

During the course of human development different kinds of needs existed. For instance, there has always been and always will be a need for improving and making new designs. Lincoln Steffenes wrote "The world is yours, nothing is done, nothing is known. The greatest poem isn't written, the best railroad isn't build yet, the perfect state hasn't been thought of. Everything remains to be done right, everything." [1]. The engineer is a person who applies scientific knowledge to satisfy humankind's needs.

One serious difficulty that engineers must overcome deals with the form in which problems are often presented to them. Even if some goals are given to the engineer, they are often not specifically stated. Problems may be presented as *"the shaft is breaking"*, *"the controls aren't producing the desired effect"*, *it costs too much to operate this engine."* Thus, the first task of the engineer involves determining the real problems which exist. Then, the engineer must determine the extent and confines of the goals.

It is necessary to formulate a clear, exact statement of the problem in familiar words and symbols. It is also necessary to isolate the problem from the general situation and to delineate its form. This definition should clearly identify every aspect of the problem on which attention should be concentrated. The non- essential should be stripped away, and the individual characteristics of the problem should be differentiated. It should be determined whether or not the immediate problem is part of the larger problem. If it is, its relationship to the total part should be determined. Let's consider the following example. A designer is presented with a situation involving formation of ice on a television tower. The ice would form during certain types of weather, fall away from the tower and cause damage to vehicles and people below. A general formulation of this problem might be: *How to prevent ice from forming on a television tower?* By asking such questions as, *What would happen if ice did form?* and *What harm would such formation do?* It was determined that the first definition was much too narrow. A much broader definition was, *How to prevent ice which forms on a television tower from doing harm or damage to people and equipment below the tower?*.

Before an engineer can define the problem properly he or she must recognize all the problems that exist. Most of the failures in machines do not occur because we make mistakes in analyzing the problem, but because we fail to recognize that there is a problem. For example, the first year maintenance cost for a paint drying oven was \$2000 (an oven whose original cost is \$1700). The high cost was due to the frequent dismantling of oil in bronze sleeve bearings mounted within the baking chamber. Once the problem was recognized the solution was relatively simple (mount the bearings outside the oven).

3.2 Objective Tree

An important step in design is clarifying the design objectives. This step is helpful in all design stages. The objective statement:

1. Should be easy to understand by the client and the designer.
2. Should be agreed on by the client and the designer.
3. Controls and manages the design.

The objective tree method offers a clear and useful format for the objective statement. It shows in a diagrammatic form the ways in which different objectives are related to each other. The objective tree method procedure was summarized by Cross [2] as:

1. Prepare a list of design objectives: These take the form of design briefs, prepared from questions to the client and from discussion with the design team.

2. Order the list into sets of higher level and lower level objectives. The expanded list of objectives and sub-objectives is grouped roughly into hierarchical levels.

3. Draw a diagrammatic tree of objectives, showing hierarchical relationships and interconnections. The branches in the tree represent relationships which suggest means of achieving objectives.

3.2.1 Worked Example

After the residents of Gotham city complained to their mayor about the city's water quality, he ordered the health unit to investigate the complaint. The health unit's recomendation was based on the chemical analysis done by the top chemist at the Department of Public Health. The task is now given to the City engineers to design water purifiers. Your task is to help them out and build an Objective Tree.

Solution

1. Prepare a list of design objectives:

    - Cost effective
    - Safety
    - Can detect chemical imbalance
    - Fewer repairs
    - Easy to repair when needed
    - Long lasting
    - Affordable
    - Low damage
    - Low or no contamination
    - Takes up least possible space
    - Safe for humans
    - Safe for environment
    - Gets the job done

- Can correct problems in least time
- Low maintainance
- Cleans high volume of water
- ...(fill up the blank)
- ...
- ...

2. Order the list into sets:

Safety	Cost Effective	Efficient
safe for humans	few repairs	can detect chemicals
safe for environment	easy to repair	long lasting
	affordable	low damage
	takes least possible space	get job done
	low maintainace	corrects problems in low time

3. Draw an objective tree 3.1.

3.2.2 Example: Automatic coffee maker

Build an objective tree for an automatic coffee maker.

1. Prepare a list of design objectives:
   - Safety
   - Efficient
   - Quality
   - Convenient
   - Easy to use
   - Fast
   - Makes good coffee
   - Doesn't burn user
   - Good mixture
   - Right Temperature
   - Splash Proof

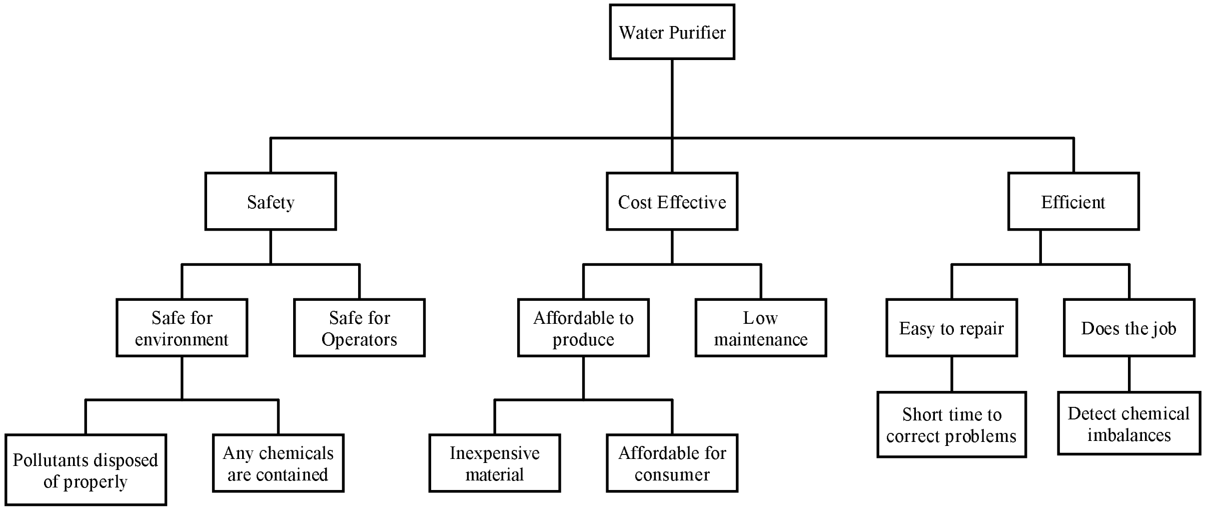


Figure 3.1: Objective tree for water purifier

Figure 3.1: Objective tree for water purifier

- Cheap to consumer
- Volume of coffee
- Automatic
- Timer
- Energy saver
- Temperature control
- Easy to Clean
- ...(fill up the blank)
- ...
- ...

2. Order the list into sets:

Safety	Quality	Convenient	Economical
to user	coffee tasts good	easy to clean	affordable
doesn't burn user	right temperature	automatic	volume of coffee
splash proof	good mixture	timer	energy saver
	temperature control		fast

3. Draw an objective tree 3.2.

3.2.3 Example: Automatic aluminum can crusher

We will use this example throughout the other chapters of this book. The example was offered as a design project for IME students during the spring semester of 1998. The project statement is given as:

Design and build a device / machine that will crush aluminum cans. The device must be fully automatic. i.e. all the operator needs to do is load cans into the device, the device should switch on automatically. It should crush the can automatically, eject the crushed can automatically and switch off automatically (unless more cans are loaded). Furthermore students should adhere to the following:

- The device must have a continuous can-feeding mechanism.
- Cans should be in good condition when supplied to the device (i.e. not dented, pressed, or slightly twisted).

Figure 3.2: Objective tree automatic coffee maker

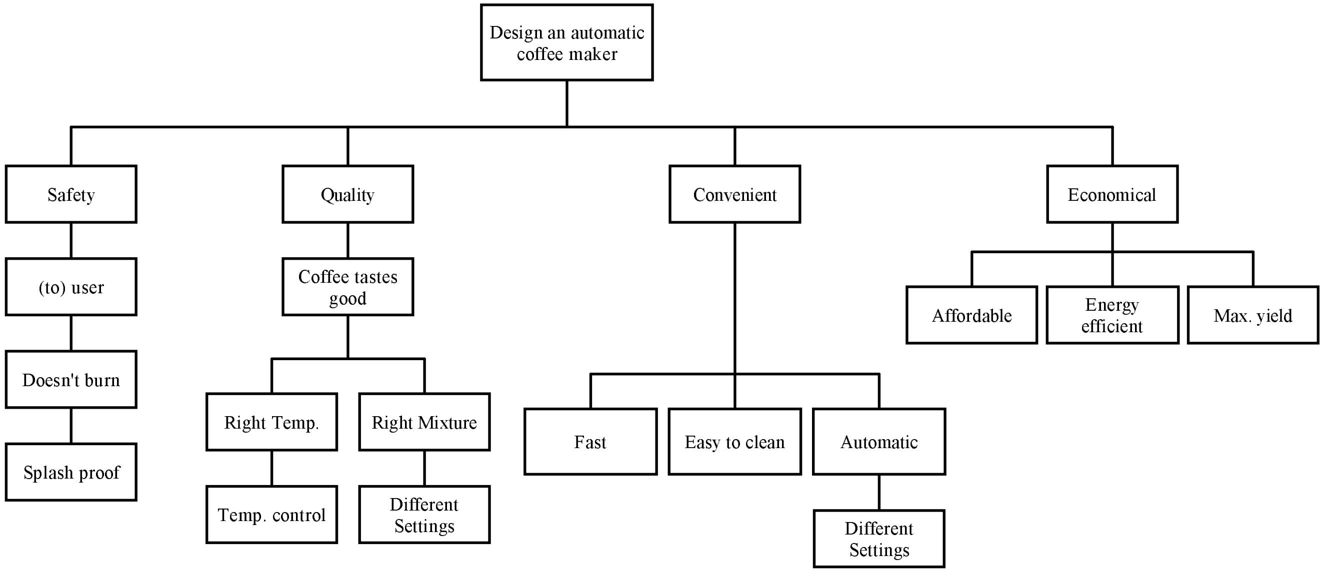


Figure 3.2: Objective tree for automatic coffee maker

- The can must be crushed to one fifth of its original volume.
- The maximum dimensions of the device are not to exceeed 1.5 x 1.5 x 1 feet.
- Performance will be based on the number of cans crushed in one minute.
- Elementary school children (K and up) must be able to operate the device safely.
- The device must be a stand alone unit.
- The total cost of the device should not exceed the given budget ($200).

Although the need statement is relatively clear, the design teams did several interviews with the client, asked questions, and carefully listened to the client's responses in order to clearly determine the goal of the intended device. Once the interview was completed, the engineering team met and constructed the following objective tree, which clearly states the goals and defines the directions of the device design. The following set of figures presents the objective tree of the automatic can crusher:

3.3 Problems

3.3.1 Team Activities

1. In this activity each group, as shown in the list below, asks as many questions as they can to clarify the given design statement:
    (a) Groups 1 and 9: Design a coffee maker.
    (b) Groups 2 and 10: Design a safe ladder.
    (c) Groups 3 and 11: Design a safe chair.
    (d) Groups 4 and 12: Design a safe lawn-mower.
    (e) Group 5: Design a coffee maker.
    (f) Group 6: Design a safe ladder.
    (g) Group 7: Design a safe chair.
    (h) Group 8: Design a safe lawn-mower.

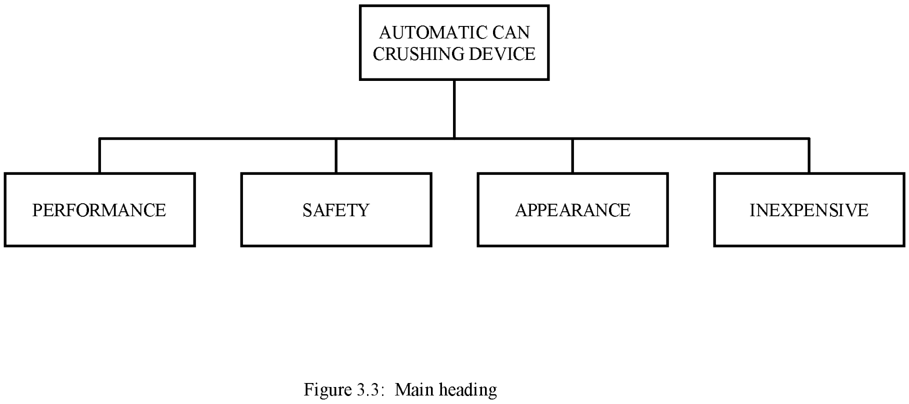


Figure 3.3: Main heading

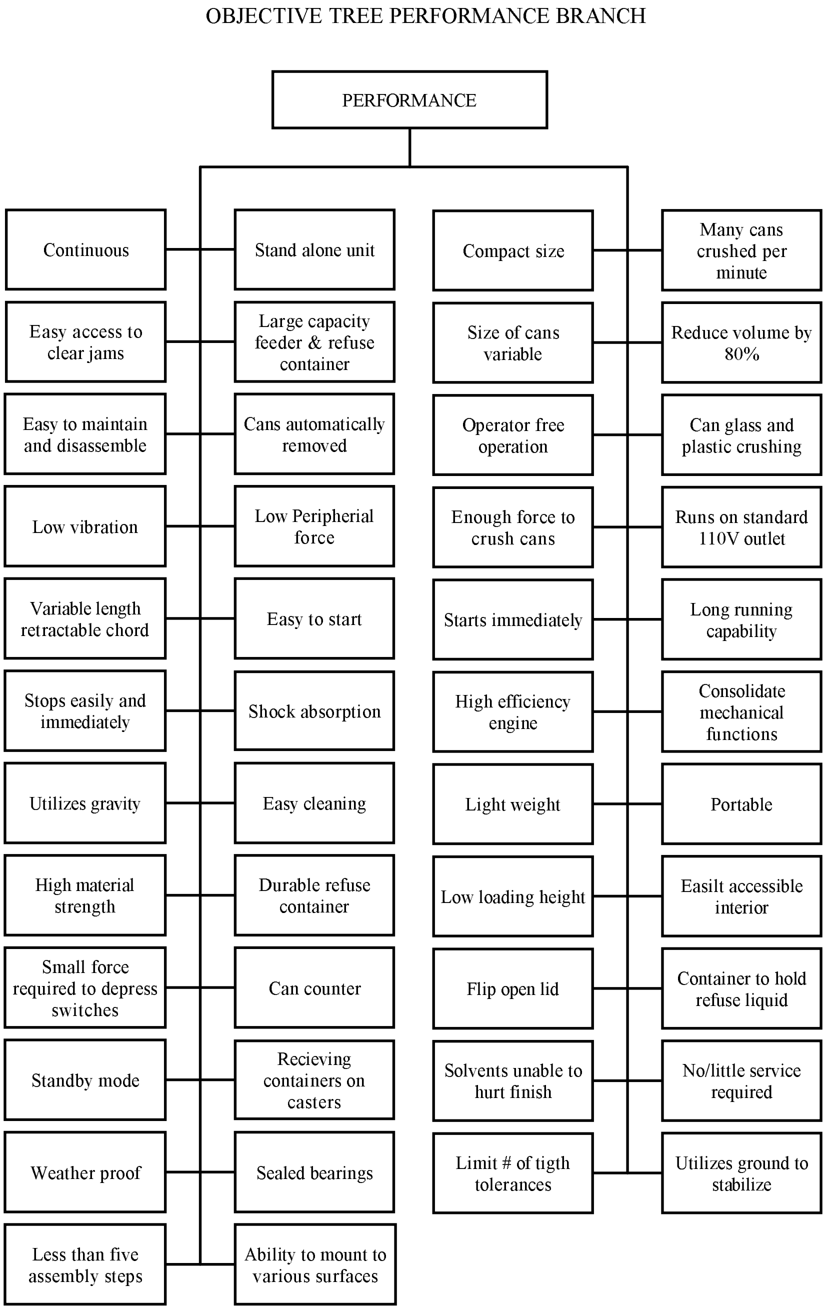


Figure 3.4: Performance branch

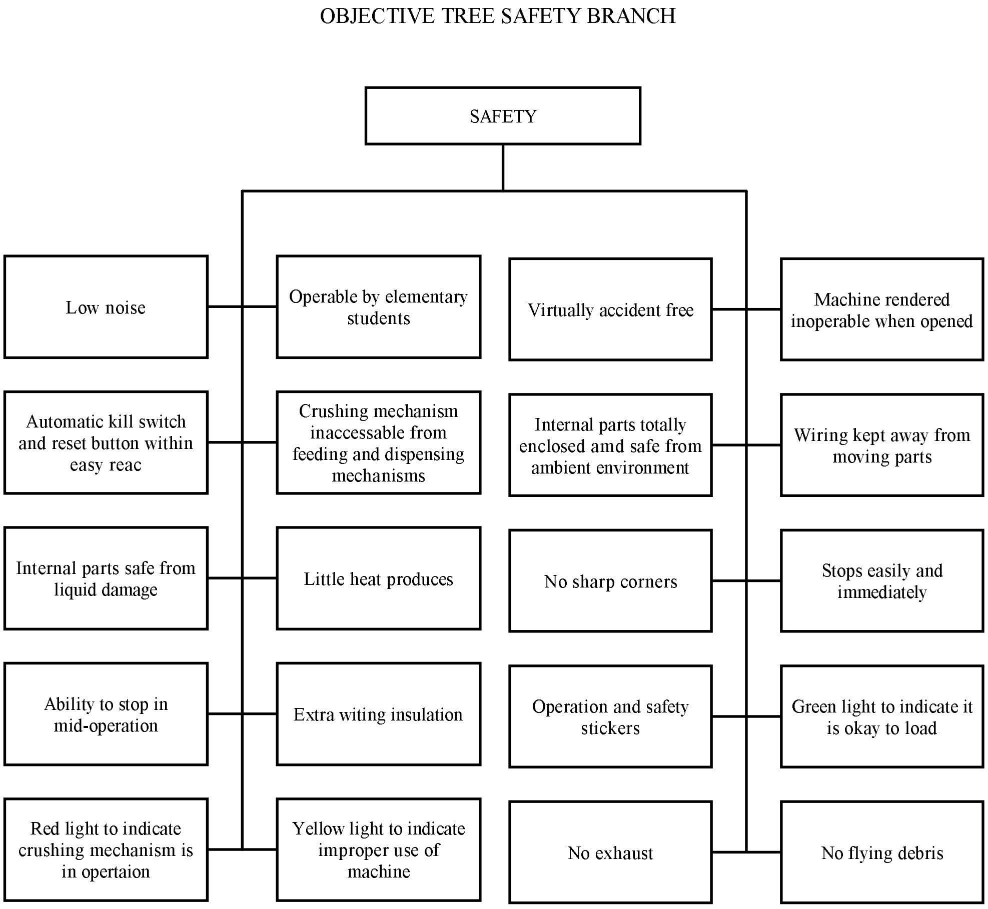


Figure 3.5: Safety branch

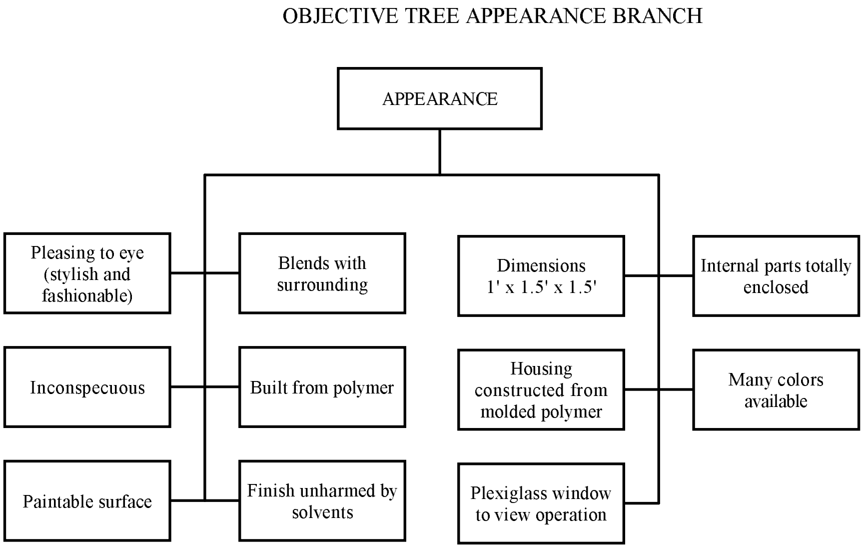


Figure 3.6: Appearance branch

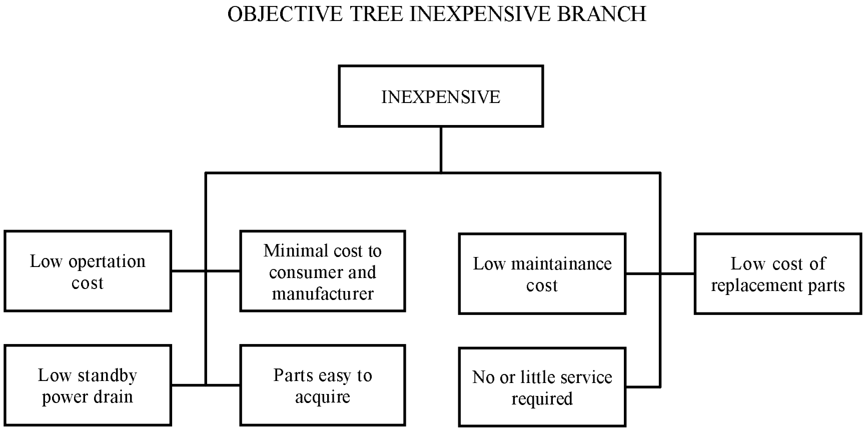


Figure 3.7: Inexpensive branch

2. Draw an objective tree for an automatic tea maker.

3. Draw an objective tree for the following:

   If you drive in the state of Florida, you may notice some traffic congestion due to the trees being trimmed on the state roads and freeways. Assume that the Florida Department of Transportation is the client. Usually, branches 6 inches or less in diameter are trimmed. The allowable horizontal distance from the edge of the road to the branches is 6ft. The material removed from the trees must be collected and removed from the roadside. To reduce the cost of trimming, a maximum of only 2 workers can be assigned for each machine. The overall cost, which includes equipment, labor, etc. needs to be reduced by at least 25% from present cost. The state claims that the demand for your machines will follow the price reduction, i.e., if you are able to reduce the cost by 40%, the demand will increase by 40%. Allowable working hours depend on the daylight and weather conditions.

