SYSTEM DESIGN

FUNDAMENTALS:

Most of the systems developed by mankind until the 2nd world war were sufficiently simple that it was perfectly possible for one man to fully understand their functioning. As O' Brien points out even the first aeroplane was fully understood by each of the Wright brothers.

However, this is no longer true. All the technological problems of today involve "complex systems". The "System" may be a rocket to be tested, a developing nation's economy, an airport or a whole city. There are so many variables and so many possible alternatives that the straightforward approaches of the past no longer suffice. A radical development that distinguishes the Engineers of today from their predecessors and just may supply him with the method for meeting these challenges is "System Engineering".

DEFINITION OF SYSTEM:

Perhaps the most difficult thing about system Engineering is the word "system" itself. A system can be defined as:

(i) An array of components designed to achieve an objective according to plan.

(ii) A set of objects with relations between the objects and their attributes.

It is more important to identify a system than defining what it is. Nevertheless there are lot many definitions of system. For example, Gosling's definition: "A system can also be defined as an engineering artifact which is most easily analysed, described or designed as an assembly of interconnected but separable and independent elements."

THE BLACK BOX CONCEPT:

The precise definition of a system, if one exists, lies in set theory. Wymore defines a system ***Z*** to be a set such that

$$Z=(S, P, I, M, T, O)$$

where,

S is the set of possible states of the system.

P is the set of the input conditions.

I is the set of input functions.

M is the set of all modes of behavior available to the system

T represents the period of time over which the system is observed.

O is the set of state transition function of the system.

The output of the system $\boldsymbol{Z}$ is represented by specifying a set '$\boldsymbol{O}$' of the output states or values and function '$\boldsymbol{g}$' defined in such a way that the output $\boldsymbol{Z}$ at time '$\boldsymbol{t}$' for an input '$\boldsymbol{i}$' and initial state '$\boldsymbol{s}$' is:

$$\boldsymbol{O} = \boldsymbol{g}\ (\boldsymbol{o}\ (\boldsymbol{i}, \boldsymbol{t})\ (\boldsymbol{s})).$$

Thus a system may be viewed as accomplishing a transformation – changing input $\boldsymbol{I}$ to output $\boldsymbol{O}$ according to the state of the system $\boldsymbol{S}$, and according to certain rules or laws of transformation $\boldsymbol{Z}$. Thus it is often convenient to think of this transformation as a black box illustrated in the figure blow.

The grouping of the details of the transformation in the black box may be because we do not choose to deal with it as a particular stage of our investigation or because we do not understand it. For many purposes it is sufficient to know that the transformation takes place without knowing how it takes place.

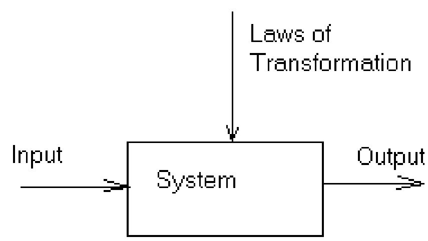


Figure 1: Black Box Concept

THE BLACK BOX CONCEPT OF A SYSTEM:

Ellis and Ludwig have translated this black box notion of a system into the following definition:

> "A system is something which accomplishes an operational process; i.e. something is operated on in some way to produce something that which is operated on is called input, that which is produced is called output; and the operating entity is called the system".

Let us apply the BLACK BOX concept to a man-machine system with which we are all familiar – a moving automobile on a highway. The inputs are gasoline, oil, water etc. and the outputs are the safe and efficient movement of persons and goods. The man and the vehicle together comprise the black box.

From another viewpoint, the moving vehicle becomes a complex of two separate systems – each of which may be viewed as a black box. The inputs to one component, the driver, are the stimuli of the roadway, other vehicles, pedestrians, signs, signals, markings and weather. The outputs are the drivers muscular motions, manifest in accelerating, braking and steering which of course, provide the input to the 2nd system, the vehicle, which in turn are converted to an output, the movement of the vehicle. Unless the driver is a physician, he knows little about the stimulus-response relations relating his own inputs and outputs; and unless he is an automobile engineer, he has only a superficial understanding of what takes place in the 2nd black box, the vehicle. Nevertheless, the overall system works quits efficiently.

CONCEPTUALISATION OF A SYSTEM:

Sometimes it is necessary to change the response of a system for a given input i.e. to alter the transformation. It is then necessary to study the system itself or in other words, to look inside the black box. The reasons for this may be the need to adjust for unintended but inevitable inputs often referred to as environmental factors, or to eliminate some undesirable outputs. Regarding the first the lateral movement of a vehicle, using the previous example, might be caused not by the driver; but by the vehicle's tyres skidding on a slippery pavement, an unintended input.

The other reason for modifying a black box transformation is the undesirable output, e.g., an undesired concomitant output of the internal combustion powered vehicle is air polluting carbon monoxide.

A system description may contain the instantaneous condition or configuration of the system referred to as the state of the system. If the structure of a system - the totality of elements and their relations to one another - changes in time the system is classified as DYNAMIC. If the structure is constant in time, the system is referred to as STATIC. Almost all systems with which the engineer works are dynamic. Even in the design of bridges, an engineer must be concerned with the accumulation of stress, the effects of corrosion, variations in temperature, wind loads, and destructive vibrations. Solutions to problems dealing with dynamic systems depend upon the formulation of a descriptive model relating the inputs, output and systems taken in time. Moreover a complete dynamic theory of a system must specify how given the state of a system at a given period, the sequence of future states can be predicted. Some systems are so complicated that it is difficult and time consuming to express these relationships and their analysis is simplified by treating them as a static system.

Some systems have the property of operating on some working fluid such that the system inputs and the outputs consist of complexes and combinations of energy, information and matter. Gosling calls such a system a "sequential" system as opposed to one not possessing "throughputs" which he calls a " conjunctive" system. Examples of the former are an electrical power distribution network, a computer, and a freeway system. Examples of the latter are a building, an organization, and a number system.

Looking again at the contents of the black box, we see that some engineering systems are most easily visualized, described, designed and analyzed as an assembly of simpler elements. There can be all sorts of systems within one large super system and each of these systems may have one or more subsystems. It is convenient to establish a hierarchy of levels such as part, component, assembly, subsystem and system (Fig.2).

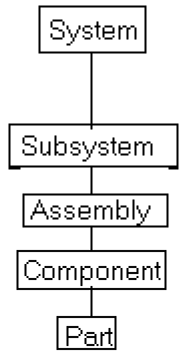


Figure 2: Hierarchy of System

A part is a fabricated item such as a beam. A component is the lowest functional item in the system such as a truss made up of beam and connections. An assembly is a coordinated group of components forming a complete section of a subsystem such as a roof-frame assembly made up of trusses. A subsystem is a group of assemblies performing a major function such as the structural subsystem of a building system used for the support and transfer of roof and floor loads.

Still, there is always a semantic problem because system subsystem and components have different meanings depending on the next higher level of aggregation and a component of still a higher level. Thus, the driver of a vehicle is a system with a nervous subsystem, respiratory subsystem etc. And yet, he is a subsystem of the man-machine system consisting of him and his vehicle, and a component of the total highway transportation system.

CHARACTERISTICS OF A SYSTEM:

It has been seen that the word 'system' is used in such a wide variety of contexts that it is difficult to define. Although, most of the systems of interests to engineers are man-made, and therefore, are designed and developed, not all are. Social systems, biological system ecological systems and the like also possess many points of interest some of which are common to man made systems, and should be borne in mind.

The real test of a system is its organization. This means that a system has certain integrity and that the relations of each of the parts to each other and to the whole can more or less be specified. A system contains certain built – in components and processes by which this organization is maintained. Every material particle or part of the system can be replaced many times during its life while still the system preserves its identity.

Systems are generally large and they are complex. There are many functions performed any many variables with interdependence. System inputs are almost always stochastic, although sometimes the input is assumed to be deterministic to simplify analysis.

ENVIRONMENT:

When a system is considered for design or analysis, a certain boundary is to be set which is called the system boundary. While dealing with the system, only those variables encompassed by the system boundary are considered. The system is surrounded by what is called the environment. Sometimes some environmental factors are also considered at the time of design and analysis of the system.

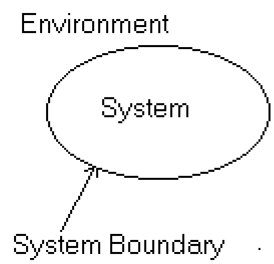


Figure 3: System

CLASSIFICATION OF SYSTEMS:

Systems are classified into different categories depending upon their performance, control and organization.

(a) Open loop system:

When the output from a system does not affect the input to the system, this type of system is called open loop system. Here, however, the inputs will have effects on the outputs. The functioning of the system components too will not be affected by the outputs. Most of the natural systems are open loop systems. Examples of open loop system are,

i. An overflowing water reservoir.
ii. An engine without a governor.
iii. Damage caused by floodwater, etc.