4. Draw an objective tree for the following statement: We have a mountain-sized pile of wood chips that we want to process into home use fire logs. We are located in Tallahassee, Florida. We can have a continuous supply of wood chips throughout the year. We should be able to produce 50 fire logs per minute. The share holders require us to have a large profit margin and our prices should be lower than our competition for the same size logs. Needless to say the logs should preduce enough heat to keep our customers faithful, and have environmentally clean exhaust.

Chapter 4

Market Analysis and Information Gathering

[1]

In the design process, it is important to determine if a business opportunity exists for a new product before investing time and money to evolve the product. Most likely, products will fail when the market analysis only skims the surface. The analysis requires a thorough study of the total market. This includes its trend, competition, volume, profit, opportunities, consumer needs, and some indication of customer feeling for the product.

King [6] defines a market as a group of potential customers who have something in common. Two different techniques are employed in market analysis:

1. Direct search: this involves obtaining information directly from the consumer, manufacturers, sales people, etc. The information is collected by interviews and surveys.

2. Indirect search: the information is collected from public sources, such as patents, journal reports, goverment analysis, newspapers, etc.

The market search should be done in a systematic and objective manner for all information that is relevant to the product. It is important to remember that an unbiased oulook is necessary when analyzing the data, in order to formulate a market analysis report. Any biases will be will be reflected in the report's view of the market, and the results could be disastrous.

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[1] Information provided in this chapter are based on Suzanne Weiner work at MIT

4.1 How to Conduct a Market Analysis

Thousands of resources, it seems, all present some variation of the same information. However, it is never presented in the form you need. Before beginning any research project it is important to plan the process. Information collection is usually one of the first steps, and unfortunately it is often anticipated with the same enthuiasm as a root canal. For the engineering student, product/market research often requires the use of unfamiliar information sources and often produces huge quantities of information. It is important that engineering skills be applied when planning and dealing with this deluge. These skills include:

- critical thinking
- strategy
- analysis
- time management (...it always takes longer than you think.)

In the product development process, market research is conducted initially to assess market potential, market segments, product opportunities, provide production cost estimates, product cost, sales potential, industry trends and customer needs and expectations. The search has the following steps:

1. **Problem definition**

   Knowing what to look for is very important before one starts gathering information. This can be accomplished by answering questions similar to:

   - What is your product/idea?
   - Who is your customer, and why would they want/need to buy it? - time saver, utility, unique value.
   - How are you going to go about getting it to them? - development cost, time, manufacturing, production investment, etc.

2. **Develop a strategy**

   It is important to set a plan for the search process. Looking through every reference book in a library, merely hoping to find the right piece of information will inevitably lead to an inefficient waste of time. It is helpful to first identify what pieces of information may be needed, and to preliminarily select where to begin the search. Searching can be accomplished by:

(a) **Identify keywords**

It is also important to have some relevant terms with which to begin the search.

(b) **Writing a plan**

It is important to realize that the search process is not linear. For example: While searching the business literature for information on industry trends, one may come across the text of an interview that directly identifies some customer needs for the product under investigation. This information can be very useful if properly contextualized, thus it is important to know the framework within which one is working.

3. **Information Checklist**

The following list can be used in two ways: as a planning tool for information collection, or as a checklist for locating relevant information.

(a) Products
    - Product Names
    - Patents
    - Pricing
    - Parts Breakdown
    - Product Features
    - Development Time

(b) Companies
    - Major Players
    - Company Financials for Major Players

    i. Annual Reports

    ii. 10K Reports

(c) Industry

    - Trends
    - Labour Costs
    - Market Size
    - Industry Facts: pieces of information gained from various sources which help to clarify anything about the industry.

  (d) Market Information

    - Market Reports
    - Market Share of Major Companies in Industry
    - Target Markets of Major Competitors
    - Demographics:

    i. Age
    ii. Geographic
    iii. Sex
    iv. Political/Social/Cultural

  (e) Consumer Trends

4.2 Relevant Information Resources

There are literally hundreds of resources in which information may be located, but several stand out due to their superiority of scope, quality and overall usefulness.

The resources can be divided into three categories:

1. Industry;

2. Company; and

3. Market Information

Most of the journal databases will provide information relevant to all of these areas, and this should be kept in mind when searching and analyzing. This will also account for the repetition of some resources in all three areas.

4.2.1 Industry Information

It is essential to know information about the industry your company is considering entering. Who are the major players? What are the current trends? How large ($) are the relevant industries? What materials are used by the relevant industries? The following resources can provide access to information to answer these questions:

1. **Standard Industrial Classification (SIC) Code**
   Many business information sources are organized by the SIC Codes. The following publications are guides to these codes:
   (a) Standard Industrial Classification Manual

       The official U.S. government manual that provides SIC codes at the 2-digit and 4-digit levels.
   (b) Web version of the Code
       This provides access only by SIC category, not subject.
2. **Trade Associations**
   (a) Encyclopedia of Associations

       Gives address, telephone, and contact information as well as a brief description of trade and industry associations and their publications. Descriptions usually include dates/places for conferences and trade shows.
3. **Industry Overview**
   (a) Manufacturing U.S.A.: Industry Analyses, Statistics, and Leading Companies

       This annual publication provides statistical data on 459 manufacturing industries, including ratios and occupational data. State-level data are included.
   (b) Forbes

       Provides an Annual Report on American Industry in the first January issue of each year.

(c) Standard and Poor's Industry Surveys

Provides a textual analysis for 22 broad industry categories which are broken down into more specific subsets.

(d) Encyclopedia of American Industries

This publication is organized by SIC code with a list of related publications for each described industry.

(e) Moody's Industry Review

This statistical source contains key financial information, operating data, and ratios on about 3,500 companies. The information is arranged by industry, in 137 industry groups. The companies within an industry group may be compared with one another, and they may also be measured against certain averages for that industry. The statistics are updated twice each year.

(f) Predicasts Basebook

Dewey Library holding begin with 1977, but in the 1983 volume, the statistics go back to 1967, and are annual since 1970. This annual statistical source contains about 29,000 time series which are arranged by a proprietary 7-digit SIC code-based system. The data include economic indicators and industry statistics. The industry statistics usually include production, consumption, exports/imports, wholesale price, plant and equipment expenditures, and wage rate.

(g) Predicasts Forecasts

This quarterly statistical source provides short and long-range forecasts for economic indicators as well as industries and products. The data are arranged by a proprietary 7-digit SIC code-based system. Each forecast includes the date and page reference of the source from which the data are taken. The front of each annual cummulation has Composite Forecasts which present historical data for over 500 key series.

4. **Statistics**
   (a) Annual Survey of Manufacturers

       This survey supplements the Census of Manufacturers.

   (b) American Statistics Index (ASI)

       Indexes and abstracts statistics published by the U.S. Government

   (c) Statistical Reference Index(SRI)

       Indexes and abstracts statistics published by trade and industry organizations and state governments.

Company Information

Company sources provide information on the players within an industry. They provide information on the company financials, products (Primary & Secondary), brands/trade names, and other "nuggets" which, in context, can help with the overall market assessment and analysis.

When searching for company information it is important to determine whether the company is public or private. Public companies are required to register and file reports with the SEC while private companies are not. Generally, it is much easier to find information on public companies.

Directory of Companies Required to File Annual Reports with the Securities and Exchange Commission: Under the Securities Exchange Act of 1934

Examples of 10K reports on the web:

1. Example # 1: Allied Products Corporation
2. Example # 2: American United Global, Inc.

These contain information extracted from annual and 10K reports of over 12,000 public companies. The data is compiled into a standard format which allows for sophisticated manipulation of data and customized display formats.

Directories

1. Hoovers Corporate Directory
   Provides the company's name, street address, phone number, and fax

number; the names of the CEO, CFO, and HR Director; the most recently available annual sales figure; the percentage change in sales from the previous year; the number of employees; a description of what the company does; and the company's status (private or public).

2. Directory of Corporate Affiliations

   Lists over 4,000 parent companies with divisions, subsidiaries, and affiliates. Geographic and SIC indexes.

3. Duns Million Dollar Disc

   Lists over 160,000 U.S. businesses with net worth over $500,000. Can be used to identify companies by state, industry, or geographic location. Provides thumbnail bios of top executives for public and private companies and basic company information.

4. Standard & Poor's Register of Corporations, Directors, and Executives, v.1, Corporations

   Corporate addresses, telephone numbers, names and titles of officers, SIC codes, products, annual sales, and number of employees for 55,000 public and private companies. Volume 3 provides an index by SIC code.

5. Corporate Technology Directory

   Directory for High Tech companies with very specific product indexes. Provides basic company information.

6. Thomas Register of American Manufacturers and Thomas Register Catalog File

   Volumes 1-8 list companies arranged by products and services. Volumes 9 and 10 provide an alphabetic list of manufacturers with addresses, subsidiaries, products, asset estimates, and in volume 10 an index of brand names. Selected company catalogs are reproduced in volumes 11-16.

7. Nynex Yellow Pages

8. Ward's Business Directory

   Ward's is a good source for private companies. It provides information on 142,000 companies, 90 percent of which are private. Volumes 1 - 4 provide individual company information. Volume 5 ranks companies by SIC code.

Corporate Reports
Moody's manuals also provide detailed information on company history, subsidiaries, business and products, comparative balance sheets, stock and bond descriptions and more. Geographic indexes classify companies by industry and product. The data in Moody's manuals is obtained from Annual & 10K reports.

4.2.2 Market Information

Market information may be found in many places. The search for information should make use of the related industry, company and product keywords. This is true when using either a paper or an electronic source. Some buzz words include: market share; target market; demographics; and market potential.

Market research reports are ready made reports which have been commissioned by companies or industrial groups. They are compiled by one of several market research companies.

Market Research Reports

1. Findex
2. Frost & Sullivan Reports

Market Share and Other Information

1. Market Share Reporter

   Annual publication providing market share data for companies, products and industries.

2. World Market Share Reporter

   Annual publication providing market share information.

3. Statistical Abstract of the United States

   Statistics on the industrial, social, political and economic aspects of the United States. A great source for all types of useful statistical information.

4. Industrial Statistics Yearbook

   Industrial statistics published by the Dept. of Economic and Social Affairs, Statistical Office of the U.N.

Demographic Information

1. American Demographics

   This journal is searchable on ABI/Inform on FirstSearch.

2. State and Metropolitan Area Data Book

   Provides social and economic data for SMSA's, cities, states and census regions. US Bureau of Census.

3. Demographics USA, county edition.

   Contains information on purchasing power, consumption rates, economic conditions and population statistics.

4.3 Web Tools

At this time the Web, by itself, does not provide access to all of the resources one needs to conduct product/market research. However, there are some great sites that point you to the resources that are available. Some of these lists include:

1. Business Researcher's Jumpstation at http://www.brint.com/sites.htm
2. Marketing Resource Directory at http://www.ama.org
3. MIT Resource List at http://me.mit.edu/resources/

Web search engines are increasing in sophistication, as well as the Web sites of companies, distributors, industrial associations, and retailers. Therefore, it is quite valuable to spend some time sifting through some of the information available on the Web, as it is searched and compiled by one of the search engines.

4.4 Example

Consider the example of the Automatic Can Crusher. Here is a short summary of the market analysis.

4.4.1 Problem Definition

The client requested a device that is able to crush aluminum cans. The device must be fully automatic. All the operator will need to do is load the cans into the device. It will then switch on automatically, crush the can and switch off automatically. The device must have a continuous can-feeding mechanism. Cans must be crushed to one fifth of their original volume. The maximum dimensions of the device must not exceed $1.5 \times 1.5 \times 1$ feet. Performance will be based on the number of cans crushed in one minute. Elementary school children must be able to operate the device safely. The device must be a stand alone unit.

4.4.2 Potential Customers

1. Schools
2. Colleges
3. Hospitals
4. Hotels
5. Resorts

6. Shopping Malls
7. Playgrounds and recreational areas
8. Apartments-Dormitories
9. Sports arenas
10. Office buildings
11. Residential homes

4.4.3 Companies

1. Edlund Company, Inc. (159 Industrial Parkway, Burlington, Vermont). Mr. R. M. Olson (President)
2. Prodeva inc. (http://prodeva.com)
3. Enviro-Care Kruncher Corporation (685 Rupert ST. Waterloo, Ontario N2V1N7, Canada)
4. Recycling Equipment Manufacturer (N 6512 Napa, Spokane, Washington 99207)
5. Kelly Duplex (415 Sliger st. P. O. Box 1266, Springfield, OH 45501)
6. Waring Commercial (283 Main St., New Hartford, Connecticut 06057)
7. DLS Enterprises (P. O. Box 1382, Alta Loma, California 91701)

4.4.4 SIC Code

- food service industry 3556
- recycling 3599

4.4.5 Trends

The Aluminum industry produces 100 billion cans a year. This number has been flat for the past three years. In 1997, 66.8 billion of the cans were returned for recycling. This figure showed an increase of about 6.3 % over the 1996 figure. The industry collected 2.05 billion pounds of aluminum in 1997.

4.4.6 Market Information

Growth opportunities for aluminum beverage cans exist throughout the world. Global aluminum can shipments are forecasted to increase 5% annually to 209 billion by the year 2000. 74% of U. S. Beverage sales occured in the convenience stores, drugstores, clubs, mass merchandise, vending machines and grocery markets. For this product, the initial market is going to schools. Leon county public schools, at the high school level, have around 48,846 students.

4.4.7 Patents

Around 56 patents are listed for the past 10 years. A Web search using the IBM patent search will show the details.

4.5 Problems

4.5.1 Team Activities

1. How is the direct search different from the indirect search?
2. Define the Market analysis and discuss how is it different from information gathering.
3. Develop a strategy for your team to conduct the market analysis task.
4. Write a plan to conduct your market analysis.
5. Estimate the time required for your team to conduct the market analysis assignment.

4.5.2 Individual Activities

1. Perform a Web search and name three industries that change a product at a frequency of at least once each year.
2. How many patents were filled in the last 10 years on money sorters? List a few and identify their differences.

Chapter 5

Establishing Functional Structure

In the older design philosophies, once a need was identified a concept was directly developed into a product. However, this rather weak philosophy did not lead to quality designs, nor did it foster the use of the latest technologies. Designers have a tendency to take their first idea and keep refining towards a product design. Recall that, if you generate one idea, it is probably a poor idea; if you generate twenty you might have one good one. Since most of the customer's need is based on meeting a functional need, we need to generate a functional decomposition tree from the problem statement based on the objective tree.

Functional decomposition supports the divergent-convergent design philosophy concept. This concept requires that a design problem be expanded into many solutions before it is narrowed to one final solution. All design problems should be decomposed into the design of functionally independent sub-systems. In this chapter, we will develop techniques for decomposing any problem into smaller, more easily manageable parts by understanding the functions required of the device and treating each function as a separate sub-system.

Solution principles or designs based on conventional methods do not provide optimum designs when new technologies and discoveries are to be used. The crux of a problem should be expressed as a list of the required functions and essential constraints. Once the problem statement is defined, the next step is to determine the overall function, sub-function and sub-sub-function of the design problem. A given function can be represented in a block diagram based on the flow of energy, materials and information. The diagram expresses the relationship between inputs and outputs regardless of the solution within the box.

A complex, overall function describing the problem statement can be broken into a number of sub-functions, and many of the sub-functions can be divided into sub-sub functions. The division depends on the type of design system being considered. In original designs, neither the individual sub-functions, nor their relationships are clearly known. Hence, in such a case, a strong effort to search for and establish an optimum function structure is required. However, in adaptive designs, general function structure and the functional relationships between various components and systems are usually well established.

The lower levels of functions carry smaller levels of complexity, and should be simple to design. Function structures are of great importance in the development of modular designs. An important advantage of a function structure is that each of the components and systems can be examined individually and modified if needed. Function structures are very useful when designing and using design catalogs, because for every function, a task- specific component or system can be identified.

An example of function structure for a tensile testing machine is shown in Figure 5.1. A typical testing machine is shown in Figure 5.2.

Now let us look at an example of determining the functional structure of an existing design. Consider the case of a flow control valve. Each of the components of the valve, e.g., the spindle, the bearing bush, sealing bush, housing and threaded bearing bush, can be identified from the engineering drawing. The specific task of each of the components can be identified. Either individually or collectively, the components serve a specific sub-function and a main function, as seen in the following figure.

Some of the basic points in generating functional diagrams are as follows:

(a) From the requirements list, establish the main function, a few

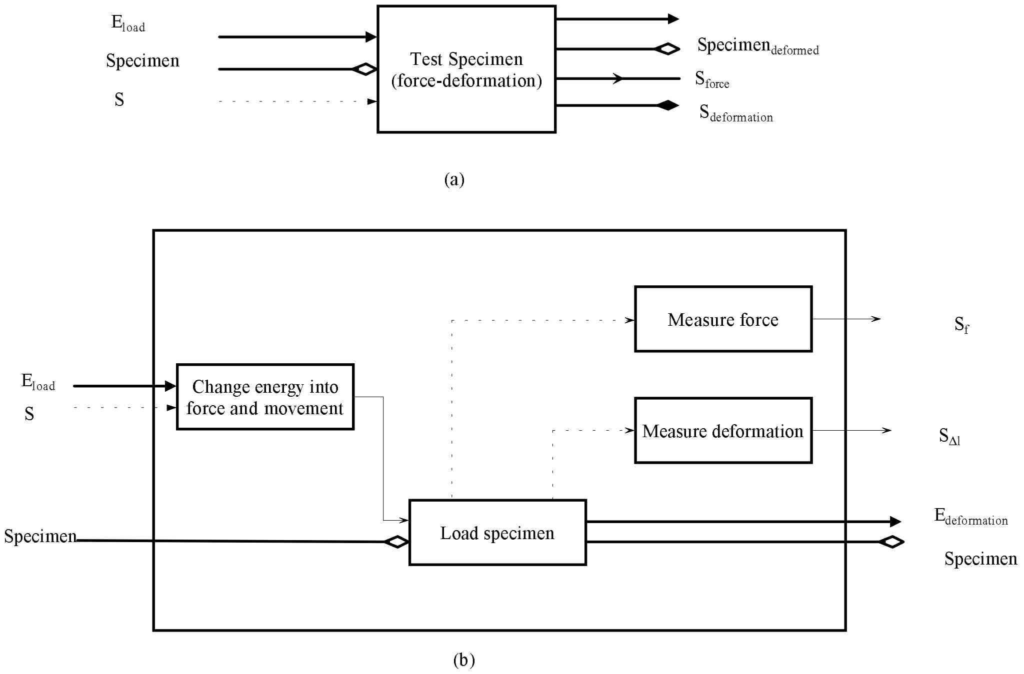


Figure 5.1: (a) Overall Fucntion (b)Subfunctions of a testing machine

Figure 5.1: (a) Overall Function (b) Sub-functions of a testing machine

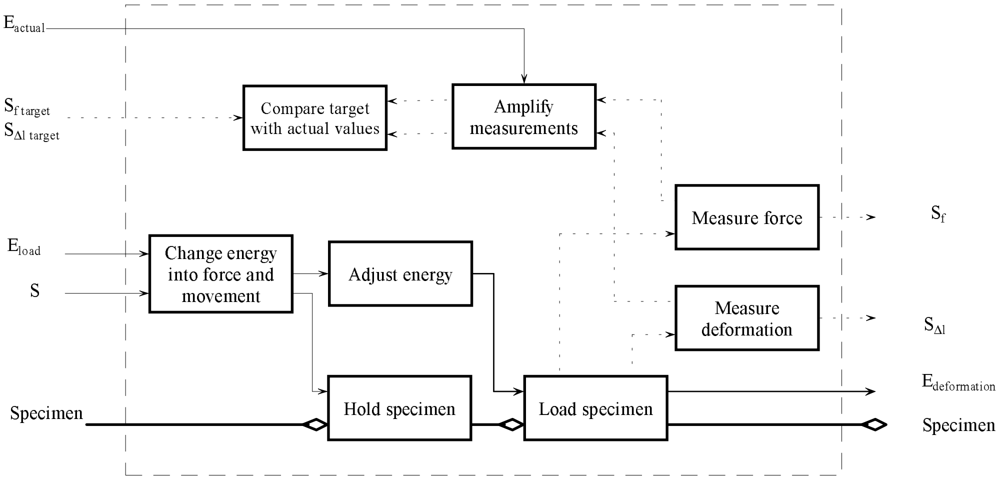
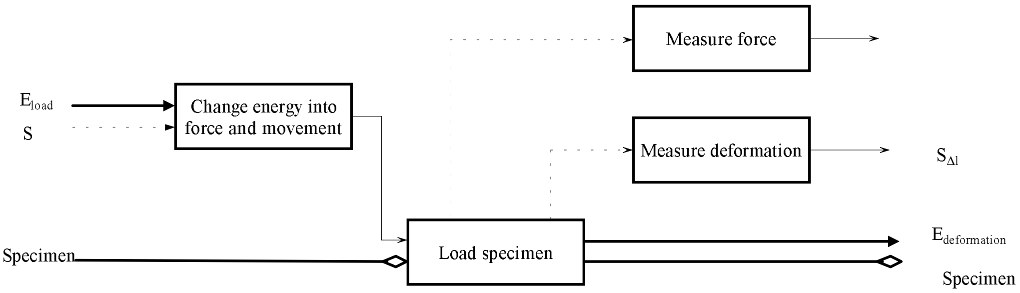


Figure 5.2 Completer function structure for the overall function set out in figure 5.1



(b)

Figure 5.1: (a) Overall Fucntion (b)Subfunctions of a testing machine

Figure 5.2: Completed function structure for the overall function set out in figure 5.1

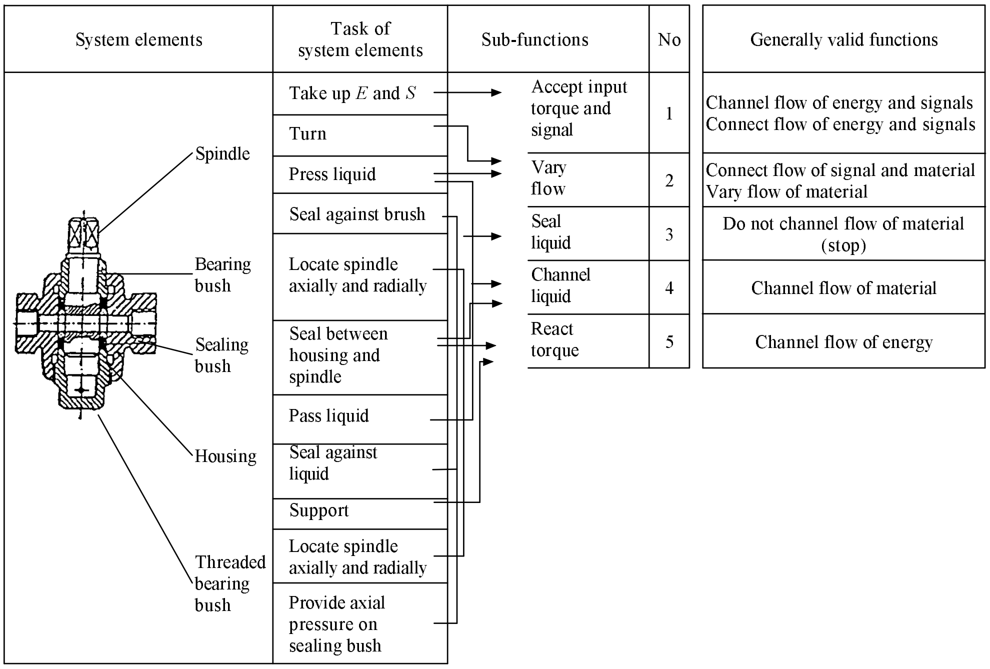


Figure 5.3: Analysis of a flow control valve in respect of its function structure

Figure 5.3: Analysis of a flow control valve in respect of its function structure

sub-functions, and some sub-sub functions for each of the sub-functions. A step by step break down at each level is needed.