(b) Close loop or Feedback system:

In closed loop system, the output from the system controls the input to the system. In turn, the output is affected by the output itself through the input. Thus there exists a feedback from the output to the input. Examples are:

i. The water cistern
ii. The driver and automobile on a road
iii. An engine with a governor, etc.

A HUMAN FEEDBACK SYSTEM:

In the vast majority of the feedback system, which we encounter in engineering, the feedback is inserted in order to control the degree to which the overall transmission characteristics of the system depend upon the variation in the values of one or more of the system parameters. Thus the critical characteristic of feedback system is most often the tendency of the system to operate satisfactorily even when the specific parameters of the various components are changing radically.

Closed loop or feedback is of two types:

i. Positive feedback – explosive
ii. Negative feedback – goal seeking.

ADAPTIVE SYSTEM:

An adaptive system may be defined as one, which is capable of modifying its operating characteristics in response to changes in environment or input signals in such a way as to improve some performance specification. Thus the adaptive system is designed to modify itself in the face of new environment so as to optimize its performance. Human body is an excellent example of adaptive system. In engineering, example of adaptive systems are an automobile with a super charger to operate at high altitude, temperature compensated jet aircraft fuel control system etc.

THE SYSTEMS APPROACH:

The systems approach to engineering is based on looking at the total activity project; design, of system rather than merely considering the efficiency of the component tasks independently. This, of course is not new; it has always been a distinguishing feature of good engineering. What is new? However, is the development of formalized techniques such as operations research and computer technology, which permit a rational, rather than an intuitive approach to total problem definition and solution.

The systems approach to engineering or systems engineering is manifest through:

(1) Science & Research – the conception of new relationship between the variables entering into the problem.

(2) System design – the application of a broad integrative outlook to the solution of desired objectives

(3) System Analysis – the methodology for exploring existing complex system.

In order to look at the systems approach in this way consider again the black box concept of a system, i.e., input being operated on in some way according to certain laws to produce outputs. In these terms, the system design task is to find the system of component, which will produce a specified output from a given input. The other two activities science and analysis can be described in a similar manner. Thus the objective of science and/or research in the system approach is the discovery of the natural laws affecting the transformation from input to output for the phenomenon being studied. The task of system analysis is to determine either the output for a given input or the input for a given output, as the case may be. Table-1 below summarizes this concept of this concept of systems approach.

Table-1: Identification of the systems approach

Task	Unknown	Known variables
System Design	System	Inputs, outputs and Laws
System Analysis	Outputs Inputs	Inputs, system, Laws Outputs, system, Laws
Research	Laws	Inputs, outputs, and System

Creative problem solving:

Systems engineering is creative problem solving. The creative problem solving process utilized may be deductive or inductive, but usually alternates from one form of logic to the other. Deductive reasoning, which goes back to the time of Aristotle, is used primarily in systems analysis. It is a conclusion (output) obtained by applying a major premise (natural laws) to a minor premise (input). The handbook of engineering of three decades ago is an example of complete adherence to the doctrine of deductive reasoning.

The process of inductive reasoning was first set forth during the Renaissance. The idea is to establish new laws or theories through experimentation to be used as major premises in deductive reasoning. This has been identified in table 1 under the contemporary term research.

Creative problem solving is solution through innovation (reform/ change) rather than through evolution, in the past technical systems often changed gradually with little risk of erring. Solutions were generally only modifications of the older solutions to other problems. The technical risks were small, but the stakes were small too. Today, we have a new set of problems to which there is no historical precedence. Innovation is needed. Remember, the urban transportation problem at the turn of the century was not solved by a modified trolley, but by a new approach to mankind's need – the auto.

More than anything else systems engineering is a methodology. There is more to it than a just a fresh look at problems, there is a systematic procedure for solving these problems. One might call it an order of action in the creative problem solving process.

First, there is recognition of a need, determining if it is a high priority need and assessing just what is the chance for success. Second is the collection of information. Even a cursory library search might spare one the embarrassment of re-inventing the wheel.

The next step is so obvious that it is often overlooked; identify the problem. Bull illustrates this using the problem of 30 yards of unpainted board fence, 1 foot high, which confronted Tom sawyer. Tom, as everyone who has read Mark Twain's classics knows, coined every kid in town into white washing the fence because he defined the problem not as "how can I paint the fence painted."

In order to be a creative problem solver, a system engineer must be able to generate new and useful ideas. The next step is the search for ideas. Some of the techniques used are:

(1) Brainstorming: - An organized group effort aimed at generating ideas by releasing the imagination of the participants from built – in constraints

(2) <u>Inversion</u>: - The conscious breaking of conventional ways of looking at the problem.

(3) <u>Analogy</u>: - Projecting from one discipline to another.

(4) <u>Empathy</u>: - Personal identification with the problem.

The remaining four steps are: the evaluation of alternative ideas, the synthesis of ideas and alternatives, making appropriate simplifying assumptions as a pre-requisite for modeling, and the presentation of the solution. Here, these are the elements of creative problem solving; of course they need not be followed in that precise order. Usually it will be necessary to repeat or retrace some of the steps.

System engineering has three major dimensions. The time dimension of system engineering includes the gross sequence or phases that are characteristics of systems' work and extend from the initial conceptions of an idea through system retirement or phase out. The logic dimension deals with the steps that are carried out at each of the systems engineering phases. The knowledge dimension refers to specialize knowledge from various professions and disciplines.

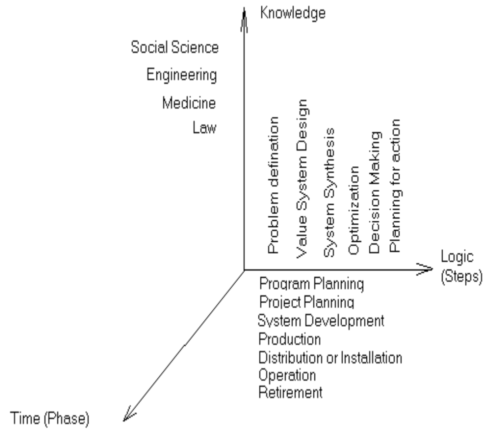


Fig.3: Three Dimensional System Engineering

The Process of Design:

To design is to innovate and to create. Designing is to suggest or outline ways to put together man-made things, or to suggest modifications in man-made things to satisfy optimally (under the given constraints) some specified human needs.

Engineering as a profession is concerned with more than just design. Its various functions are shown below:

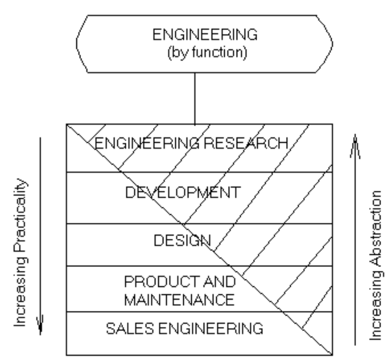


Fig.4: Functions of Engineering

“Scientist studies the world as it is engineers create the world that never has been.”

Principles of system Design:

- The fundamental principle of system design is simply to maximize the expected value.
- Principle of event of low probability -- The fundamental mission of the system should not be jeopardized, nor its fundamental objectives significantly

compromised in order to accommodate events of low probability.

- In many systems a compromise is possible; the system can be designed to handle most events automatically and to sound an alarm which calls for manual intervention when an uncommon event occurs which is beyond its capabilities. For example an automatic mail sorting system would throw out those letters, which were not of standard size, shape or location of address. The principle of centralization refers to centralization of authority and decision-making.
- The principle of sub-optimization states that optimization of each subsystem independently will not in general lead to a system optimum and more strongly that improvement of a particular subsystem may actually worsen the overall system.

Classical and Modern Approach to Design:

Early man as a designer:
Man mastered not only his natural enemies but also the nature itself to some extent by utilizing the resources that nature placed at his disposal. Man has the tool making and using capabilities. Early man learnt the use of sticks, sharpened stones as a tool or weapon. He mastered the use of fire and the art of fire making. He learned to make pottery, clothing and shelter for protecting himself against cold and rain. He discovered agriculture and developed the art of tilling the land and sowing the seeds. He tamed wild animals and used them to do work for him. He discovered the wheel and made the bullock cart.

Early Design Process:
The Process of Evolution:

Most of the tools and implements took a long time, sometimes many centuries of slow change to acquire their present form. Devices changed gradually as time passed, each change making a small improvement on the preceding model. Each change was made to overcome some difficulties faced by the users or to introduce some new features that would render the device more useful. The development of the bullock cart in its present form took thousands of years of slow progress. The leisurely pace of the activity of the earlier times permitted such evolution of designs. Unlike today, the penalty for making a wrong choice was not too severe because only one prototype of a design was made. If a wrong choice was made, it could be easily undone but if it is added to the utility of the design it was copied on a larger scale and became a permanent feature of the design.