(b) Arrange the sub-functions so that there is some relationship between them. Do not worry about the physical or logical relationship at this stage.

(c) Determine the flow of energy, materials, and information. Find the main and auxiliary flow of these three items.

(d) Establish a structure such that the main function is on top of the tree, branches into sub-functions and then repeats to sub-sub functions.

(e) Function structures should be kept as simple as possible. Simplicity leads to simple and economical solutions.

The primary purpose of function structures is to facilitate the discovery of solutions. Though the structure should not presuppose any solution, it is legitimate to conceive of a preliminary solution and abstract the solution. However, through a process of iteration, the structure should be made generic to prevent precluding new and innovative solutions.

Some task specific functions are:

- Conversion of energy:
  - Changing energy -e.g., electrical to mechanical energy
  - Varying energy components- e.g. increasing speed, torque
  - Storing energy- e.g. Storing potential or kinetic energy
  - Connecting energy with information- switch to start a motor
- Conversion of materials
  - Changing matter - e.g., melting (solid to liquid)
  - Connecting matter with energy - e.g. moving parts
  - Rearranging materials - e.g. mixing or separation
  - Storing materials- e.g. storing material in a silo
- Conversion of information
  - Changing signals- e.g. mechanical to electrical
  - Connecting information with energy- e.g. amplifying signals
  - Connecting information with matter - e.g. marking metals
  - Storing signals - e.g. data banks

5.1 Procedure

(a) Express the overall function for the design in terms of conversion of inputs and outputs.

The key is to determine what needs to be achieved by the new design, and how it is to be achieved. This can be accomplished by representing the product or device (to be designed) simply as a black box which converts given inputs to desired outputs. The black box specifies all the functions required to convert the input into output. It is important not to place any restrictions on the function. Such restrictions limit the solution space or system boundary. For example, the function push from A to B, restricts the solutions from ejecting, throwing, rolling, lifting, or even catapulting the object from A to B. Thus, it is important to widen the solution space or system boundary as much as possible.

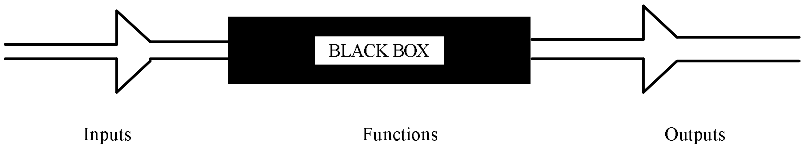
It is important to try to ensure that all the relevant inputs and outputs are listed clearly. As mentioned earlier, they can be classified as flows of materials, energy and information.

(b) Break down the overall function into a set of essential sub-functions.

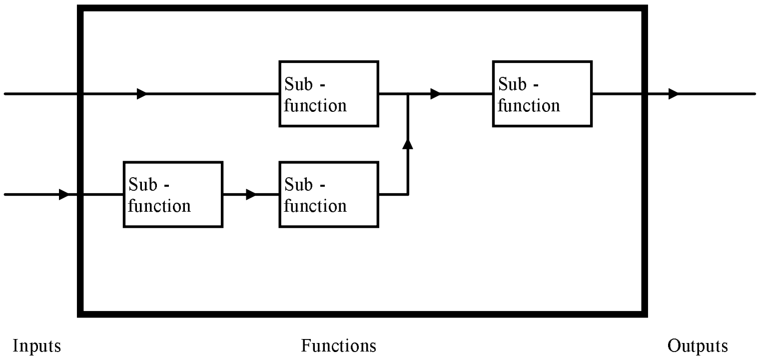
The conversion of the set of inputs into the set of outputs at the main function level is usually very complex. Thus the black box needs to be broken into sub-tasks or sub-functions. The break up depends on the experience of the designer, availability of components capable of performing specific tasks, and the latest technologies. In specifying sub-functions, it is necessary to express the task as a verb plus a noun- e.g., amplify signal, count items, decrease speed, increase diameter. Each sub-function has its own input(s) and output(s).

(c) Draw a block diagram showing the interactions between sub-functions.

A block diagram consists of all sub-functions separately identified by enclosing them in boxes. They are linked together by their inputs and outputs in order to satisfy the overall function of the product or device that is being designed. In other words, the original black box of the overall function is redrawn as a transparent box in which the necessary sub-functions and their links can be seen.



The 'black box' systems model



A transparent box model

Figure 5.4: The box diagram

When drawing this diagram we decide how the internal inputs and outputs of the sub-functions are linked together so that we may make a feasible working system. We may find that inputs and outputs may have to be juggled and perhaps redefined, and some sub-functions may need to be reconnected. It is advised that different types of lines (continuous, dotted and dashed lines) be drawn to indicate the different types of flows (material, energy, and information) within the block diagram.

(d) Draw the system boundary

In drawing the block diagram we also need to make decisions about the precise extent and location of the system boundary. For example, there can be no loose inputs or outputs in the diagram, except those that cross the system boundary.

The boundary now needs to be narrowed again because of its earlier broadening during the consideration of inputs, outputs and overall function. The boundary has to be drawn around a subset of the functions that have been identified in order to define a feasible product. It is also possible that the designer may not have complete freedom when drawing the system, since it may be restricted by the customer.

(e) Search for appropriate components for performing each sub-function and its interactions.

If the sub-functions have been defined adequately and at an appropriate level, then it should be possible to identify a suitable component for each sub-function. The identification of a component will depend on the nature of the product or device. For example, a component can be a mechanical, electrical or a combination device. A microprocessor based electronic device can substitute some older versions of electro-mechanical devices. Since function analysis method focuses on functions leaving the means to achieve them, new devices can be substituted even at later stages of design or development.

5.1.1 Example of a washing machine

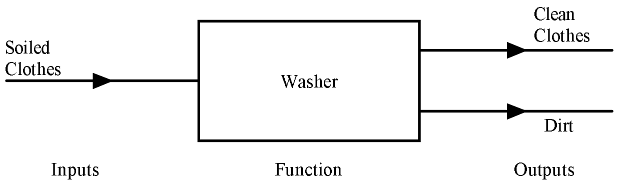
A simple example of the use of function analysis method is the design of the domestic washing machine. The overall function of the machine is to convert an input of soiled clothes into an output of clean clothes, as shown in figure 5.5.

Inside the black box a process that separates the dirt from the clothes must occur, and the dirt itself must also be a separate output. We know that the conventional process involves water as a means of achieving this separation. Thus, a further stage must be added to convert clean but wet clothes to clean and dry clothes. Even further stages involve pressing and sorting clothes.

The essential sub-functions, together with the conventional means of achieving them (for converting soiled clothes into clean, pressed clothes) would therefore be as follows: Essential sub-functions, Means of achieving sub-functions.

Loosen dirt	Add water and detergent
Separate dirt from clothes	Agitate
Remove dirt	Rinse
Remove water	Spin
Dry clothes	Blow with hot air
Smooth clothes	Press

The development of the washing machine involves progressively widening the system boundary, as shown in the figure. Early washing machines simply separated dirt from clothes, but did nothing to remove excess water from the clothes. The process of wringing the clothes dry was left to the human operator. The inclusion of a spin-drying function removed excess water, but still left a drying process. This process is now incorporated into a washer-dryer system. Perhaps the smoothing and ironing of clothes should be incorporated in future designs, in addition to the current process.



Black box model of a washing machine

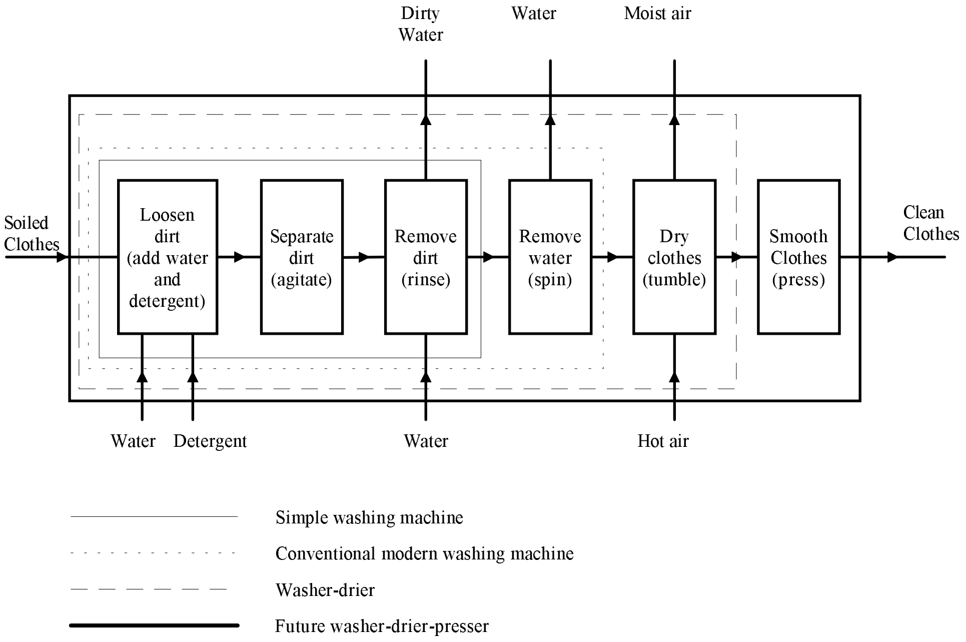


Figure 5.5: Function analysis of washing machine

Figure 5.5: Function analysis of washing machine

5.2 Functions

Some guidelines on identifying certain functions

Functions should consider what and not how, and they should break the functions down as finely as possible. Functional decomposition is represented as:
a box
an action-verb
an object on which the action-verb takes place (verb-noun combination)
known flow of materials, energy and information

5.2.1 Some examples of overall function

Consider the function of a splash guard system on a bicycle. The most important function is to:
protect the rider from water and dirt. The primary function of a chair is to seat a person.

Some of the essential features that should be considered are:
List all the alternative functions.
Include all the inputs and outputs.
For redesign problems, disassemble the sample to find functions.

5.3 Sub-function

The flow should be in a logical or temporal order.
Identify redundant functions and combine them.
Functions not within the system should be eliminated.

Specifically, there are flows associated with materials, energy and information. Some functions associated with the flow of materials are:

(a) Material can be designed to alter its position or shape. Usual action verbs are lift, position, hold, support, move, translate, rotate and guide.

(b) Material can be divided into two or more bodies. The action verbs are disassemble, and separate.

(c) Material assembly. Usual terms are mix, attach, and position relative to.

Functions associated with the flow of information are usually in the form of mechanical or electrical signals, or software.

Functions concerned with the flow of energy: The type of energy normally identified with electromagnetic system are mechanical, electrical, fluid and thermal. Energy of this type of can be supplied, stored, transformed, or dissipated.

5.4 Example

Let's refer to our example of an automatic can crusher. The design team reviewed the objective tree and their market analysis findings before they started structuring a function tree. They kept their minds open to all possible methods for accomplishing the stated goals. The function tree is shown in the figure below. 5.6

As shown in figure 5.6 the input is the aluminum cans and energy to crush the cans. The output of the system is crushed cans. A loader is utilized to input the cans into the system. The aligner will position the cans inside the device for crushing. A holder will fix the can in place during the crushing. An actuator will send a signal to the crushing device. Then, after the crusher, an ejector must remove the cans from the system.

5.5 Problems

5.5.1 Team Activities

Develop a function tree to produce a device that is capable of converting wood chips to fire logs.

(a) Express the overall function for the system.

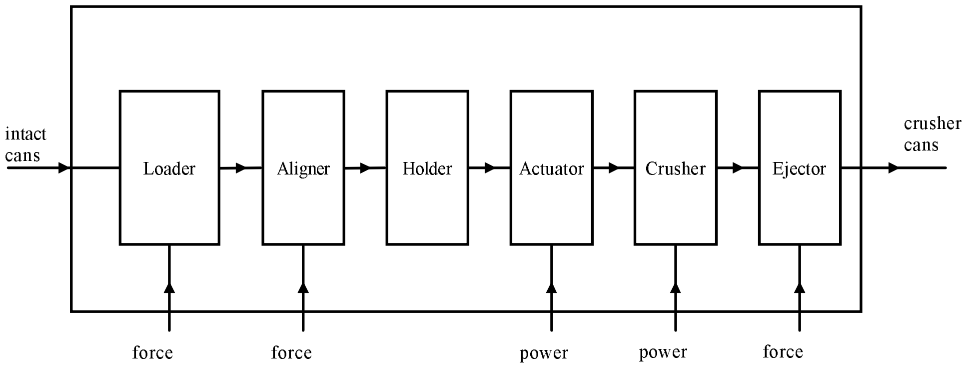


Figure 5.6: Function tree of the automatic can crusher

Figure 5.6: Function tree for the automatic can crusher

(b) Break down the over all function into a set of sub-functions.

(c) Draw a block diagaram showing the interactions between the sub-functions.

(d) Draw the system boundary.

5.5.2 Individual Activities

(a) Generate a function tree for a coin sorter device.

(b) Generate a function tree for a leaf removing device.

Chapter 6

Specifications

Specifications are highly important in order to provide a successful design. All engineering design problems are set within certain limits. Once a problem is defined and recognized clearly via the objective tree and the function structures, the development of detailed specifications becomes vital. The development of specifications may be considered the last step in defining the problem. The objective tree defines the vague statements that are generally introduced by the customer. But the objective tree and the structural functions do not set specific limits on the different functions and objectives. The objective tree or function structures are statements of what a design must achieve or do, but they are not normally set in terms of precise limits, which is what a performance specification does. For example, an objective may be stated to develop a product which has low weight. Yet, the term ”low weight” is not clearly defined. Does it mean 20 lb or 100 lb as low weight?

Based on the customer, the requirement may be well defined and the specifications well set. An example of such is found in the announcement from the National Inventors Council to design a stair climbing wheel chair. The announcement is as follows:

NATIONAL INVENTORS COUNCIL
U. S. DEPARTMENT OF COMMERCE
WASHINGTON, D. C. 20550

There is a great need for a STAIR-CLIMBING WHEEL CHAIR. The objective of such a chair is to give an active handicapped individual an additional range of mobility. The desired design should enable the individual to cope with the usual problems he or she might encounter when traveling to and from work, moving about industrial buildings, and the like. It must be remembered that the chair will perform the usual wheel chair function approximately 95conventional wheel chair's versatility and convenience should be sacrificed in order to provide the climbing function. In this connection, it might be valuable to point out that many active handicapped persons are able to fold a conventional wheel chair, put it in an automobile and drive to work. If this cannot be accomplished with a climbing chair, the overall objectives of providing the handicapped with independent mobility will not be achieved. The following factors are to be taken into consideration:

(a) WEIGHT OF OCCUPANT: Assumed to be 200 pounds.

(b) WEIGHT OF CHAIR: 50 to 75 pounds, maximum.

(c) COLLAPSIBILITY: Capable of being folded by user and stowed in the interior of a standard automobile or taxi cab. Special loading ramps which are not carried as a part of the chair system, or special modifications to the automobile to accommodate chairs will not be considered.

(d) WIDTH of CHAIR: 25 inches maximum. The American Standards Association utilized this width as the maximum for standard wheel chairs, when establishing architectural standards which provide the physically handicapped with freedom of movement in buildings and other structures. However, a lesser width for a chair, or a means of temporarily reducing the full open width for passage through narrow doorways, would provide a definite asset for negotiating door openings in private homes or other structures which do not conform the new standards.

(e) TURNING ABILITY: The turning radius should be held to a bare minimum. Turning should be accomplished without damage to floors or carpets. Chair must be able to negotiate an L or a U type stair landing. Ability to negotiate an L-type Landing as small as 3 ft by 3 ft would be considered an asset.

(f) CLIMBING ABILITY: The chair should be able to negotiate street curbing and any stair with average height risers and depth tread that is found in office buildings and homes. Ascent should be performed in presence of litter and moisture without damaging stair treads and risers. Any transition or adjustments required between normal and ascending and descending functions must be accomplished in a minimum time to eliminate delays at street curbing and stairways.

(g) PROPULSION SYSTEM: The chair may be propelled by the occupant or by a motorized unit; however, total cost, weight, and collapsibility requirements are the same for either type of drive. If self-driven, a minimum arm strength of 10 pounds may be used in devising drive mechanism.

(h) CHAIR SAFETY: The presence of an attendant, though undesirable, is permissible during ascent or descent. However, the chair occupant should always be in a reasonable state of balance, so that no more than 15 to 25 pounds of weight will be transferred to the attendant. The chair must be "fail safe" to prevent uncontrolled descent in the event something happens to the occupant, attendant, or mechanism.

(i) COST: In order for the maximum number of handicapped persons to be able to purchase a stair-climbing wheel chair, every effort should be made to keep its cost at a bare minimum. The retail cost should be no more than $200. Current models of standard tubular frame folding wheel chairs are priced at approximately $150.

(j) OTHER CONSIDERATIONS: Chair should be capable of performing all its normal functions without undue josting or jouncing of the occupant. Since most paraplegics have little control of the lower limbs, a method of retaining them in position is often required. The foot rests should be movable in order to enable the occupants to raise themselves to a standing position on the floor.

(k) The chair should not require the installation of special ramps, mechanical contrivances, or electrical outlets in buildings.

The above example has a clear statement with a clear set of requirements. Therefore, an objective tree, a function structure and even the market analysis may not be required because all necessary details and specific requirements are spelled out in the statement. This is not always the case, as a matter of fact 80-90% of the time, the statement given to the design engineer is very vague. For instance, it may simply say, "design a stair climbing wheelchair." In this case an objective tree, functional analysis and market analysis are needed to clarify the statement. The ability to write a good set of engineering specifications is proof that the design team understands the problem. There are many techniques for generating engineering specifications. Hubka [4] separates the properties affected by the constraints into categories based on operational, ergonomic, aesthetic, distribution, delivery, planning, design, production and economic factors. Pahl and Beitz [7] based the specifications on the fulfillments of the technical functions, the attainment of economic feasibility and the observance of safety requirements for the human and environment.

The approach that will be followed here to develop a set of requirements will be based on the performance specification method and the quality function deployment method. In the performance specification method, the specification defines the required performance instead of the required product. It also describes the performance that a design solution has to achieve, but not any particular physical component which may constitute a means of achieving that performance. In the quality function deployment method, the attributes of a required performance are translated into engineering characteristics.

6.1 Procedure for Performance Specification Method

The following are the steps in producing a set of specifications using the performance specifications method:

(a) Consider the different levels of generality of solution which might be applicable:

Specifications that are set at a too-high level of generality may allow inappropriate solutions to be suggested. However, too-tight specifications may remove all of the designer's freedom and creativity for the range of acceptable solutions. This level of limitation may also be connected with the definition of the customer you are dealing with, because the customer may also limit the class and the set of specifications. For example, designing a space shuttle puts the designer on a tighter limit of specification. Another example that may demonstrate this point involves the design of an air jet for civilian use. Such a design has a different set of requirements than designing an air jet for military use. Recognizing the customer's needs is an important factor in defining the range for the set of requirements.