Another characteristic feature of this slow evolutionary process of design was the absence of any visible channels of information transmission from one designer to another and any record of design details. Fragmentary information was stored in the memory, learnt and passed down during the period of apprenticeship. Though the shape of the product as a whole, and sequence for making it were stored in the minds of craftsman, the reasons for choosing that particular shape were pretty well lost through the generations of Artisans.

And because of this, the details and overall shape of the product could not be acquired all over again. Such alterations were therefore attempted when drastic new conditions posed demands that would not be made but gradual evolution.

Though this process of evolution appears to be very crude and cumbersome, this was the only way early designers could cope with the complex and conflicting requirements of even simple devices. This process of trial and error over many centuries through countless failures and successes, was needed in absence of analytical capabilities which were either late in developing or even when developed would not permeate fast enough from the academicians in the universities to the craftsman involved in the actual creative process. It is astonishing how this slow search for good design can ultimately result in a product quite suited to the users requirements. Thus the plough used by the Indian farmer is a very suitable design under constraints of the materials and techniques available to the plough maker.

This design by evolution was resorted to not only by craftsman of the pre-industrial era, but was used even in the early industrial and even now is being used to some extent. In the case of most major inventions, the design process is essentially one of evolution, though the time spent is much reduced and the process is accelerated. Bicycles, steam locomotives, automobiles, aeroplanes etc. all went through a process of evolution in which designer tried one concept after another. The early designs of these are also marked by almost a total lack of analytical methods. The designers went about their designs in a process of trial and error, making modifications that appeared to have promise. If the promise was fulfilled, the modification in the design was caught on; otherwise it was rejected in later models.

The evolutionary process in these designs was not so rudimentary as in craft evolution. In this, there was a better system of communicative ideas. Drawings of components and systems assured that they could be properly fitted together. Also many more modifications could be handled at one stage than was possible earlier. While in the earlier process, only one craftsman had to build the whole thing with others possibly assisting him, it was possible to delegate work to a number of craftsman, once the production drawings were made.

Inadequacy of Evolutionary Method in Modern Design Situation:

The traditional methods of designing by evolution and slow change through trial and error are no longer adequate in the modern industrial world. Perhaps the most visible sign of the need for newer and better methods of designing is the existence of massive unsolved problems that afflict modern society. In industrially advanced as well as not so advanced countries the magnitude of such problems is usually frightening. If the world has to be fed and the standard of living of a vast majority of its population has to be raised above the bare subsistence level at which it is at present, we need a design revolution. Even the well to do countries are tottering under the burden of the problems created by the very industrial activity, which is responsible for their wealth. The severe problem of pollution, traffic congestion on roads, crimes in the cities, break down on essential services etc. are results of the increased industrial activity and the lack of foresight on the part of the designers to anticipate such problems as byproducts of their design.

Modern design problems are far more complicated than the traditional ones and cannot be handled by the traditional methods because of the following reasons:

1. The traditional designer was concerned with only one component or one product at a time but because of the increased industrial activity, there is now more and more interdependence of various products; while in an earlier era, a designer of a transportation system had to design only the details of the vehicle, his modern counterpart must worry about the relationship of this vehicle with the total environment, the network of roads, congestion on the roads and the parking places, pollution that might result from the vehicle and a myriad other such problems.

The existing problems of cities can be seen to be the result of design activities carried out at only the product level. Individual houses were designed, and then a road system was imposed in them. Power supply, water supply and sanitation were all later piece- meal addition with the result that all such services are very inefficient and subject to frequent breakdowns. It is only recently that comprehensive discipline of town planning has emerged.

<u>Four levels of design activity</u> :-
i) Community level
ii) System level
iii) Product level and
iv) Component level.

2. The traditional craftsman made things at a very small scale and thus the penalty of a wrong choice in design was only limited. But the scale of production is now of larger orders of magnitude and consequently the risks involved are much higher.

3. The increasing scale of production has also introduced another complication in the process of design. The small scale of an earlier craftsman restricted him to produce only for limited clients. A village plough maker was making ploughs only for the residents of the village and other neighbouring villages. He could gain complete familiarity to the type of soil and ploughing conditions in the neighbourhood and by trial and error, could evolve a plough suitable for use in and nearby village. A modern farm implement however must be suitable for a wide variety of soil because of its larger scale of production necessitated by economic consideration.

4. The rapid pace of technological change makes drastic and novel demands which cannot be met by small changes. A totally new conception of design is very often demanded.