Different types of generality levels can be listed from the most general to least general, and may be demonstrated as:

- product alternatives
- product types
- product features

Let us consider an example to illustrate these levels. Suppose that the product in question is a domestic aluminum can disposal. At the highest level of generality, the designer would be free to propose alternative ways of disposing of aluminum cans such as, crushing, melting, tearing, chemical deposing, etc. There might even be freedom to move from the concept of one-can to multi-can, or from domestic to factory. At the intermediate level, the designer would have much more limited freedom, and might only be concerned with different types of can crushers such as foot operated, or automatic can crushers. At the lowest level of generality, the designer would be constrained to only consider different features within a particular type of crusher, such as if it hangs on the wall or is self standing, processes one or multi-cans in one step, etc.

(b) Determine the level of generality at which to operate: In general the customer/client determines the level of generality at which the designer may operate. For example, the customer may ask the designer to design a safe, reliable aluminum can crusher. Here, the type of product has already been established by the customer, and the constrain is already placed on the type of aluminum can disposable unit: it must be a crusher. Hence, the set of requirements will follow for a can crusher, not a can disposable unit.

(c) Identify the required performance attributes. For clarifying the customer statement, the objective trees, function analysis and market analysis are used. The objective trees and functional analysis determine the performance attributes of the product. Some of the requirements in the customer statement are "must meet," (called Demands) and others are "desirable" (called wishes). Solutions that do not meet the demands are not acceptable solutions, whereas wishes are requirements that should be taken into consideration whenever possible. Pahl and Beitz [7] developed a checklist that can be used to derive attributes beside the objective trees and the function analysis. The checklist can be seen in figure 6.1.

Once the attributes are listed, it is recommended to distinguish whether the attribute is a demand or a wish, and then to tabulate the requirements.

(d) State succinct and precise performance requirements for each attribute: The attributes that can be written in quantified terms must be identified. The performance limit should be attached to the attribute. The limits may be set from the customer statement of the federal and government agency standard offices. These attributes may include, but are not limited to maximum weight, power output, size, volume flow rate, etc.

For the wishes, which cannot have a number attached to them, we use the quality function deployment method. The next section describes the quality function deployment method.

Example: Water Tap

Design a one-handed water mixing tap with the following requirements:

- flow-rate :10 l/min
- maximum pressure: 6 bar
- normal pressure : 2 bar
- hot water temperature: 60^oC

Main headings	Examples
Geometry	Size, height, breadth, length, diameter, space, requirement, number, arrangement, connection, extension
Kinematics	Type of motion, direction of motion, velocity, acceleration
Forces	Direction of force, magnitude of force, frequency, weight, load, deformation, stiffness, elasticity, stability, resonance
Energy	Output, efficiency, loss, friction, ventilation, state, pressure, temperature, heating, cooling, supply, storage, capacity, conversion.
Material	Physical and chemical properties of the initial and final product, auxiliary materials, prescribed materials (food regulations etc).
Signals	Inputs and outputs, form, display, control equipment.
Safety	Direct safety principles, protective systems, operational, operator and environmental safety.
Ergonomics	Man-machine relationship, type of operation, clearness of layout, lighting, aesthetics.
Production	Factory limitations, maximum possible dimensions, preferred production methods, means of production, achievable quality and tolerances
Quality Control	Possibilities of testing and measuring, application of special regulations and standards
Assembly	Special regulations, installation, siting, foundation
Transport	Limitations due to lifting gear, clearance, means of transport (height and weight), nature and conditions of dispatch.
Operation	Quietness, wear, special uses, marketing area, destination (for example, sulphurous atmosphere, tropical conditions).
Maintenance	Servicing intervals (if any), inspection, exchange and repair, painting, cleaning.
Recycling	Reuse, reprocessing, waste disposal, storage.
Costs.	Maximum permissible manufacturing costs, cost of tooling, investment and depreciation
Schedule	End date of development, project planning and control, delivery date.

Figure 6.1: Checklist for drawing up a requirement list

Figure 6.1: Checklist for drawing up a requirement list

- connector size: 10 mm

Attention must be paid to appearance. The firm's trade mark-e should be prominently displayed. Finished product should be marketed in two years time. Manufacturing costs should not exceed \$30, each at a production rate of 3000 taps per month. The specifications are shown in figure 6.2.

This example is a specification for a domestic water mixing tap that can be operated with one hand. The initial statement has been considerably expanded. Some details in the statement have been changed, for example, the maximum pressure as a result of establishing the national standards that apply to such a product. The range of users has also been taken into account, as have safety considerations. The demands (D) and wishes (W) have been distinguished in the left column.

6.2 Example: Automatic can crusher

In the design process, after the designers have created the objective tree and the function tree, it is important that the designers complete a table of specification. The designers must decide on the level of generality of the specifications. Market analysis results should be reviewed at this time. From the need statement, the specifications that *must* be met are:

(a) The design of the crushing mechanism is not to exceed $1.5 \times 1.5 \times 1 ft^3$ in the total size.

(b) The can crusher must have a continuous feed mechanism.

(c) The cans must be crushed to $\frac{1}{5}$ of its original volume.

(d) It must operate safely. It will be used by children.

(e) The device is fully automatic.

The designers came up with specifications that were ranked as wishes. Not all wishes have the same level of importance. Because of that, the design team gave a number for the rank of wishes. The figure below shows the specification table that the design team came up with for the automatic can crusher.

	Specification for one headed mixing tap	page 1

Changes	D or W	Requirements	Responsible
	D	1 Throughput (mixed flow) max. 10 l/min. at 2 bar	
	D	2 Max. pressure 10 bar (test pressure 15 bar as per DIN 2401)	
	D	3 Temp. of water: standard 60°C. 100°C (short-time)	
	D	4 Temperature setting independent of throughput and pressure	
	W	5 Permissible temperature fluctuation ± 5°C at a pressure of 1.00 ± 5 bar between hot and cold supply	
	D	6 Connection: 2 *x* Cu pipes, 10 *x* 1 mm, l = 400 mm	
	D	7 Single-hole attachment 0.35^{+2}_{-1} mm, (observe basis dimensions DIN EN 31 DIN EN 32 DIN 1368)	
	D	8 Outflow above upper edge of basin: 50 mm	
	D	9 To fit household basin	
	W	10 Convertible into wall fitting	
	D	11 Light operation (children)	
	D	12 No external energy	
	D	13 Hard water supply (drinking water)	
	D	14 Clear identification of temperature setting	
	D	15 Trade mark prominently displayed	
	D	16 No connection of the two supplies when the valve shut	
	W	17 No connection when water drawn off	
	D	18 Handle not to heat above 35°C	
	W	19 No burns from touching the fittings	
	W	20 Provide scalding protection if extra small	
	D	21 Obvious operation, simple and convenient handling	
		22 Smooth, easily cleaned contour, no sharp edges	
		23 Noiseless operation (≤ 20 dB as per DIN 52216)	
	W	24 Service free 10 years at about 300 000 operations	
	D	25 Easy maintenance and simple repairs. Use standard spare parts	
	D	26 Max. manufacturing costs DM 30 (3000 units per month)	
	D	27 Schedules from inception of development	

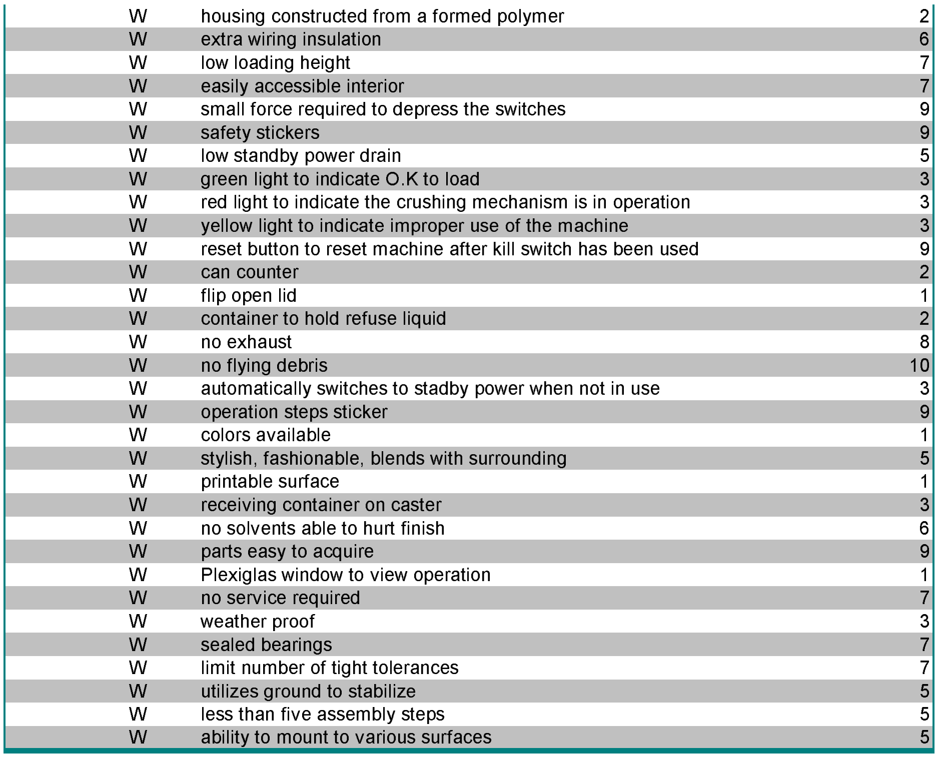
	Conceptual design	Embodiment design	Detail Design	Prototype	
alter	2	4	6	9	months

Figure 6.2: Specification for a one-handed mixing tap

SPECIFICATION TABLE

Changes	D or W	Requirements	importance (1=Low,10=High)
	D	dimensions 1'x1.5'x1.5'	
	D	continuous can feed mechanism	
	D	crush to 1/5 original volume	
	D	can be operated safely by elementary school students	
	D	stand alone unit	
	D	total manufacturing cost <= $200,000	
	D	ability to mount to various surfaces	
	D	automatic removal of crushed crushed cans	
	D	enough force to crush cans ~30 lbs ~72 J	
	D	wiring kept away from moving parts	
	W	Machine rendered inoperable when opened	10
	W	internal parts totally enclosed and safe from ambient environment	10
	W	crushing mechanism humanly inaccessible from feeder and dispenser	10
	W	runs on 110V standard US house outlet	9
	W	retails for < $50.00	3
	W	variable length / extractable cord	3
	W	enough force to crush glass, plastic	5
	W	internal parts safe from liquid damage	8
	W	large storage of crushed cans	3
	W	crushes plastic, glass and aluminum containers	2
	W	ability to crush various sizes of containers	3
	W	easily accessible kill switch	10
	W	large can capacity loader	4
	W	crush many cans/min.	8
	W	low noise output	7
	W	inconspicuous	5
	W	easy to disassemble	3
	W	easy access to clear jammed cans	6
	W	little heat produced	6
	W	no sharp corners	8
	W	easy to start	9
	W	starts up immediately	7
	W	long running capabiliy	9
	W	stops easily and immediately	8
	W	ability to stop in mid operation	10
	W	low vibration	8
	W	low peripheral force	8
	W	shock absorption	8
	W	high efficiency engine	9
	W	consolidate mechanical functions	5
	W	utilize gravity in design	8
	W	drain for residual liquid from machine	2
	W	easy cleaning	3
	W	light weight	3
	W	portable	4
	W	high material strenght	9
	W	durable refuse container	4
	W	built from a polymer	2

Figure 6.3: Specifcation table for automatic can crusher



	W	housing constructed from a formed polymer	2
	W	extra wiring insulation	6
	W	low loading height	7
	W	easily accessible interior	7
	W	small force required to depress the switches	9
	W	safety stickers	9
	W	low standby power drain	5
	W	green light to indicate O.K to load	3
	W	red light to indicate the crushing mechanism is in operation	3
	W	yellow light to indicate improper use of the machine	3
	W	reset button to reset machine after kill switch has been used	9
	W	can counter	2
	W	flip open lid	1
	W	container to hold refuse liquid	2
	W	no exhaust	8
	W	no flying debris	10
	W	automatically switches to stadby power when not in use	3
	W	operation steps sticker	9
	W	colors available	1
	W	stylish, fashionable, blends with surrounding	5
	W	printable surface	1
	W	receiving container on caster	3
	W	no solvents able to hurt finish	6
	W	parts easy to acquire	9
	W	Plexiglas window to view operation	1
	W	no service required	7
	W	weather proof	3
	W	sealed bearings	7
	W	limit number of tight tolerances	7
	W	utilizes ground to stabilize	5
	W	less than five assembly steps	5
	W	ability to mount to various surfaces	5

Figure 6.4: Specification table (cont.)

6.3 Quality Function Deployment Method (QFD)

The QFD method was first developed in JAPAN in the mid 1970's, and used in the United States in the late 1980's. Through the use of the QFD method, Toyota was able to reduce the cost of bringing a new car model to the market by more than 60%, and the time was reduced by about 33/The quality function deployment method is defined as the strategic arrangement (deployment) throughout all aspects of a product (function) of appropriate characteristics (quality), according to customer demands. Because the QFD recognizes that the person who buys a product is the most important person in determining the commercial success of a product, the QFD is essentially concerned with the translation of the customer requirements into engineering characteristics. Although the QFD method can be used for the whole design process, it will be used here for the wishes in the requirement list. The QFD method procedure is as follows:

(a) Identify the customer requirements in terms of product attributes. This can be done through market research techniques such as:

  - Product clinics: Customers are quizzed in depth about what they like and dislike about a particular product.
  - Hall test: Various competing products are arranged on display and customers are asked to inspect the products and give their actions.

  In the QFD, consumers are the most important factor and the design should be arranged in a manner to meet their satisfaction. The Kano model can be used to measure customer satisfaction. In the Kano model, customer satisfaction is measured by the product function as shown in figure 6.5.

  In the Kano model, there are three different types of product quality that give customer satisfaction: basic quality, performance quality and excitement quality. With basic quality, customers' requirements are not verbalized because they specify assumed functions of the device. The only time a customer will mention them if they are missing. If they are not fully implemented in the final product the customer will be disgusted with it. If they are

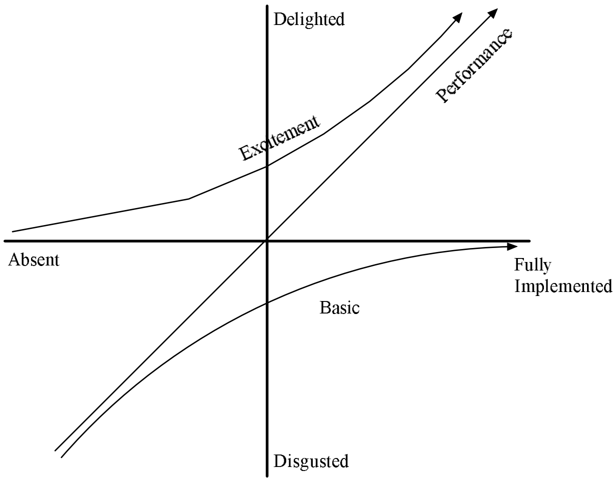


Figure 6.5: Kano Model for customer satisfaction

included, the customer will be neutral. An example is the requirement that a bicycle should have brakes. The performance quality refers to customers' requirements that are verbalized in the form that indicates, the better the performance, the better the product. The excitement quality involves those requirements that are often unspoken because the customer does not expect them to be met in the product. If they are absent, customers are neutral. However, if the customers' reaction to the final product contains surprise and delight at the additional functions, then the product's chance of success in the market is high.

(b) Determine the relative importance of the attributes: The demands are absolute requirements. The wishes, however, are not in the same order of importance. The customers are asked to rank these requirements in order, and hence generate an ordered list of required wishes. Then the design team allocates points to the various attributes.

(c) Evaluate the attributes of competing products: The objective here is to determine how the customer perceives the competition's ability to meet each of the requirements. Usually the customers make the judgments about the product in terms of comparison with other products. This step is very important because it shows opportunities for product improvement.

(d) Draw a matrix of product attributes against engineering characteristics: Attributes are in general vague and general, the characteristics are measurable, real and quantitative.

(e) Identify the relationship between the engineering characteristics and the product attributes: Each cell in the table represents how an engineering characteristic relates to the customer requirement. Many characteristics will measure more than one customers' requirements. The strength of the relationship can vary, with some engineering parameters providing strong measures for customers' requirements and others providing no measure at all. The relation is conveyed through numerical values such as:

  - 9=strong relationship
  - 3=medium relationship
  - 1=weak relationship

  - blank=no relationship
  - x=demand

(f) Identify any relevant interactions between engineering characteristics: Engineering characteristics may have relationships between each other. For example, a powerful engine is also likely to be a heavier engine. This interaction is added as a roof to the matrix. This is called the house of quality.

(g) Set target figures to be achieved for the engineering characteristics: to improve over competitors. The market analysis may be important at this stage to identify the market limits.

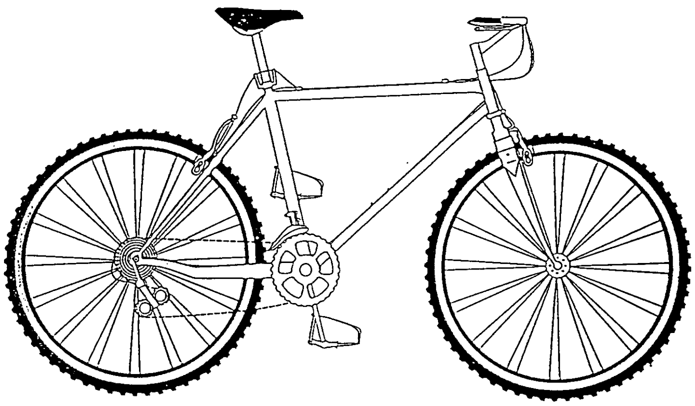
Example : Splashgard

This example is of a relatively simple product. Yet, it illustrates that considerable effort can be necessary in designing, in order to satisfy customer requirement, even for a simple product. The design team identified three important customers for the product: the rider, the mechanic and the marketing. The mechanics are considered customers because they will sell, and perhaps install, the Splashgard. Marketing is added to the customer list to ensure capture of production and marketing needs. Figure 6.6 shows a mountain bicycle and the customer's list of requirements for the Splashgard.

Figure 6.7 shows the house of quality that is developed based on the QFD method for a Splashgard.

6.4 Example: Automatic can crusher

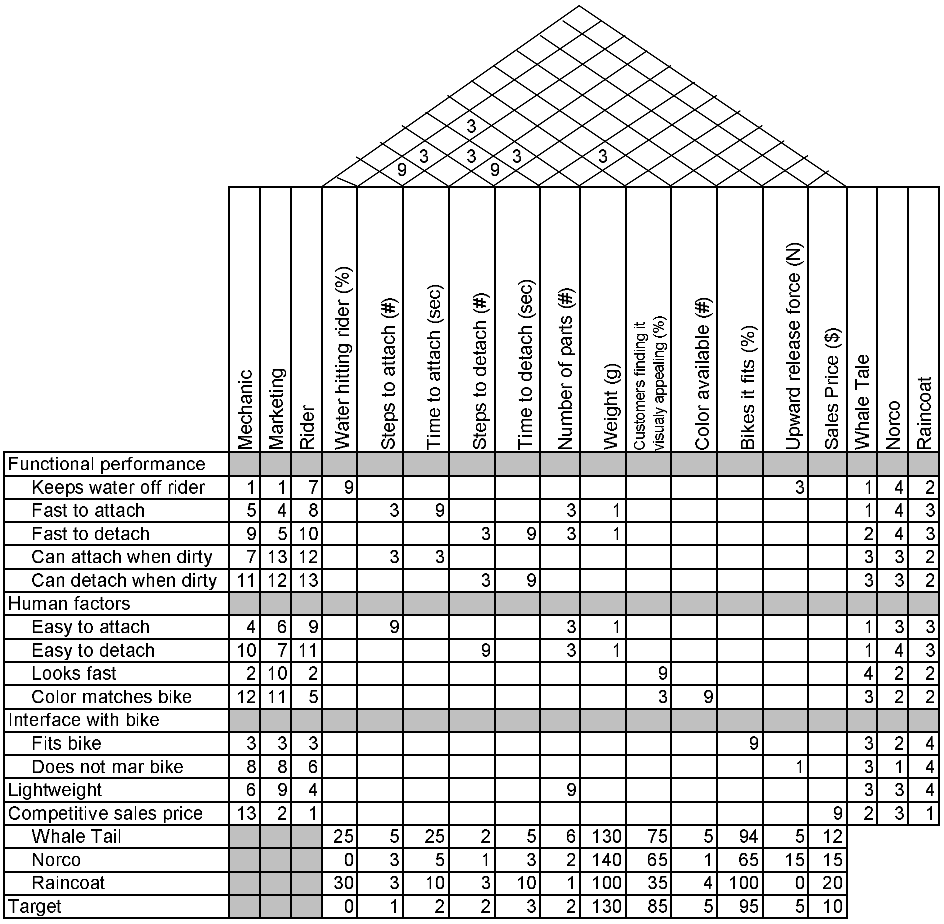
The design team has taken the wishes and objectives from the specification table and the objective tree and placed them into the house of quality. Because of the large number of wishes they listed on their table, they were unable to show the house of quality in one figure. However, two tables are shown below that represent the house of quality. On the first table, the wishes are placed with the engineering chracteristics, while on the second table, the engineering characteristics are evaluated against each other. The engineering characteristics are obtained by



Preliminary list of customers'
requirements for the splashgard

- Riders' and bike shop mechanics' requirements
  - Keeps water off rider
  - Is easy to attach
  - Is easy to detach
  - Is quick to attach
  - Is quick to detach
  - Won't mar bicycle
  - Won't catch water/mud/debris
  - Won't rattle
  - Won't wobble
  - Won't bend
  - Has a long life
  - Won't wear out
  - Is lightweight
  - Won't rub on wheel
  - Is attractive
  - Fits universally
  - If permanent piece on bike, then is small
  - If permanent piece on bike, then is easy to attach
  - If permanent piece on bike, then is fast to attach
  - If permanent piece on bike, then is noninterfering
  - Won't interfere with lights, rack, panniers, or brakes
- Company management requirements
  - Capital expenditure is less than $15,000
  - Can be developed in 3 months
  - Can be marketable in 12 months
  - Manufacturing cost is less than $3
  - Estimated volume is $200,000 per year for five years

Figure 6.6: Requirements for Splashgard



	Mechanic	Marketing	Rider	Water hitting rider (%)	Steps to attach (#)	Time to attach (sec)	Steps to detach (#)	Time to detach (sec)	Number of parts (#)	Weight (g)	Customers finding it visualy appealing (%)	Color available (#)	Bikes it fits (%)	Upward release force (N)	Sales Price ($)	Whale Tale	Norco	Raincoat
Functional performance																		
Keeps water off rider	1	1	7	9										3		1	4	2
Fast to attach	5	4	8		3	9			3	1						1	4	3
Fast to detach	9	5	10				3	9	3	1						2	4	3
Can attach when dirty	7	13	12		3	3										3	3	2
Can detach when dirty	11	12	13				3	9								3	3	2
Human factors																		
Easy to attach	4	6	9		9				3	1						1	3	3
Easy to detach	10	7	11				9		3	1						1	4	3
Looks fast	2	10	2								9					4	2	2
Color matches bike	12	11	5								3	9				3	2	2
Interface with bike																		
Fits bike	3	3	3										9			3	2	4
Does not mar bike	8	8	6											1		3	1	4
Lightweight	6	9	4						9							3	3	4
Competitive sales price	13	2	1												9	2	3	1
Whale Tail				25	5	25	2	5	6	130	75	5	94	5	12			
Norco				0	3	5	1	3	2	140	65	1	65	15	15			
Raincoat				30	3	10	3	10	1	100	35	4	100	0	20			
Target				0	1	2	2	3	2	130	85	5	95	5	10			

Figure 6.7: House of quality for the Splashgard

including a metric, a value and a unit. Numerical values between (1) and (9) are assigned between each wish and engineering characteristic to rank the corrolation between them. One is a very low corrolation and nine is a very high corrolation. Blank spaces correspond to no correlation.