5. The rapid pace of change also requires the designer to not only keep pace with existing technology but also to anticipate future changes. There is no point in designing a product, which, by the time, becomes off the production line, is already obsolete. Also in designing a complicated product or system, a designer may hope to use technology, which, though not available at that time, may reasonably be expected to be available when the design is ready and the technology needed.

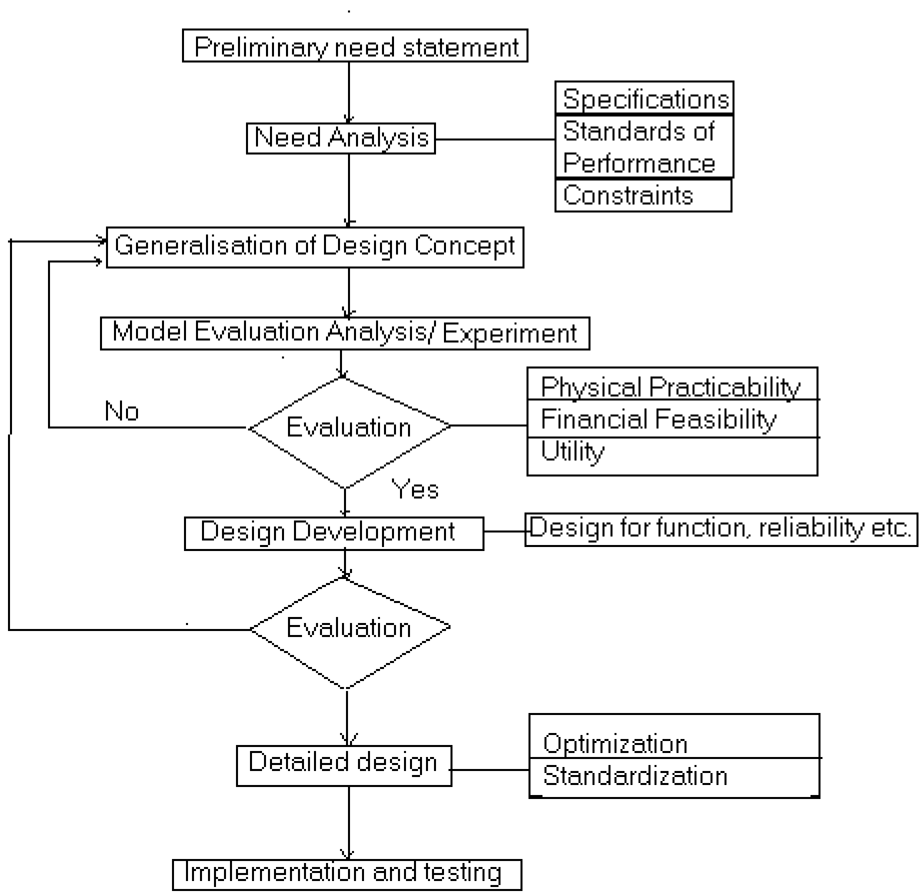
It is clear from the above discussion that the needs of modern industrial man cannot be met by the slow evolution of the existing products. Sometimes a major rethinking of the existing design is called for, and sometimes drastically new products of which there is no precedent are needed.

The structure of the Design Process:

The design histories of the different inventions reveal a definite pattern of development. It is noticed that a design project is conceived and developed; certain events take place in a more or less chronological order, forming a pattern, which is a common to all projects. It is essential to identify and study this pattern to understand the organization of the design activity.

The design process involves three stages of development. They are:

(i) The explorative phase or divergence phase
(ii) The transformation phase
(iii) The convergence phase.



The explorative phase:
In this phase, we start with a description of the need. In this phase, the aim of the designer is to get as much understanding of one problem as possible. Usually this understanding involves getting familiar with the existing solution, if any, their short coming etc, it is necessary that in this explorative phase, the designer take care not to be unduly influenced by the existing design. The aim is to avoid, as far as possible, imposing a prematured pattern on the designer's thinking. For this, it is essential that the designer conceive the elements of the problem in as broad terms as possible.

The transformation phase:
This is the creative phase wherein the designer summons all his experience, innovating capabilities in sight and genius to think of plausible scheme for achieving the desired result. For this, he uses all the information collected in the first phase. This stage is termed as transformation, because it serves as a bridge between the information

concerning the problem and inputs on one hand and the desired results on the other. It is in this stage that all permutations and combinations are tried and novel ideas are thought of.