6.5 Problems

6.5.1 Team activities

(a) Given the following need statement: Design a domestic heating appliance. Generate different levels of generality of solutions.

   i. Alternatives
   ii. Types
   iii. Features

(b) Generate engineering characteristics for the following:

   i. Easy to hold
   ii. Cost effective
   iii. Safe for the environment
   iv. Easy to maintain

(c) Consider the statement you worked on previously during an in-class team activity. By looking at your objective tree, generate a list of specifications and house of quality for the statement.

   If you drive in the state of Florida, you notice some traffic congestion due to the trees being trimmed on the state roads and the freeways. Assume that the Florida Department of Transportation is the client. Usually, branches 6 inches or less in diameter are trimmed. The allowable horizontal distance from the edge of the road to the branches is 6ft. The material removed from the trees must be collected and removed from the roadside. To reduce the cost of trimming, a maximum of only 2 workers can be assigned for each machine. The overall cost, which includes equipment, labor, etc. needs to be reduced by at least 25% from present cost. The state claims that the demand for your machines will follow

	probability of injury < 0.1 %	weight < 30 lbs	Sales Price < $50.00	Number of parts < 100	Dimensions (inch)	Crushing force > 30 lbs	People able to use > 5 yrs	Manufacturing cost <$200	Steps to operate (1)	maintenance cost < $10 annually	efficiency rating > 95 percentile	internal parts enclosed (100%)
easy access to clear jammed cans	3			6			3	3		3	6	
crushing mechanism humanly inaccessible	9	1	3	3	3		9	3				9
Machine rendered inoperable when opened	9		1	6			9	9				1
easily accessible kill switch	9		3	7			9	3	3			
ability to stop in mid operation	9		1	3			9	6	1			
no flying debris	9						9			1		6
runs on 110V standard U.S house outllet			6	3		3	9	9	6		9	
eay to start			3				9	6	6			
long running capabiliy			6	1			7			9	9	
high efficiency engine			6	1		9		9		9	9	
high material strenght		9	6			3		9		6		
small force required to depress the switches	9						9	3				
safety stickers	9						9	2	2			
machine reset button after kill switch activated	9			6			9	3	2			
operation steps sticker				6			9	3	9			
parts easy to acquire			6				3	9		9		
internal parts safe from liquid damage	2		4	4				3		9	6	9
crush many cans/min.			9	6	1	9	3	9			6	
no sharp corners	9						9	6				
stops easily and immediately	9			3			9	6	1	6		
low vibration		6		3	3	6		3		1		
low peripheral force		6		3	3	6		3		1		
shock absorption		6		3	3	6		3		1		
utilize gravity in design		9	3	6	9			9			1	
no exhaust	9		1	1			9					
low maintenance cost			6	6			8	3		9	6	1
low noise output	9		4	3			6	6				9
starts up immediately			3	5				3			6	
low loading height	6		1		9		9					
easily accessible interior	3		3				6	3		3		3
no service required			9	2			6			9	9	
sealed bearings								3				6
limit number of tight tolerances												
low operation cost			9	3			6	3		6	6	
easy access to clear jammed cans	6		3				3	3		6	3	3
little heat produced	1			1		2					9	
extra wiring insulation	6	1		1				1				
enough force to crush glass, plastic						9	6	9				
inconspicuous			6		6		6	3				

Figure 6.8: House of Quality

consolidate mechanical functions		3		9				6	2		9	
low standby power drain			1				3				9	
aesthetically pleasing/blends with surrounding			9	2	6		8	6				
utilizes ground to stabilize				1								
less than five assembly steps			3	6			3	1				
ability to mount to various surfaces		3	6		3		3	3				
large can capacity loader		3	6		3		3	3	6			
portable		9	6		3		6	3				
durable refuse container								3				
retail for < $50.00			9				9	9				3
variable length/retractable cord			3				2	1				
large storage of crushed cans		1	4		3		2	1	6			
ability to crush various sizes of containers			9	3	8		6	9				
easy to disassemble			3	6			3	3		6		
easy cleaning			6				3	1		3		6
green light to indicate O.K to load	9		6				9	2				
red light to indicate the crushing mechanism is in operation	9		6				9	2				
yellow light to indicate improper use of the machine	9		6				9	2				
automatically switches to stadby power when not in use											6	
receiving container on caster		2										
weather proof			1	3				3		6		9
crushes glass, plastic and aluminum containers			9	6	3	9	7	9				
drain for residual liquid from machine	1			1				1		6		
built from a polymer		6	6					6				
housing constructed from a formed polymer		6	6					6				
can counter			3	2			1	2				
container to hold refuse liquid		2										
flip open lid												
colors available			9				3					
paintable surface			8				2					
Plexiglas window to view operation			8					2				6

Figure 6.9: House of Quality (cont.)

storage of crushed cans (60 cans	loader capacity > 30 cans	crush >= 15 cans/min.	crush >= 1.2 x 10^{-2} m^3/min	crush >= 0.57 kg/min.	noise output < 30 dB	Starts < 10 sec.	runs > 2hrs at a tims	stops < 5 sec.	vibration magnitude < 5 mm	vibrations < 4/sec	withstand <= 250 N	maintenance < 4hrs/yr	# colors (6)	lifespan > 4000 hrs
		6	6	6								3		3
								1						
								9						
								9						
		1	1	1				9						
		6	6	6	3		1							
						9								
	1	2	2	2	3		9		2	1		9		9
		6	6	6	2				2	2		9		9
		1	1	1								6		9
						6								
												9		
												6		9
6	9	9	9	9	9	1	1		3	3				3
								9						
		9	9	9	9				9	9				3
		9	9	9	9				9	9				3
		9	9	9	9				9	9				3
					3				1	1				3
					1									
							6		6	6	7	9		9
		1	1	1	9		1		3	3				
		1	1	1		9								
	9													
		3	3	3				1				9		6
							3				6	9		9
												9		6
		3	3	3										
							6					9		3
		3	3	3				6				6		4
							3		1	1		1		4
														2
		9	9	9							9			
6	6								6	6			9	

Figure 6.10: House of Quality (cont.)

Figure 6.11: Engineering Characteristics

the price reduction, i.e., if you are able to reduce the cost by 40%, the demand will increase by 40%. Allowable working hours depend on daylight and weather conditions.

6.5.2 Individual Activities

A specification consists of a metric and a value. For example, "average time to assemble" is a metric, while "less than 75 seconds" is the value of this metric. Note that the value may take on several forms, including a particular number, a range or an inequality. Values are always labeled with the appropriate units. Together, the metric and value form a specification. The product specifications are simply the set of the individual specifications.

(a) Develop a list of specifications for the following objectives. The table should include metrics, the corresponding values (assume a value) and units.
   i. easy to install
   ii. reduces vibration to the hand
   iii. is not contaminated by water
   iv. lasts a long time
   v. is safe in a crash
   vi. allows easy replacement of worn parts

(b) List a set of metrics corresponding to the need that a pen writes smoothly.

(c) Devise a metric and a corresponding set for the need that a roofing material lasts many years.

(d) How might you establish precise and measurable specifications for intangible needs such as, "The front suspension looks great?"

(e) Can poor performance relative to one specification always be compensated for with high performance on the other specifications? Give examples.

(f) Develop a house of quality for the following need statment: " We have a mountain size pile of wood chips that we want processed into home use fire logs. We are located in Tallahassee, Florida.

We can have a continuous supply of wood chips through out the year. We should be able to produce 50 fire logs per minute. The share holders require us to have a large profit margin, and our prices should be lower than our competition for the same size logs. Needless to say the logs should preduce enough heat to keep our customers faithful, and have environmentally clean exhaust.

Chapter 7

Developing Concepts

So far we have developed methods to understand and define customers' needs as clearly as possible. We have used objective trees to expand on the needs and determine the various levels of goals. Functional trees were then used to address the different functions that need to be carried out in an hierarchical manner, to satisfy the needs. Then we drew up the specification chart based on what we needed to achieve, and what we needed to do to achieve them. The specifications that must be satisfied were classified as "must", and those that will simply enhance the product quality as "desired". However, specifications described what needs to be achieved in a measurable quantity rather than describing a qualitative desire expressed at the objective stage. The next step is to come up with more than one artifact that will satisfy the needs of the customer, taking into consideration the desires and wishes of the specifications. These concepts represent muliple solutions to the problem.

The generation of concepts is the central aspect of the design process. The mysterious process of generating an entirely new product is considered creative. The logical steps that we adapt rationalize the design process and provide opportunities for creativity. Though creative design can produce a revolutionary product, it is much more common that creativity is applied to the evolution of an exisiting product or system. Usually customers prefer the improved performance of a standardized product rather than a novelty. Making variations on established artifacts is therefore an important feature of design activity. This is the usual way in which creative thinking is put into use. In particular, creativity can often be seen as the rearrangement of exisiting components.

7.1 Visual Thinking and Creativity

Creativity is one of the most written about and controversial subjects. Since creativity is defined in a number of ways, there are many books that claim to suggest ways to improve it. To engineers, especially mechanical engineers, creativity means the act of solving a problem in a clever and novel manner. In design, this means seeing the product in an imaginative way, since the product can only be imagined. Visual thinking enhances the imagination, and written/oral thinking translates the imagination in a form that others can understand. Visual thinking pervades the entire spectrum of human society; for instance, mathematicians consider abstract space-time relationships, chemists construct new molecular models, pharmacists adapt a new catalyst in a drug, a professor concocts a new method of teaching through group learning, and a football coach dreams up a new offense strategy. Hence, visual thinking is not restricted to Picasso, Rembrant or Van Gogh. It is utilized by many people in the everyday activities of life.

Visual thinkers utilize seeing, imagining and drawing in an integrated and dynamic way to create solutions. With a visual understanding of a problem, well defined by the objective and functional structures and a corresponding specification, they imagine alternative solutions. Rather than committing the solutions to memory, they draw a few sketches which they later embody into a workable solution. Such solutions can then be compared to what they imagined as the goal, before modifications are iteratively made until the problem is solved.

Creativity depends on the process of thinking, which in turn depends on the interaction of thinking with observing, imagining and drawing. When Sir Alexander Fleming observed that the contamination of his samples was caused by bacteria, he went on to discover penicillin. Needless to say, many others discarded the same contamination as a nuisance and did not imagine the use in a different sphere. Similarly, a child playing with legos is imagining a solution while seeing the construction pieces.

The inner imagery of the mind's eye has played a central role in the thought processes of many creative individuals. Albert Einstein ascribed his thinking ability to imagining abstract objects. Kekule discovered the all-important structure of the benzene ring in a dream. Most visual thinkers clarify and develop their thinking with sketches. Drawing not only helps them to bring vague inner images into focus, it also provides a record of the advancing thought stream. Sketches expand the ability to hold and compare more information than is possible from simple recall from the brain. Sketches are usually extensions of thought, and they provide a conference table to talk to oneself.

Researchers have varied opinions about whether or not creative thinking can be taught. Some reports show that direct training in thinking can produce the advancement of thinking skills in significant increments. A number of thinking strategies can be taught, for example, the thinker who fluently produces a number of possible solutions to a problem is usually more successful than a thinker who settles for a one solution. Our traditional educational system which emphasizes the 3R's, usually ends up reducing or destroying the ability to appreciate imagination and mental visualization. Seeing, dreaming and drawing are essential to visual thinking and hence, to creativity. Contrary to common belief, seeing is an active art and not a passive experience. The common complaint that a person can lack imagination is baseless, because one who dreams does imagine, and everyone dreams. The fact that kids draw more than adults indicates that drawing is simply not encouraged among adults, and that drawing is not complex.

Visual thinking is not just thinking upon seeing. Seeing is more than sensing; seeing requires matching an incoming sensation with a visual memory. A knowledgeable observer sees more than a less knowledgeable companion since he or she has richer stock of memories with which to match incoming visual sensations. Recentering is seeing from a new perspective, abandoning familiar points of view, and fostering new ideas. In other words, making the familiar strange and strange familiar. One should develop the ability to break away from the "objective" reality, and move to a "subjective" level which will encourage the associative flexiblitity inherent in the creative art.

7.2 Developing Working Structures

Once the various functions at various levels are known, it is then important to find the principles working for each of the sub-functions. A working principle must be based on the physical affect needed to achieve the given function based on the flow of materials, energy and information within each function. Each function may be achieved in a number of ways. One important tool that can be effectively used is a design catalogue. Figure 7.1 shows the schematic of a design catalogue where each sub-function is shown in the left column and the many possible solution in the rows. Figure **??** shows an extract from a classification scheme for an impulse-loading rig. The first four entries are the functional requirements of energy conversions (electrical to mechanical, electrical to hydraulic, mechanical to mechanical and mechanical to hydraulic), the fifth is to store energy, the next is to control energy and the last to vary the component of energy. In some cases, there are as many as eight possible ways to achieve the same function. The general idea is to identify as many possible means to achieve the same functional requirement.

Another frequently occuring design situation involves using the same working principle, but changing the geometry or material combination (FORM) to enhance the functional requirement.

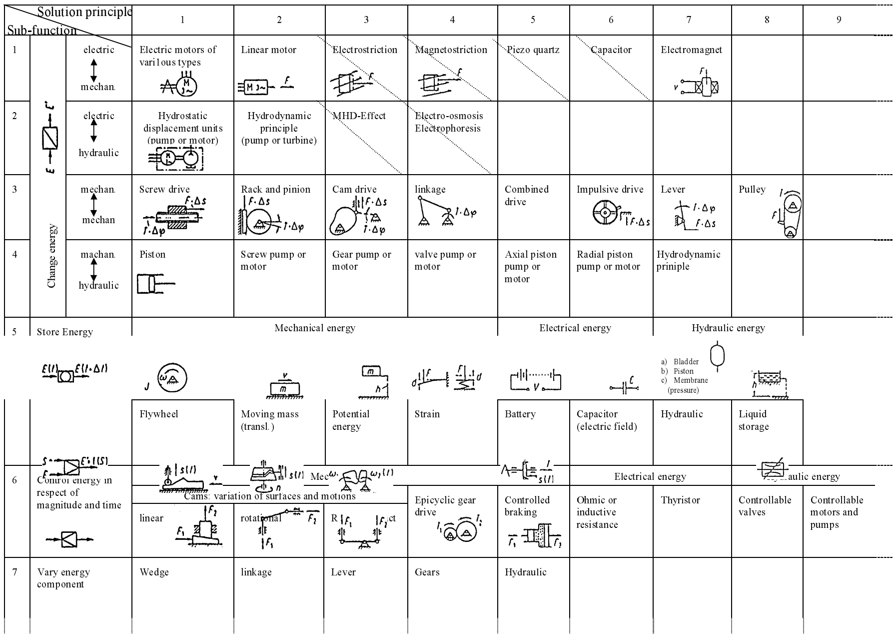
7.3 Steps to Develop Concepts from Functions

(a) Step 1: Developing concepts for each function.

The goal of this first step is to generate as many concepts as possible for each of the functions identified in the decomposition. There are two activities here that are similar to each other. First, for each function, develop as many alternative functions as possible. Second, for each sub-function the goal is to develop as many means of accomplishing the function as possible. In the earlier example, storing mechanical energy could be achieved using a flywheel, a translating mass or raising the mass, or as stored energy

Sub Function Solutions		1	2	...	j	...	m
1	F_1	S_{11}	S_{12}		S_{1j}		S_{1m}
2	F_2	S_{21}	S_{22}		S_{2j}		S_{2m}
:		:	:		:		:
i	F_i	S_{i1}	S_{i2}		S_{ij}		S_{im}
:							
n	F_n	S_{n1}	S_{n2}		S_{nj}		S_{nm}

Figure 7.1: Basic structure of a classification scheme with the sub-functions of an overall function and associated solutions



Sub-function		Solution principle	1	2	3	4	5	6	7	8	9
1	Change energy	electric ↕ mechan.	Electric motors of vari1ous types	Linear motor	Electrostriction	Magnetostriction	Piezo quartz	Capacitor	Electromagnet		
2		electric ↕ hydraulic	Hydrostatic displacement units (pump or motor)	Hydrodynamic principle (pump or turbine)	MHD-Effect	Electro-osmosis Electrophoresis					
3		mechan. ↕ mechan	Screw drive	Rack and pinion	Cam drive	linkage	Combined drive	Impulsive drive	Lever	Pulley	
4		machan. ↕ hydraulic	Piston	Screw pump or motor	Gear pump or motor	valve pump or motor	Axial piston pump or motor	Radial piston pump or motor	Hydrodynamic priniple		
5	Store Energy		Mechanical energy				Electrical energy		Hydraulic energy		
			Flywheel	Moving mass (transl.)	Potential energy	Strain	Battery	Capacitor (electric field)	Hydraulic a) Bladder b) Piston c) Membrane (pressure)	Liquid storage	
6	Control energy in respect of magnitude and time		Mec					Electrical energy		aulic energy	
			Cams: variation of surfaces and motions								
			linear	rotational	R ct	Epicyclic gear drive	Controlled braking	Ohmic or inductive resistance	Thyristor	Controllable valves	Controllable motors and pumps
7	Vary energy component		Wedge	linkage	Lever	Gears	Hydraulic				

Figure 7.2: Extract from a classification scheme for impulse-loading test rig label extract

inside a cantilever. Or, the mechanical energy can be converted into electrical energy and stored in the battery or in the capacitor. If there is a function for which there is only one conceptual idea, this function should be reexamined.

If there is a very limited idea, it may be due to the fact that the designer has made a fundamental assumption without realizing it. For example, one function typically encountered in attaching is to move in closely. If moving by hand is the only way, then the implicit assumption is that the part will be assembled manually. This may not be a bad assumption, except that it may not have a universal validity. The function may be indicated as how and not what. If the funciton is to roll on the rail, then the general concept of move has been specifically indicated to the movement along the rail. The designers may have a limited idea of other fields. It is generally important to keep the level of abstraction (details)at the same degree.

(b) Step 2: For each function or functions, list the means or methods to be used.

These secondary lists are the individual sub-solutions which, when one is combined from each list, form the overall design solution. These sub-solutions can also be expressed in rather general terms, but it is probably better if they can be identified as reak devices or subcomponents. For example, when you want to lift, you may like to use a ladder, screw, hydraulic piston or rack/pinion. The list of solutions should not only contain the known components but also any new or unconventional methods or solutions for achieving the specific task. Many brainstrorming or lateral thinking concepts can be employed in order to arrive at the solution. One should remember that many possibilities (at least three) are necessary for each function. Also when trying to identify artifacts for a given function, only that specific function or sub-function should be the criterion, not the overall function or whether the overall function is possible in that case. Those eliminations will be taken care of at a different time in the design process.

(c) Step 3: Draw up the chart containing all the possible sub-solutions. This chart is called the morphological chart.

The morphological chart is constructed from the functional list.

At first this is simply a grid of empty squares. The left hand column lists each function identified in the functional diagram. Across each row, it lists all means (methods)for achieving the function. On the left hand column, one each is entered in a square. As many methods as possible for each function should be entered. Once finished, the morphological chart contains the complete range of all different theoretically possible solution forms for the product. This complete range of solutions consists of the combinations made up by selecting one sub- solution at a time from each row. The total number of combinations is rather large. The list of methods should be kept to about five to keep the total solutions within a reasonable range.

(d) Step 5: Identify feasible combinations.

A list of concepts will be generated from the previous step for each function. The next step is to combine the individual concepts into complete conceptual designs. The method here is to select one concept for each function and combine those selected into a single design. Some of these combinations, probably a small number, will be existing solutions; some new solutions; and some (usually a great number) impossible solutions. It is necessay to identify potential solutions for further consideration. One or more of those better solutions, for reasons of cost, performance or novelty will be explored for further development.

7.4 Sources of Concept Ideas: Techniques to Enhance Creativity

Dreaming up new ideas is an enjoyable experience. If the idea is translated into an artifact that works as desired, the designer takes great pride in his or her creativity. It may turn out that the idea may not be entirely new; since there is never a unique way of finding out whether a similar idea has ever been used.

Patents can serve as an excellent source of ideas. However, it is difficult to identify the specific patent that contains the idea that you are looking for. There are two main types of patents: utility patents and design patents. Utility patents deal with how the idea works for a specific function. Design patents only cover the look or form of the idea. Hence, utility patents are very useful since they cover how the device works, not how it looks. Since there are about five million utility patents, it is important to use some strategies in order to hone in on the one that you may be able to use. Use the class and subclass concept to identify the artifact of interest. Figure **??**, shows the class/subclass structure for a bicycle and some components that go in the bicycle.

The next obvious place to find information is in reference books and trade journals in the relevant area.

Another obvious information source is consulting experts. If designing in a new domain, we have two choices for gaining the knowledge sufficient for generating concepts. We either find someone with expertise in that time, or spend time gaining experience on our own. Experts are those who work long and hard in a domain, performing many calculations and experiments themselves to find out what works and what does not. If we cannot find one or afford one, then the next best source is the manufacturer's catalogue or manufacturer's representative. One of the ways to identify who the manufacturers are is by using catalogues, such as the Thomas Register, or in current technology on-line searches.

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

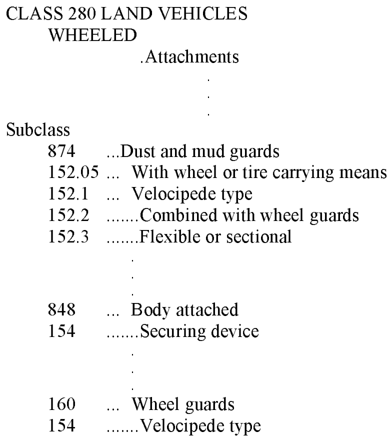
(a) Record all ideas. That is the role of the recorder.

(b) Generate as many ideas as possible, then verbalize these ideas.

(c) Think wild. Silly, impossible ideas sometimes lead to useful ideas.

(d) Do not allow the evalution of ideas at this time. It is time for generation of them. This rule is very important. Ignore any evalution, judgement, or other comments on the value of an idea.

It is very imporant to encourage humor and a relaxed atmosphere during brainstorming, only then can ideas flow freely.



CLASS 280 LAND VEHICLES
WHEELED
.Attachments
.
.
.
Subclass
874 ...Dust and mud guards
152.05 ... With wheel or tire carrying means
152.1 ... Velocipede type
152.2 ....Combined with wheel guards
152.3 ....Flexible or sectional
.
.
.
848 ... Body attached
154 ....Securing device
.
.
.
160 ... Wheel guards
154 ....Velocipede type

Figure 7.3: From Manual of classification under class 280 labelmanclass

7.5 EXAMPLES

Example of a Potato Harvestor

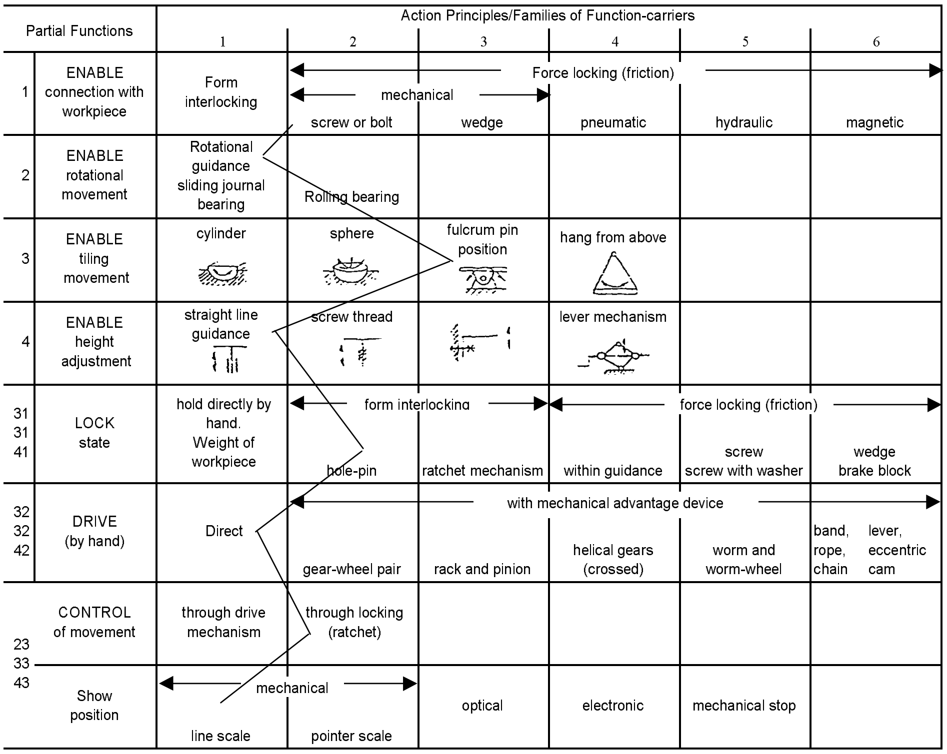
Consider the case involving a design need to improve a potato harvesting machine. The figure shows the morphological chart for the problem. It is presumed that objective tree, functional tree and specification have already been identified for the problem. In the functional decomposition (based mainly on the flow of material) lift, sift, separate leaves, separate stones, sort potatoes and collect have been identified as the sub-functions. Accordingly, the six functions are entered on the left hand column of the chart. Each row represents a specific function. For example, row 2 is the function "sift", and we need to find means to achieve the function of sifting. The chart shows four different means or methods to achieve it, using sifting belts, sifting grids, sifting drums or sifting wheels. They are entered using words and diagrams in each of the four sqaures following the sift square.

The chart thus contains the six functions and 4, 4,3,4,4,3 ways of achieving each function. Thus, theoretically there are 2304 possible different potato harvesting machines, combining the various means. However, many of them are not viable. A machine that uses 3,1,1,2,3,1 methods is a possible solution. At least four to five of such combinations will be identified for building the system.

7.5.1 Automatic can crusher

The design team now lists all the functions that must be accomplished. Then they generate a matrix that has the functions on the right column, and they pointed out different ways to acheive these functions. It should be emphasized, here, that creativity should be exerised during this activity. One may list the different possibilities in text or in sketches. Both methods are exercised in this situation. The available power sources are:

- Hydraulic
- Magnetic
- Gravity



Partial Functions		Action Principles/Families of Function-carriers 1	2	3	4	5	6
1	ENABLE connection with workpiece	Form interlocking	Force locking (friction)				
			mechanical				
			screw or bolt	wedge	pneumatic	hydraulic	magnetic
2	ENABLE rotational movement	Rotational guidance sliding journal bearing	Rolling bearing				
3	ENABLE tiling movement	cylinder	sphere	fulcrum pin position	hang from above		
4	ENABLE height adjustment	straight line guidance	screw thread		lever mechanism		
31 31 41	LOCK state	hold directly by hand. Weight of workpiece	form interlocking		force locking (friction)		
			hole-pin	ratchet mechanism	within guidance	screw screw with washer	wedge brake block
32 32 42	DRIVE (by hand)	Direct	with mechanical advantage device				
			gear-wheel pair	rack and pinion	helical gears (crossed)	worm and worm-wheel	band, rope, chain lever, eccentric cam
23 33 43	CONTROL of movement	through drive mechanism	through locking (ratchet)				
	Show position	mechanical					
		line scale	pointer scale	optical	electronic	mechanical stop	

Figure 7.4: Potato Harvestor

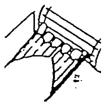
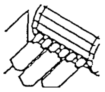
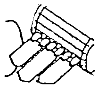
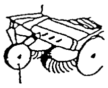
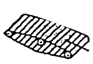
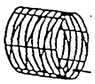
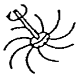
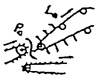
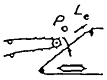
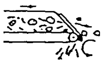
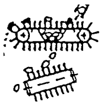
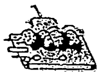
Solutions Sub-functions		1	2	3	4	...
1	Lift	 and pressure roller	 and pressure roller	 and pressure roller	 Pressure roller	...
2	Sift	 Sifting belt	 Sifting grid	 Sifting drum	 Sifting wheel	...
3	Separate leaves			 Plucker	...	...
4	Separate Stones					...
5	Sort Potatoes	by hand	by friction (inclined plane)	check size (hole gauge)	check mass weighting	...
6	Collect	Tipping hopper	Conveyor	Sack-filling device	...	...

Figure 7.5: Potato Harvestor

- Thermal
- Sound
- Pneumatic
- Solar
- Electric
- Combustion

Several designs can be generated from the morphological chart. Five concepts are sketched here.

7.6 Problems

7.6.1 Team Activity

Consider the statement you worked on previously in a class team activity. By looking at your objective tree, generate a list of specifications and house of quality for the statement. Develop a morphological chart and evaluate the alternatives.

If you drive in the state of Florida, you may notice some traffic congestion due to the trees being trimmed on the state roads and the freeways. Assume that the Florida Department of Transportation is the client. Usually, branches 6 inches or less in diameter are trimmed. The allowable horizontal distance from the edge of the road to the branches is 6 ft. The material removed from the trees must be collected and removed from the roadside. To reduce the cost of trimming, a maximum of only 2 workers can be assigned for each machine. The overall cost, which includes equipment, labor, etc. needs to be reduced by at least 25% from present cost. The state claims that the demand for your machines will follow the price reduction, i.e., if you are able to reduce the cost by 40%, the demand will increase by 40%. Allowable working hours depend on daylight and weather conditions.

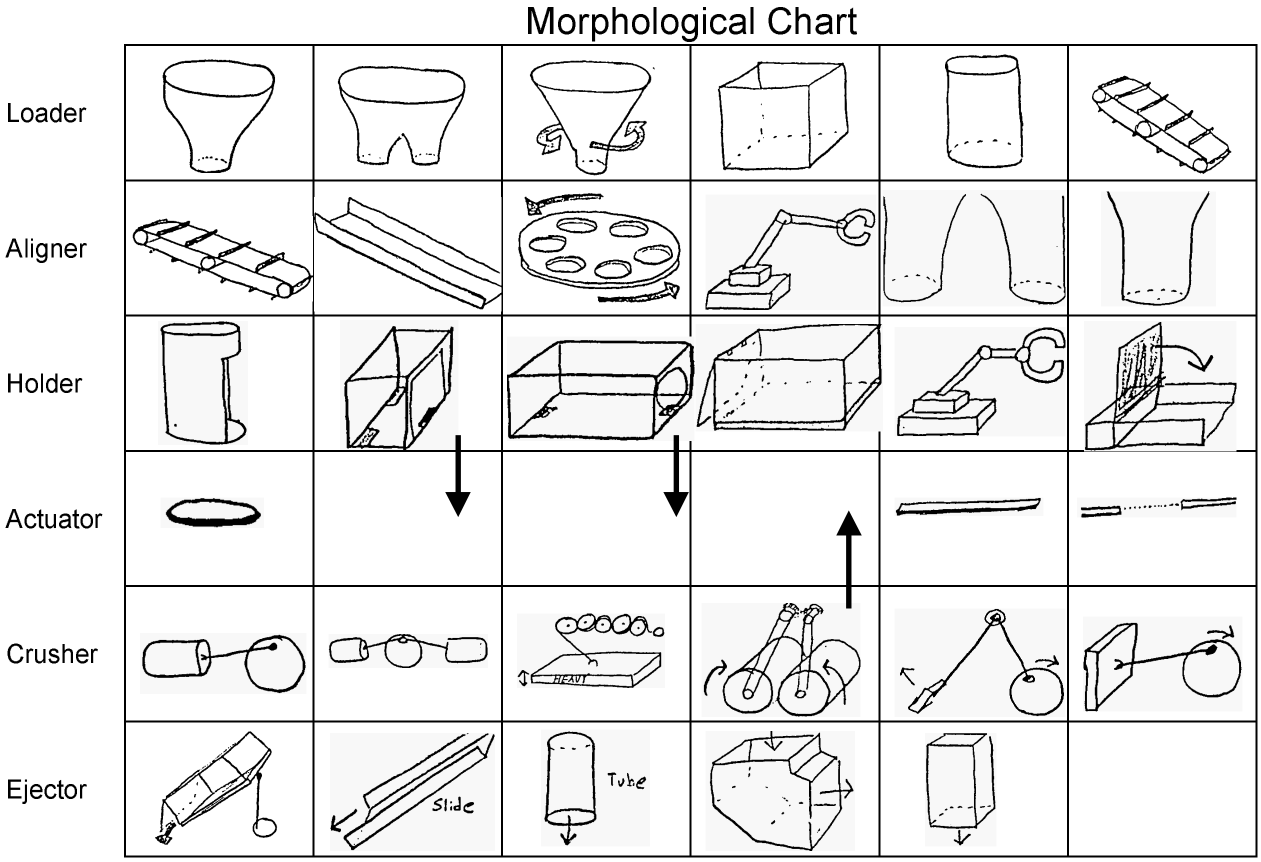


Figure 7.6: Morphological Chart

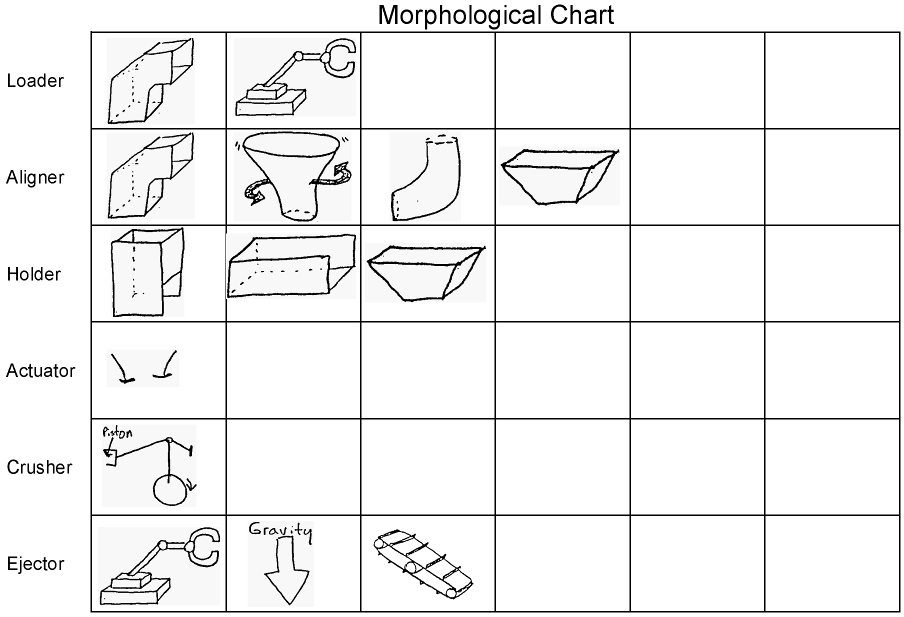


Figure 7.7: Morphological Chart (cont.)

Chapter 8

Concepts Evaluation

In the previous chapter, we developed a technique for generating different concepts that satisfy the need statement. As it was demonstrated, the number of possibilities that may satisfy the need is a function of the number of entries (different ways) that fulfill a function. The larger the number of entries the larger the number of concepts. Obviously, not all combinations through the morphological chart will lead to a feasible product. The goal of this chapter is to provide a methodology for evaluating the different devices. By the end of the evaluation process, a product which has the highest potential for becoming the quality product will be identified with the availability of the many concepts that were generated by the morphological chart. The difficulty in concept evaluation resides in that the designing team must choose a concept to spend time developing while they still have limited knowledge and data on which to base their selection. Concepts at this point are still abstract, have little details and cannot be measured. The essential question then becomes, should time be spent refining and adding minute details to all concepts and then measuring their outputs? Or would developing a mechanism to point out one concept that will most likely become the quality product, prove to be a more efficient option?

The screening of concepts can be accomplished by using different levels, which are:

(a) The concepts are directly measured with respect to a fixed set of limits (specifications). If a concept doesn't satisfy the specification requirement it will be dropped.

(b) The design team uses their experience (Engineering gut feeling) to eliminate some concepts because the technology is not yet available to facilitate the concept. Or, by their judgement, the product is not feasible.

(c) The concepts are evaluated with respect to each other using measures defined by the criteria (specifications/wishes). This screening method was developed by Stuart Pugh in the 1980's, and is often called Pugh concept selection. The purposes of this stage are to narrow the number of concepts quickly.

8.1 Decision Matrix

The decision matrix method, or Pugh method, is based on comparing alternatives with the wishes list in the specification table. An alternative should meet the customer demands, otherwise it will be dropped in the initial screening. Also, the concept should seem feasible to the engineering group, or it will be dropped by the second stage of screening. The concepts that pass the initial two stages need to be evaluated with respect to each other, using a fixed criteria (specification table). The Pugh evaluation method tests the completeness and understanding of requirements, rapidly identifies the strongest alternative and helps foster new alternatives. This method is most effective if each member of the design team performs it independently, and the individual results are then compared. The results of the comparison lead to a repetition of the technique, with the iteration continued until the team is satisfied with the results. The Pugh evaluation method is performed using the following steps:

(a) **Choose the Comparison Criteria**. If all alternatives fulfill the demands on the same level, then the criteria should be the wishes in the specification table. Remember, the wishes were organized in an ordered fashion before they were used in the house of quality. The order is based on the level of importance according to the design team. A weighting factor between 0 and 10 is assigned by the design team for each wish. The basis for the weighting factor depends on the engineering team's feeling of how important the attribute may be to the final product. If the alternatives contain differences in the levels at which demands may be fulfilled, then the demands can be entered in the comparison criteria.

(b) **Select the Alternatives to be Compared** From the morphological chart, different alternatives will be generated, some of these alternatives will be dropped because they do not satisfy the customer demands or they are not feasible. The rest of the alternatives are possible candidates. However, by using the initial screening stages, few alternatives will be left for the final stage.

(c) **Generate Scores**. After careful consideration, the design team chooses a concept to become the benchmark or datum against which all other concepts are rated. The reference is generally either an industry standard or an obvious solution to the problem. It can be a commercially available product, an earlier generation of the product, or any one of the concepts under consideration. It may also be a combination of subsystems, which have been combined to represent the best features of different products.

For each comparison, the concept being evaluated is judged to be 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, the concept is given [0]. If the concept does not meet the criterion as well as the datum does, it is given a [-].

(d) **Compute the Total Score** 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. The weighted total is the sum of each score multiplied by the importance weighing. The scores can be interpreted in a number of ways:

  - If a concept or a group of similar concepts has a good overall total score, or a high + total score, it is important to notice what strength they exhibit. In other words, notice which criteria they meet better than the datum. Likewise, the grouping of - scores will show which requirements are difficult 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 to generate better concepts. Or, it may be that the criterion is ambiguous, or it may be interpreted differently by different members of the team.
- To learn even more, redo the comparison, with the highest scoring concept used as the new datum. This iteration should be redone until the clearly "best" concept or concepts emerge.

After each team member has completed this procedure, the entire team should compare their individual results. Then a team evaluation needs to be conducted.

8.2 Example

In designing a Splashgard for a mountain bicycle, the design team generated the following function diagram.

The preliminary list of customer requirements for the Splashgard are shown in the following table.

The morphological chart is shown in the following diagram.

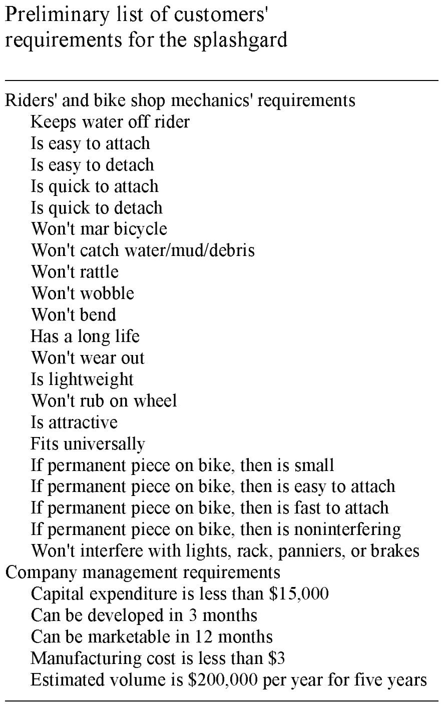
From the morphological chart the following concepts were generated.

The decision matrix is evaluated with respect to concept VII as the datum.