The convergence phase:
In this phase the designer attempts to eliminate the unworkable or not so good solution in the creative search for ideas and he attempts to converge on to the best solution of the problem. It involves choosing from among the various possible creative transformations, developing it further, testing it as to whether it can fulfill all the expectations, resolving some problems that may brought up at this stage and finally giving it a form which best meets the needs of the problem. Thus the purpose of this phase is to reduce the range of options generated in the second phase to a single optimum design and to develop it such that the manufacturer profitably produces it.

The Morphology of Design:

The three broad features of the design process discussed earlier reveal, on closer examination, a number of steps through which a design project proceeds in chronological sequence. These steps give a vertical structure in the sense that a new step does not begin till the previous one is completed, although it is necessary sometimes to go back to the refinement of some of the information already gathered.

The most general design problem can be stated as: Devise or Design, subject to certain constraints, a product, system, or process to accomplish the given task or fulfill the given need optimally.

Usually the problem statement a designer states is very rough. He has only a vague awareness of the need. The divergence phase of design has two tasks:
1. Establishing a preliminary statement of the need; and
2. Analyzing that need to determine its exact nature.

This analysis of need consists of exploring the design situation, establishing the specification of the system desired, residing on the standards against which the performance of the design can be measured and stating the constraints within which one has to work. In this phase, the optimality criterion has also to be decided upon. The information about the existing solutions to the problems and the strong and weak points thereof are to be collected.

The convergence phase starts with narrowing down the field of plausible solutions to the most promising one on the basis of physical realizability, anticipated utility and financial feasibility. Next the different elements of the proposed design concepts are synthesized in such a manner that the resulting product or design gives the required level of performance as established at the need analysis step. Considerations of functional suitability, production method, handling, maintenance, use and appearance all go in at this step to determine the best arrangement of component, parts, and elements.

The next step, involving further convergence to the final design is the evaluation of preliminary designs to see how they will fare in time. Levels of reliability and consequent deterioration in quality and performance must be studied. The rate of obsolescence (becoming out of date) depending on the projected changes in customer's taste, state of technology and competitive offerings should also be considered.

In detailed design, the preliminary design is carried through the finality. In this step detailed dimensions, tolerances, finishes and other engineering descriptions are furnished. The optimum use of resources both raw materials and production feasibilities is also ensured. The outcome of this stage is that the design is complete in every way so that it defines the exact product or system, as it should be, when it comes of the production line. The only remaining step after this is the implementation and testing of the design.

The Realization of Need:

The sources from which the need perception results are as varied as the needs themselves.

- Need communicated by the designer.
- Need recognized by the designer.
- Need arising out of monotony and repetitive work.
- Need originated from the desire to improve the existing system.
- Need originated from desire to increase comfort.
- Need arising out of existing situations.
- Technical needs.

Could the same principle be used in some other situation to advantage? It is only this sort of awareness of the design features of the material world, which goes to make a good designer. The experience of the designer coupled with an ability to transcend that experience so that it does not create a mental set of fixity, is his best tool.

Use of Check List:

The use of checklist to remind oneself of all that needs looking into is a standard practice in many areas. An aeroplane pilot going through the checking procedures before taking off uses a checklist.

For engineering design situations, a useful checklist is one, which is designed to incorporate the ways an engineer looks for design solutions. A lot of research into the patterns of creativity is being done at present. Some of the things that act as catalyst in innovative designing are the following:

- Memories of the past design
- Competitor's product
- Deliberate doodling and day dreaming
- Self questioning
- Analogies
- Word association
- Science fiction
- Deliberate distortion

- Trying to describe the process
- Use of formal proposals.

A sample checklist is shown below:

Check list for an Engineering Design Problem:

* What similar problems exist in other areas whose solution might give hints?
  (a) Look for the ways nature might have solved similar problems.
  (b) Go to a junk market and walk around.

* What prior solutions, though inefficient or unsatisfactory, exist?

* Can we change something in a prior system to give better results? Can we rearrange it? Can we increase something? Can we invert something – making moving parts stationary and vice versa? Can we combine something?

* Deny that the problem exists. Can we do away with the problem?

* Can we solve a similar problem?

* Defy a natural law. For example, assume gravity does not exist. Can we solve it now? How does one make gravity disappear, if only apparently?

* Try fantasy. Recall how it is done in fairy tales.

* Step into the system. Pretend you are the mechanism. How do you feel? If you had to do it your own, entire how would you do it?

* Break up the problem into essential functional requirements. Try various combinations.

* Give up for the time being and join in some fun (incubation). Attempt this only after a long and exhausting try at the other stems.