8.3 Example: Automatic can crusher

From the morphological chart many possible combinations of devices can be obtained, but not all of these processes are positive or able to be effectively accomplished. In this stage, the design team begins to limit the possible designs based on specifications, manufacturability, cost and other factors. The surviving designs are then evaluated against each other. The concepts are shown in the follwoing sequence of figures. A decision matrix is constructed to evaluate the designs based

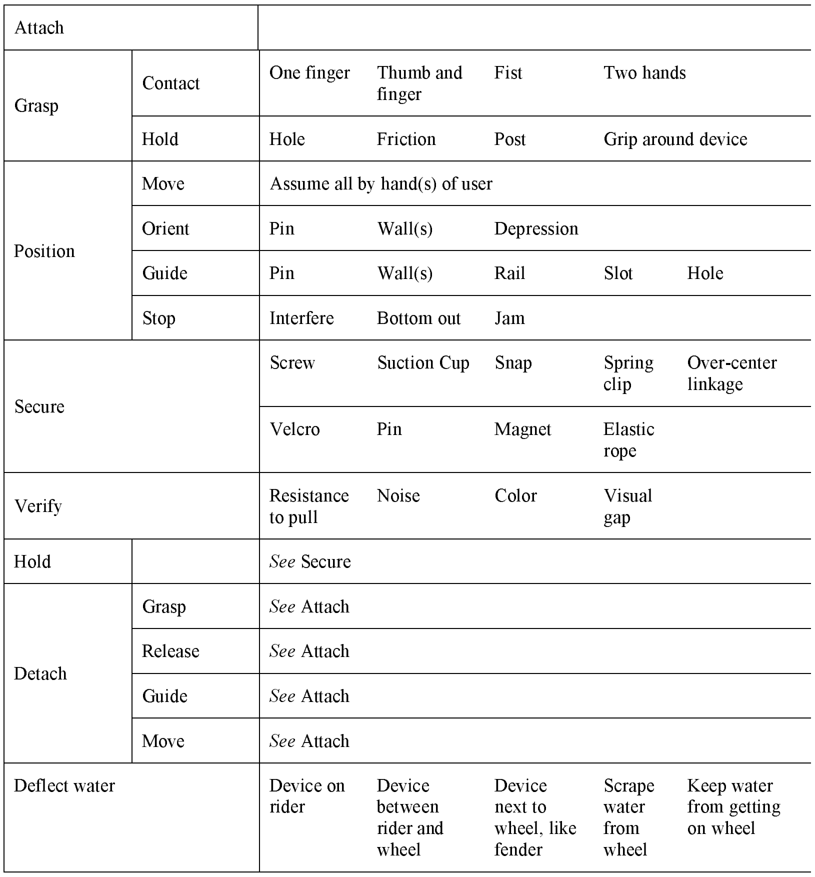
Figure 8.1: Function diagram for Splashgard



Preliminary list of customers'
requirements for the splashgard

- Riders' and bike shop mechanics' requirements
  - Keeps water off rider
  - Is easy to attach
  - Is easy to detach
  - Is quick to attach
  - Is quick to detach
  - Won't mar bicycle
  - Won't catch water/mud/debris
  - Won't rattle
  - Won't wobble
  - Won't bend
  - Has a long life
  - Won't wear out
  - Is lightweight
  - Won't rub on wheel
  - Is attractive
  - Fits universally
  - If permanent piece on bike, then is small
  - If permanent piece on bike, then is easy to attach
  - If permanent piece on bike, then is fast to attach
  - If permanent piece on bike, then is noninterfering
  - Won't interfere with lights, rack, panniers, or brakes
- Company management requirements
  - Capital expenditure is less than $15,000
  - Can be developed in 3 months
  - Can be marketable in 12 months
  - Manufacturing cost is less than $3
  - Estimated volume is $200,000 per year for five years

Figure 8.2: Preliminary List of Customer Requirements for Splashgard



Attach						
Grasp	Contact	One finger	Thumb and finger	Fist	Two hands	
	Hold	Hole	Friction	Post	Grip around device	
Position	Move	Assume all by hand(s) of user				
	Orient	Pin	Wall(s)	Depression		
	Guide	Pin	Wall(s)	Rail	Slot	Hole
	Stop	Interfere	Bottom out	Jam		
Secure		Screw	Suction Cup	Snap	Spring clip	Over-center linkage
		Velcro	Pin	Magnet	Elastic rope	
Verify		Resistance to pull	Noise	Color	Visual gap	
Hold		*See* Secure				
Detach	Grasp	*See* Attach				
	Release	*See* Attach				
	Guide	*See* Attach				
	Move	*See* Attach				
Deflect water		Device on rider	Device between rider and wheel	Device next to wheel, like fender	Scrape water from wheel	Keep water from getting on wheel

Figure 8.3: Morphological Chart for the Splashgard

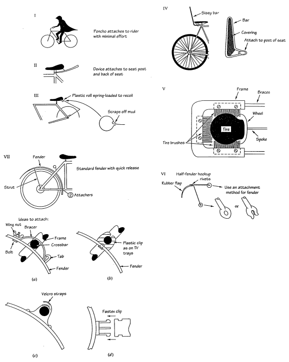
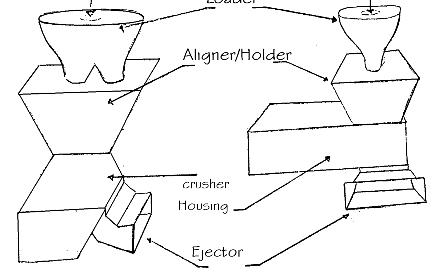


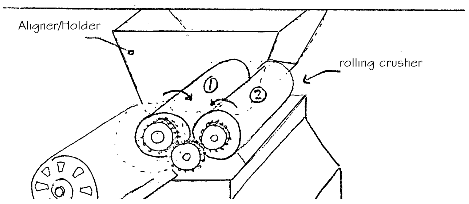
Figure 8.4: Concepts Sketch

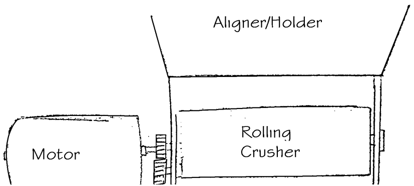
upon the wishes obtained from the specification table. Specifications are weighted by importance, with one being the lowest and ten being highest importance. The concepts are evaluated and one design is chosen by the design team to be the best possible design. This design is considered the datum by which all of the other designs are compared. Then, all of the other designs are evaluated against the datum by a "+" if they exceed the datum in a wish, a "-" if they are below the datum in the wish and "0" if they are equal to the datum in the wish. The results are tallied and scores are evaluated, then the best design is placed as the datum, and the evaluation is done again. The highest scoring design is the chosen design to be built.

		Concepts				
Critertion	**Wt**	**I**	**II**	**III**	**IV**	**V**
East attach	7	+	+	+	+	+
Easy detach	4	-	+	+	+	+
Fast attach	3	+	+	+	+	+
Fast detach	1	+	+	+	+	+
Attach when dirty	3	+	+	+	+	S
Detach when dirty	1	-	+	-	+	S
No mar	10	+	+	+	+	S
Not catch water	7	-	+	-	S	S
No rattle	8	-	-	-	-	S
Not wobble	7	-	-	-	S	S
Not bend	4	-	-	-	S	-
Long life	11	-	S	-	S	-
Lightweight	7	+	S	S	-	S
Not release accidently	10	+	S	S	S	S
Fits most bikes	7	+	S	S	S	S
Streamlined	5	-	S	-	-	+
Total +		8	8	6	7	5
Total -		8	3	7	3	2
Overall total		0	5	-1	4	3
Weighted total		1	17	-15	9	5

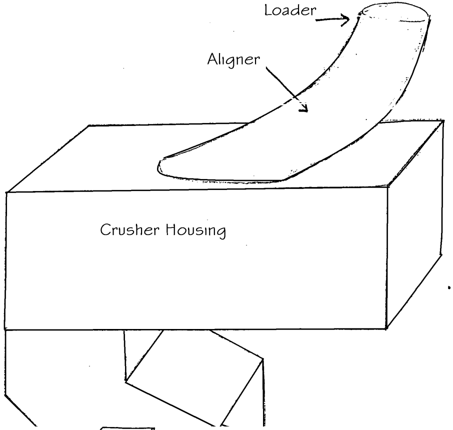
Figure 8.5: Initial decision matrix for Splashgard water deflection subsystem



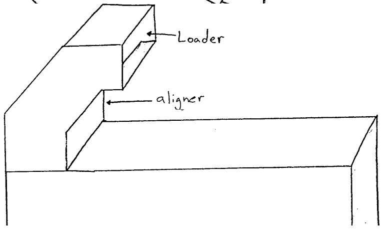




6: Concept I



e 8.7: Concept II



3: Concept III

Concept IV

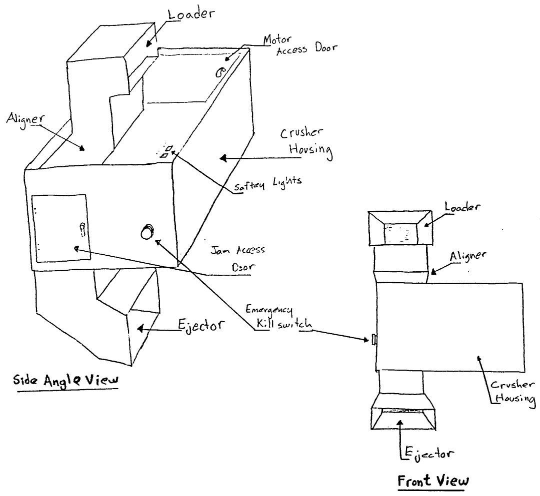


Figure 8.10: Concept V

		Concepts				
Critertion	**Wt**	**I**	**II**	**III**	**IV**	**V**
inoperable when opened	**10**	0	0	0	0	
runs on standard 110V outlet	**7**	0	0	0	0	
< $50 retail	**9**	0	0	0	0	
enough force to crush glass and plastic	**3**	0	0	0	0	D
large storage of crushed cans	**5**	0	0	0	0	A
easily accessible kill switch	**3**	0	0	0	0	T
no sharp corners	**10**	0	0	0	0	U
easy to start	**8**	0	0	0	0	M
stops easily and immediately	**9**	0	0	0	0	
can stop in mid operation	**8**	0	0	0	0	
drains residual fluid from machine	**10**	0	0	0	0	
low vibration	**8**	0	0	0	0	
low peripheral force	**8**	0	0	0	0	
shock absorption	**8**	0	0	0	0	
high efficiency engine	**8**	0	0	0	0	
high material strength	**9**	0	0	0	0	
small force to depress switches	**9**	0	0	0	0	
safety stickers	**9**	0	0	0	0	
reset button	**9**	0	0	0	0	
no flying debris	**9**	0	0	0	0	
operating steps stickers	**9**	0	0	0	0	
low loading height	**7**	0	0	0	0	
easily accessible interior	**7**	0	0	0	0	
crushing mechanism inaccessible	**10**	-	0	-	0	
crush many cans a minute	**9**	+	+	0	0	
utilize gravity in design	**4**	0	0	0	0	
low noise output	**5**	0	0	0	0	
starts up immediately	**5**	0	0	0	0	
easy access to clear jams	**6**	-	-	0	0	
large capacity loader	**5**	+	+	0	0	
long running capability	**7**	0	0	0	0	
parts easy to acquire	**8**	-	-	0	0	
internal parts safe from liquid damage	**9**	0	0	0	0	
low operating cost	**5**	0	0	0	0	
easy cleaning	**6**	-	-	0	0	
easy to disassemble	**6**	0	0	0	0	
crushes along major axis	**2**	0	0	0	-	
no exhaust	**2**	0	0	0	0	
Total +		2	2	0	0	
Total -		4	3	1	1	
Overall total		-2	-1	-1	-1	
Weighted total		-16	-6	-10	-2	

Figure 8.11: Evaluation of designs: V is datum

		Concepts				
Critertion	**Wt**	**I**	**II**	**III**	**IV**	**V**
inoperable when opened	**10**	0	0	0	0	
runs on standard 110V outlet	**7**	0	0	0	0	
< $50 retail	**9**	0	0	0	0	
enough force to crush glass and plastic	**3**	0	0	0	0	D
large storage of crushed cans	**5**	0	0	0	0	A
easily accessible kill switch	**3**	0	0	0	0	T
no sharp corners	**10**	0	0	0	0	U
easy to start	**8**	0	0	0	0	M
stops easily and immediately	**9**	0	0	0	0	
can stop in mid operation	**8**	0	0	0	0	
drains residual fluid from machine	**10**	0	0	0	0	
low vibration	**8**	0	0	0	0	
low peripheral force	**8**	0	0	0	0	
shock absorption	**8**	0	0	0	0	
high efficiency engine	**8**	0	0	0	0	
high material strength	**9**	0	0	0	0	
small force to depress switches	**9**	0	0	0	0	
safety stickers	**9**	0	0	0	0	
reset button	**9**	0	0	0	0	
no flying debris	**9**	0	0	0	0	
operating steps stickers	**9**	0	0	0	0	
low loading height	**7**	0	0	0	0	
easily accessible interior	**7**	0	0	0	0	
crushing mechanism inaccessible	**10**	-	0	-	0	
crush many cans a minute	**9**	+	+	0	0	
utilize gravity in design	**4**	0	0	0	0	
low noise output	**5**	0	0	0	0	
starts up immediately	**5**	0	0	0	0	
easy access to clear jams	**6**	-	-	0	0	
large capacity loader	**5**	+	+	0	0	
long running capability	**7**	0	0	0	0	
parts easy to acquire	**8**	-	-	0	0	
internal parts safe from liquid damage	**9**	0	0	0	0	
low operating cost	**5**	0	0	0	0	
easy cleaning	**6**	-	-	0	0	
easy to disassemble	**6**	0	0	0	0	
crushes along major axis	**2**	0	0	0	+	
no exhaust	**2**	0	0	0	0	
Total +		2	2	0	1	
Total -		4	3	1	0	
Overall total		-2	-1	-1	1	
Weighted total		-16	-6	-10	2	

Figure 8.12: Evaluation of designs:IV is datum

Chapter 9

Embodiment Design

In the previous two chapters, different devices that perform the requirements were derived by using the morphological chart idea. The concepts were sketched, not in great detail, but in a way that presents the major functions that compose the device. These concepts were then evaluated based on three different stages. The first stage involves subjecting the concept to the specification table, if it passes the demands then a feasibility test is conducted. If the concept passes the first two stages, then it will be subjected to relative evaluation based on the Pugh method. In this stage of the design process, the design team starts what could be called the "embodiment design stage." The word "embody" means, to give something a a tangible expression.

This chapter discusses the presentation of the concept(s) that pass the evaluation criteria. The idea of presenting the information through drawings was introduced when different concepts were generated from the morphological chart. The sketches that present the concepts are not detailed: they simply provide enough information to demonstrate the combination of the different function mechanisms that produce the concept. The following figure shows four conceptual sketches of a device that removes leaves from lawns.

It should be reemphasized that the design process is an iterative process. This means that if additional refinements are found necessary, after the skeleton sketches or while in the evaluation stage, the designer should iterate back to the concept phase and possibly generate

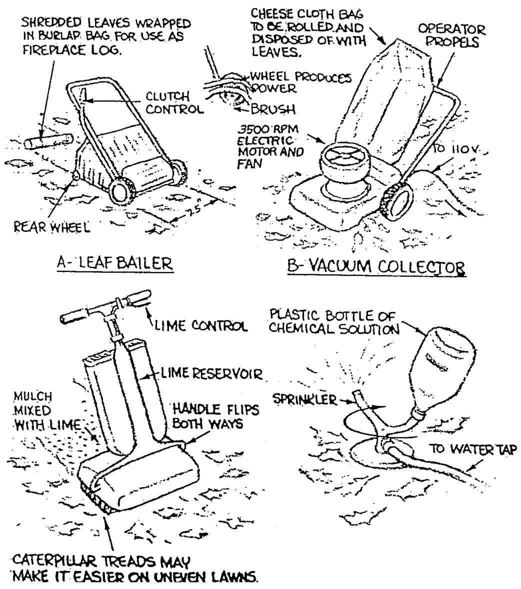


Figure 9.1: Conceptual Sketches

new concepts. The drawback of this process is that it takes time, but that time should be initially implanted in the scheduling of events.

In the world of engineering, information needs to be passed on through drawings. The analysis, manufacturing and assembly of the product is based on drawings. The following section discusses the type of drawings that are required by the designing team.

9.1 Product Drawings

In the design process, drawings may be used to serve the following objectives:

(a) Drawings are the preferred form of data communications in the world of engineering.

(b) Drawings are used to communicate ideas between the designers and between the designers and manufacturing personnel.

(c) Drawings simulate the operation the product.

(d) Drawings are used to check for the completeness of the product.

There are different types of drawings that can be used at different levels, these include:

(a) **Sketches (Layout Drawing):** Sketches are generated during the conceptualization stage of the design process. Different mechanisms of each function or sub-function are first sketched. These sketches are then used to build devices. These sketches serve

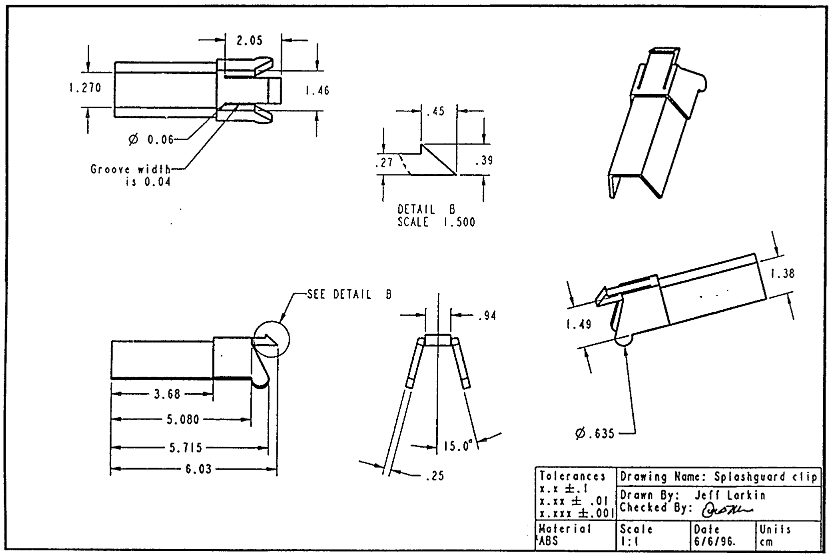


Figure 9.2: Typical Detail Drawing

the purpose of presenting the completeness of the device. These sketches are working documents that support the development of the major components and their relations. They are made to scale, but only the important dimensions are shown in the layout. Tolerances are usually not shown unless they are critical. This form of drawing is needed in the analysis. When an individual component is analyzed, a sketch presents the relation of this part with its surroundings.

(b) **Detail Drawings:** As the product evolves, a detail of individual components develop. A typical detail drawing is shown in the figure. 9.2

The important characteristics of a detail drawing include:

i. All dimensions must be tolerances.

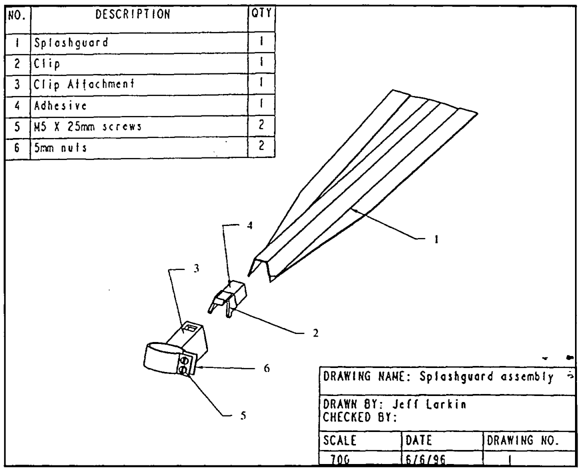
ii. Materials and manufacturing detail must be clear and presented in specific language.

These drawings are made using a CAD system, such as Pro/E.

(c) **Assembly Drawings:** The goal of the assembly drawing is to show how components fit together. Figure 9.3 shows a typical assembly drawing. An assembly drawing has the following characteristics:

i. Each component is identified with a number referenced to a list of all components.

ii. Necessary, detailed views are included to explain information that is not clear in other views.



NO.	DESCRIPTION	QTY
1	Splashguard	1
2	Clip	1
3	Clip Attachment	1
4	Adhesive	1
5	M5 X 25mm screws	2
6	5mm nuts	2

DRAWING NAME: Splashguard assembly

DRAWN BY: Jeff Larkin
CHECKED BY:

SCALE	DATE	DRAWING NO.
70G	6/6/96	1

Figure 9.3: Typical Assembly Drawing

Figure 9.4: Bill of Materials

9.2 Bill of Material

The bill of material is an index of the parts that were used in the product. A typical bill of material is shown in the table below.

The following information should be on a bill of material:

(a) The item number: This is a key to the components on the assembly drawing.

(b) The part number: This is a number used throughout the purchasing, manufacturing and assembly system to identify the component. The item number is a specific index to the assembly drawing, the part number is an index to the company system.

(c) The quantity needed in the assembly.

(d) The name and description of the component.

(e) The material from which the component is made.

(f) The source of the component.

(g) The cost of the individual component. This part will be kept for the design team.

9.3 Prototype

The experimental phase of the engineering design requires the transformation of paper drawings into hardware, which is constructed and tested to verify the concept's workability.

There are three construction techniques that are available for the designers, namely:

(a) **Mock-up**: This is generally constructed to scale from plastics, wood, cardboard and so forth to give the designer a feel for his or her design. It is often used to check the clearance, assembly techniques, manufacturing consideration and appearance. This is the least expensive technique, relatively easy to produce and can be used as a tool in selling the idea to clients or management. A solid model in the CAD system can often replace the mock-up. Mock-ups are usually referred to as a proof of concept prototype.

(b) **Model**: The model relates the physical behavior of the system through mathematical similitude. The modeling is usually referred to as proof of product prototype. There are different types of models used to predict the behavior of a real system.

   i. **True** is an exact geometric reproduction of the real system, built to scale and satisfying all restrictions imposed by the design parameters.

   ii. **Adequate** is constructed to test specific characteristics of the design and is not intended to yield information concerning the total design.

   iii. **Distorted** purposely violates one or more design conditions. This violation is often required when it is difficult or impossible to satisfy the specific conditions due to time, material or physical characteristics, and it is felt that reliable information can be obtained through the distortion.

(c) **Prototype**: This is the most expensive technique, and the one producing the greatest amount of useful information. The prototype is a constructed, full scale working physical system. The prototypes can be comprehensive or focused. A comprehensive prototype corresponds to a full scale, fully operational version of the whole product. An example of the comprehensive prototype is the beta prototype, which is given to customers in order to identify any remaining design flaws, before committing to its production. In contrast to comprehensive prototypes, focused prototypes correspond to one or few of the product elements. Examples of focused prototypes include foam models used to explore different forms of a product.

9.4 Example: Automatic can crusher

Details of the chosen design are sketched, and a bill of material is generated for that design.

9.5 Problems

9.5.1 Team Activity

Consider a regular stapler and a hole puncher.

(a) Draw a function tree.

(b) Sketch the indvidual elements that were used to perform the functions.

(c) Sketch the overall device (combine the elements to obtain the full device).

(d) Construct a limited bill of material for the device.

Chapter 10

Cost Analysis

One of the most essential tasks in engineering design involves estimating the production cost of a new product. Generally speaking, the lowest cost design will be the most successful in a free marketplace. Understanding the elements that make up the cost is essential. Furthermore, cost estimates are used:

(a) to provide a basis for estimating the selling price of the new product.

(b) to distinguish between the different concepts based on material and manufacturing processes.

(c) to provide information on the new product profit.

(d) to be used as a basis for redesigning certain elements to reduce the cost.

It is important to generate a rough cost estimate as early as possible in the design process, and then to refine the cost estimate as soon as the embodiment phase is reached. As the design is refined, the cost estimate is also refined until the final product is produced.

Cost evaluation includes the estimation of the cost of building a plant, or the cost of installing a process within a plant to produce a product or a line of products. It also involves the estimation of the cost of manufacturing a part based on a particular sequence of manufacturing steps.

In design, it becomes important to find techniques that help reduce the cost. Some of the cost reduction techniques that can be used are:

(a) Introduce new processes.
(b) Take advantage of the increase in knowledge that is increased as experience increases, and with the standardization of parts, materials and methods.
(c) Employ a steady production rate, when feasible.
(d) Utilize all production capacity.
(e) Have product specific factories or production lines.
(f) Improve methods and processes to eliminate rework, and reduce the work in process and inventory.

Also, it become important to avoid factors that tend to increase the cost while in the design process. Some factors that tend to increase costs are:

(a) Incomplete product design specifications.
(b) Redesign due to failures.
(c) Supplier delinquency.
(d) Management and/or personnel changes.
(e) Relocation of facilities.
(f) Unmet deadlines.
(g) The product becomes too complex.
(h) Technology and/or processes are not developed as well as they were thought to be.
(i) Inadequate customer involvement.
(j) Disregarding the needs.
(k) Not subjecting a new product idea to competitive evaluation.
(l) Not demonstrating that a new design can function properly under realistic conditions.
(m) Designing without considering manufacturing processes.
(n) Not continually improving and optimizing the product.
(o) Relying on inspection (last minute test).

10.1 Costs Classifications

Each company or organization develops its own bookkeeping methods. In the following, the different classification divisions of costs are presented. It should be realized that cost estimation within a particular industrial or governmental organization will follow a highly specialized and standardized procedure, particular to the organization.

(a) Nonrecurring-Recurring: There are two broad categories of costs:
   i. Nonrecurring costs: These are one-time costs, which are usually called capital costs, such as plant building and manufacturing equipment.
   ii. Recurring costs: These costs are direct functions of the manufacturing operations.

(b) Fixed-Variable costs: Fixed costs are independent of the rate of production of goods; variable costs change with the production rate.
   i. Fixed Costs include:
      A. Investment costs
         - Depreciation on capital investment
         - Interest on capital investment
         - Property taxes
         - Insurance
      B. Overhead Costs include:
         - Technical service (Engineering)
         - Nontechnical service (Office personnel, security, etc.)
         - General supplies
         - Rental of equipment
      C. Management expenses
         - Share of corporate executive staff
         - Legal staff
         - Share of corporate research and development staff
      D. Selling Expenses
         - Sales force

        - Delivery and warehouse costs
        - Technical service staff
    - ii. Variable Costs:
        - A. Materials
        - B. Direct labor
        - C. Maintenance cost
        - D. Power and utilities
        - E. Quality-control staff
        - F. Royalty payments
        - G. Packaging and storage cost
        - H. Scrap losses and spoilage
- (c) Direct-Indirect: A cost is called a direct cost when it can be directly assigned to a particular cost center, product line or part. Indirect costs cannot be directly assigned to a product, but must be spread over the entire factory.
    - i. Direct costs: include
        - A. Material: Includes the expenses of all materials that are purchased for a product, including the expense of waste caused by scrap and spoilage.
        - B. Purchased Parts: Components that are purchased from vendors and not fabricated in-house.
        - C. Labor Cost: Wages and benefits to the workforce needed to manufacture and assemble the product. This includes the employees' salaries as well as all fringe benefits, including medical insurance, retirements funds and vacation times.
        - D. Tooling Cost: All fixtures, molds and other parts specifically manufactured or purchased for production of the product.
    - ii. Indirect Costs include:
        - A. Overhead: Cost for administration, engineering, secretarial work, cleaning, utilities, leases of buildings, insurance, equipment and other costs that occur day to day.
        - B. Selling expenses:

Reason to make	Reason to Buy
Cheaper to make	Cheaper to buy
Company has experience making it	Production facilities are unavailable
Idle production capacity available	Avoid fluctuating or seasonal demand
Compatible and fits in production line	Inexperience with making process
Part is proprietary	Existence and availability of suppliers
Wish to avoid dependency on supplier	Maintain existing supplier
Part fragility requiring high packing	Higher reliability and quality
Transportation costs are high	

10.2 Cost Estimate Methods

The cost estimating procedure depends on the source of the components in the product. There are three possible options for obtaining the components:

(a) Purchasing finished components from a vendor.
(b) Have a vendor produce components designed in-house.
(c) Manufacturing components in-house.

There are strong incentives to buy existing components from vendors. Cost is only one factor that determines whether a product or a component of a product will be made in-house, or brought from an outside supplier. Some of the reasons for each decision include:

If the quantity to be purchased is large enough, most vendors will work with the product design and modify existing components to meet the needs of the new product. If existing components or modified components are not available off the shelf, then they must be produced. In this case, a decision must be made regarding whether they should be produced by a vendor or made in-house. This buy-make decision is based on the cost of the component involved, as well as on the capitalization of equipment and the investment in manufacturing personnel.

When manufacturing an element, the methods used to develop cost evaluation fall into three categories:

(a) Methods Engineering (Industrial Engineering Approach): The separate elements of work are identified in detail and summed into total cost per part. Machined components are manufactured by removing portions of the material that are 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. An example for the production of a simple fitting from a steel forging is shown here:

Operations	Material	Labor	Overhead	Total
Steel forging	37.00			37.00
Set-up on milling machine		0.2	0.8	1.00
Mill edges		0.65	2.6	3.25
Set-up on drill press		0.35	1.56	1.91
Drill 8 holes		0.9	4.05	4.95
Clean and paint		0.3	0.9	1.2
Total	37.00	2.40	9.91	49.31

(b) Analogy: Future costs of a project or designs are based on past costs of a similar project or design, with due allowance for cost escalation and size difference. The method, therefore, requires a backlog of experience or published cost data.

(c) Statistical Approach: Techniques such as regression analysis are used to establish relations between system costs and initial parameters of the system: weight, speed, power, etc. For example, the cost of developing a turbofan aircraft might be given by:

$$C = 0.13937 x_1^{0.7435} x_2^{0.0775}$$

where C is in millions of dollars, x_1 is the maximum engine thrust, in pounds, and x_2 is the number of engines produced.

10.3 Labor Costs

The most accurate method of determining labor cost is to setup a manning table and to find the actual number of people required to run the process line. Be sure to account for standby personnel. Cost of operating labor includes fringe benefits. As an order of magnitude estimate of labor costs:

$$\frac{\text{Operating man-hour}}{\text{Tons of product}} = K\frac{\text{no. of process steps}}{(\text{tons/day})^{0.76}}$$

where
K=23 for a batch operation
K=17 for average labor requirements
K=10 for an automated process

10.4 Product Pricing

Pricing can be defined as the technique used for arriving at a selling price for a product or service that will interest the customer, while simultaneously returning the greatest profit. Different methods are available to assist in arriving at the optimum price for a product. One of these methods is known as the **Break-Even Chart**.

10.4.1 Break-Even Chart

The break-even chart is designed to show, graphically, the profits and losses on the selling price and manufacturing costs of the product. The manufacturing costs of a product include:

(a) Material: Credit should be accounted for recycled scrap and by products.
(b) Purchased parts
(c) Labor
(d) Tooling
(e) Overhead

Material, purchased parts and labor are variable costs that depend on the number of goods produced while tooling. Overhead are fixed costs, regardless of the number of goods produced. The fact that the variable costs depend on the rate or volume of production while fixed costs do not, leads to the idea of a break-even point. The determination of the production lot size needed to exceed the break-even point and produce a profit is an important consideration. To draw a break-even point chart, follow the following steps:

(a) Determine the variable costs per product: Variable costs depend on the number of products and include
    i. Material
    ii. Purchased parts
    iii. Labor

(b) Determine the fixed cost: Fixed cost does not depend on the volume or the number of products.

(c) Draw, on the chart, the total cost as a function of the number of products. The total cost = Fixed cost + Variable cost.

(d) Determine a sale price of the product. Draw the sales as a function of the number of products.

(e) The intersection of the sales line with the total price is the break-even point.

10.4.2 Linear Programming

Linear programming is a tool that is used to represent a situation in which an optimum goal is sought, such as to maximize profit and minimize cost. Mathematically, it involves finding a solution to a system of simultaneous linear equations and linear inequalities, which is optimized in linear form. An illustrative example is listed here for demonstration of this technique.

A manufacturer of desk staplers and other stationary items produces two different stapler models. One is manual in operation, retails at \$12.50 and returns \$2.00 to profit. The other is automatic and sells for \$31.25, returning \$5.00 to profit. The manufacturer is concerned with how to utilize his production facilities in order to maximize profits. One constraint placed upon the maximizing of profits can be written as follows:

$$P = 2Q_M + 5Q_A$$

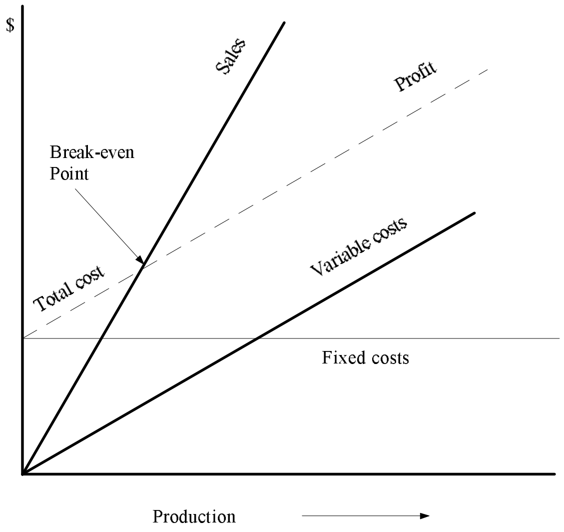


Figure 10.1: Break-even chart

where P is profit function
Q_M is the quantity of manual staplers, and
Q_A is the quantity of automatic staplers.

Assume the manufacturing operation is such that labor skills and plant facilities are completely interchangeable; thus, varying quantities of manual and automatic staplers may be produced on the same day. Also, assume that the present demand is such that the company can sell as many as it can produce. There are certain production restraints. Most of the major components are prepared on separate assembly lines, prior to moving to the final assembly area. There is a sufficient inventory of components for both staplers to satisfy daily production, with the exception of solenoids for the automatic model, which has a daily production capacity of 200. This constraint may be written as:

$$Q_A \leq 200$$

Among other duties of employees, fabrication and assembly requires 18 man-minutes for each manual model and 54 man-minutes for each automatic stapler. The plant employs 45 men for this task, on an eight-hour shift. Since there is only one shift, the capacity is 8 × 45 × 60, or 21,600 man-minutes per day. This may be defined mathematically by:

$$18Q_M + 54Q_A \leq 21,600$$

The final adjustment in the manual stapler requires 3 man-minutes on the assembly line, whereas the automatic model requires 5.4 man-minutes. This phase requires 6 men, and the daily capacity is $8 \times 6 \times 60$ or 2,880 man-minutes. This constraint is expressed as:

$$3Q_M + 5.4Q_A \leq 2880$$

Final inspection for workability requires 1 man-minute for manual models and 1.5 man-minutes for the automatic model. There are 4 half-time inspectors assigned to this task, the inspection capacity is 8 × 2 × 60 or 960 man-minutes. The inspection constraint is:

$$Q_M + 1.5Q_A \leq 960$$

	Manual	Automatic
Selling price	31.25	12.5
Profit	\$2	\$5
Constraints		power supply 200 per day
Labor	18 man-minutes	54 man-minutes
Adjustment	3 man-minutes	5.4 man-minutes
Inspection	1 man-minute	1.5 man-minutes

The following table summarizes the given information: The constraints equations are:

$$P = 2Q_M + 5Q_A$$

$$Q_A \leq 200$$

$$18Q_M + 54Q_A \leq 21,600$$

$$3Q_M + 5.4Q_A \leq 2880$$

$$Q_M + 1.5Q_A \leq 960$$

Plotting these equations yields graphs 10.2 and 10.3.

Linear programming is used to find the iso-profit line that is farthest away, yet still contains at least one point that is technically feasible.

A combination of the break-even and linear programming can be used to set a price for a product. The linear programming approach can be used to determine the optimum number of goods, then that number may be used on the break-even chart to determine the selling price. The actual setting of a price resides at the heart of business practice, but describing it briefly is not easy. A key issue in establishing a price involves the reaction of the competition and the customer. When competition is fierce, the sales force may push hard for price reductions, claiming they can make-up the lost revenues by increasing the volume. Special offers, such as promotional discounts, premiums, extras, trade-ins, volume discounts and trade-in allowances are often used.

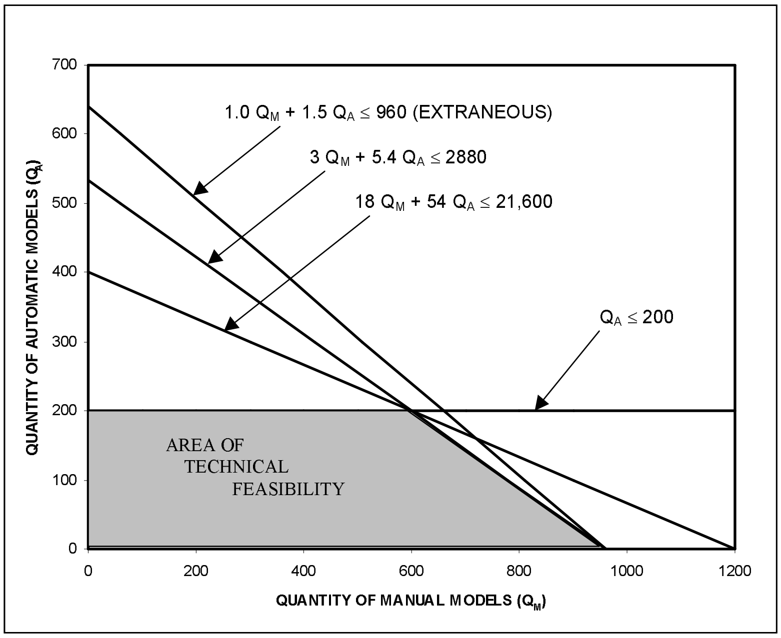


Figure 10.2: Constraints equation without profit

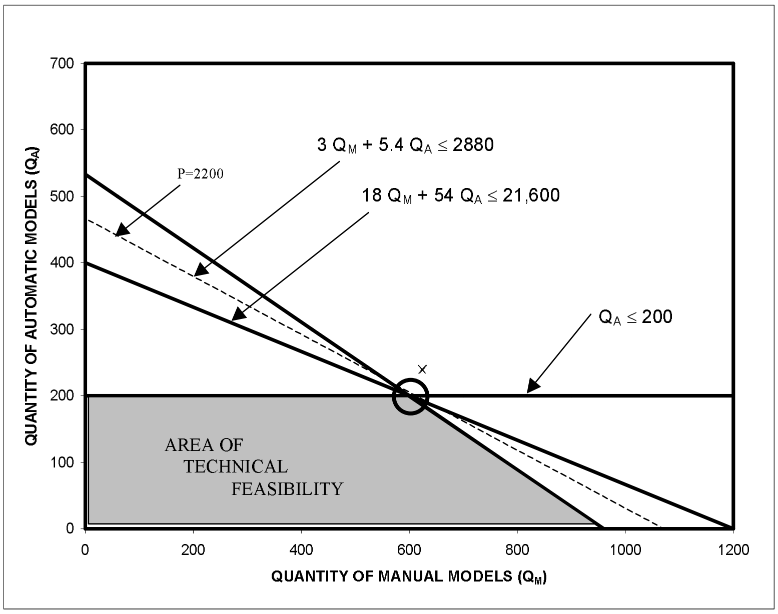


Figure 10.3: Constraints equation with profit

10.5 Problems

10.5.1 Team Activities

The objective of this exercise is to use C++ programming to write a program that can find the cost of different alternatives for your design project in Introduction to Mechanical Engineering. Manufacturing cost is an important factor in evaluating the different alternatives. Some alternatives will be eliminated because of their high manufacturing cost.

Outline

In engineering design projects, students are expected to build a device by the end of a limited time period. With a limited amount of money, students need to figure out the manufacturing costs of different designs before they actually start building these devices. A manufacturing cost is a key determinant of the economic success of a product. When computing the manufacturing cost, one can divide the cost into two broad categories (a) Fixed cost and (b) Variable cost. Fixed costs are those that are incurred regardless of the number of products that are manufactured, while variable costs depend on the amount of goods that are produced. In student design projects, students are not expected to buy major tools nor rent warehouses for production, hence the fixed costs and variable costs in this case may use the following components:

(a) **Fixed Cost**

  i. **Tooling Cost** Tooling cost can include buying or renting. Renting depends on the charge per unit time, regardless of the number of units produced. Buying in this case will be for this project only, and it will be assumed that it is paid for in full (i.e. no interest and no depreciation).

  ii. **Setup Cost** This is the cost required to prepare equipment for a production, and it is fixed regardless of the number of units produced.

(b) **Variable Cost**

  i. **Material Cost** See Table 10.4 for reference.

   ii. **Processing Cost** Varies with the type of manufacturing equipment used, and includes charges for both machine time and labor.

Programming Requirements The program should be readable all items from the terminal and sorted into "ready" and "need-manufacturing" items. The information should be fed by the user. Ready items need prices from the vendor, while items that need manufacturing require the following calculation:

(a) User inputs the following information:
   - i. user inputs the mass of the material (see provided table)
   - ii. user inputs the total number of units of this type
   - iii. user inputs the the setup cost
   - iv. user inputs the tooling cost
   - v. user inputs the processing cost

(b) The computer calculates the manufacturing cost for each element.

The output should be in the following format:

Component	Martial	Ready	Part Number	Vendor	Fixed Cost	Variable cost	Total Cost

Table 10.1: Table Title: Concept number 1, attach a figure

10.5.2 Individual activities

1. Name three different cost classifications, and state the differences among them.
2. What are the three cost estimate methods and what is the difference between them? What method is more appropriate for your design project and why?
3. What is the break-even chart?
4. Using the break-even method, find break-even points if:

(a) the fixed cost is \$12,000.

(b) the variable cost is \$17.95 per unit.

(c) the sale price is \$29.50 per unit.

5. What would be the break-even in the previous question if the fixed cost is the same but the variable cost becomes \$29.50 and the selling price becomes \$37.50?

6. The following data are for a company that produces black-and-white and color TV sets:

   - Black-and-white sets retail for \$198 and contribute \$15 to profit.
   - Color sets retail for \$499.95 and contribute \$45 for profit.
   - The color cathode-ray tube is limited in production capacity to 50 tubes, while all other components have no limits.
   - Chassis assembly requires 6 man-hours for each black-and white set and 18 man-hours for each color set. The plant employs 225 workers for an eight-hour shift to perform chassis assembly operations.
   - A black-and-white set spends 1 man-hour on the assembly line, a color set 1.6 man-hours. There are 30 men on a single eight-hour shift assigned to assembly.
   - Final inspection requires 0.5 man-hour for a black-and white set and 2.0 man-hours for color. The plant employs 20 full time inspectors and one part time for 2 hours per day.

   (a) Write a linear programming model.

   (b) What is the optimum number of black-and-white and color sets.

   (c) Calculate the maximum profit.

   (d) The linear programming and break-even are used to find the selling price for both the black-and-white and color, based on (10,000 fixed cost for both black-and-white and color) with a variable cost of \$160 for the black-and white and \$330 for the color. Find out how many days it will require until the company starts making a profit for the color and the black-and white. Use \$198 and \$500 as selling prices for the black-and-white and the color respectively.

Figure 10.4: Material cost

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