Note that the checklist for design unlike some other checklists is not meant to be used serially and only once. Use it whenever stuck and decide as to how to proceed. Come back to the checklist repeatedly to generate as many solution concepts as possible.

Morphological Analysis:

This method serves to force the designer to increase the area of his search for design concepts. The step–by–step procedure is:

1) Recognise the parameters essential to the design. This can be the functions that any acceptable design must perform or the qualities that the design must have.

2) Determine a number of possible ways for achieving each of the parameters.
3) Set up a chart or matrix in the left hand column of which, are listed all the parameters and in the rows against each of these parameters are listed the possible methods of achieving them.
4) Study all combinations, all sub-solutions for feasibility and select the best on the basis of some valid criteria.

Analysis of Interconnected Decision Areas (AIDA)

This method may be best described as a procedure to identity and evaluate compatible (*suitable) combination of some solutions generated by morphological analysis. If we view each of the design parameter as a decision area where the designer has to choose from amongst the available options. These decision areas are somewhat interconnected. Ideally if there were selected to be mutually independent, all combinations of the sub solutions will be compatible. But such simplicity is hard to come by and we end up with some combinations that are incompatible.

Brain storming: Idea hunting by a group:

A group of persons usually 5 or 6 is selected and the problem with all its relevant details is given to the group. The members are asked to suggest as many solution ideas as possible, with no immediate thought as to their value or feasibility. The members are encouraged to combine and improve on the ideas suggested by others. Strict rules forbidding any criticism are enforced so that the members are encouraged to mention all ideas, however wild. These ideas may be combined with a better idea or insight to give a really valuable design concept.

Synectic:

A typical synectic group consists of about 6 persons, drawn from diverged areas with one expert from the problem area. A leader is selected who simply conduct the proceedings but does not contribute any idea. The expert explains the problem. The group makes us analogies to understand the essential nature of the problem and to direct the thinking to a wide range of design concepts.

Feasibility:

Technical Feasibility:

To explore whether the available technical facilities will be adequate to produce the product. The following aspects are to be considered:

- Availability of raw material
- Manufacturing process
- Technical know-how (method)
- Manufacturing facilities
- Skilled labour
- Environmental factors.

Evaluation of Alternatives:

In the transformation phase of design, a set of ideas is generated each of which is a rather rough outline of how the major elements of the design are to be connected. Each of these outlines needs to be developed further, the details worked out and the procedures specified and outlined. It is generally true that nearly all the design concepts proposed by an experienced designer, can work provided they are developed sufficiently. But the development of design cost time and money and in almost all cases both are limited. The dead lines of time and budgets of money are real constraints within which a designer must work. A designer should attempt to develop only those concepts that he is reasonably sure about. Those, which appear difficult to develop within the budgeted time and money, should not be attempted. This means that we should try to determine which of the design concepts are physically realizable within the given budgets of time and money.

A product to be acceptable must be worthwhile from the economic point of view i.e. it must be such that both the persons making it and using it get their money's worth. The manufacturer is happy when what he spends in making a product is substantially less than what the customer is willing to pay for it and in addition, he feels that the given design maximizes his return on the investment. Thus the designer should select that design which promises to cost least, as compared to what the customer is willing to pay for it. The customer pays more for the design which offers him better service or the performance of which is superior. Thus the real worth of a design in relation to its cost can be measured in terms of its overall performance rating.

Physical Feasibility of the Design concept:

The physical feasibility of a design concept can be measured in terms of the confidence the designer has in his being able to transform the abstract concept into its physical embodiment. This confidence is expressed as statement of subjective probability. Thus a physical feasibility index of 0.75 means that the designer considers the odds in favor of his completing the design are 3 to 1. He can estimate the probabilities of successful solution of the last level of sub problems and from this he calculates the probability of his being able to transform the concept into a working proposition. Thus in evaluating the feasibility of a design concept we examine the solvability of the sub- problems, which need solving for evolving a successful design.

Financial Feasibility:
To explore whether the project will be financially feasible the following points are to be considered.

- Fund availability
- Sources of fund
- Terms and conditions in obtaining fund
- Interest rate
- Rate of return
- Growth of the project.

Technical Feasibility:

Economic Feasibility:
A design is of no use if it does not make money for the manufacture or it does not give enough benefits to its user to justify its cost. The production of an item is said to be economically feasible or viable when the total revenue earning from the product is more than total cost incurred to produce the item. A look at the cost structure is necessary at this point.

Fixed cost:
Cost, which does not vary with the variation in the production, is called fixed cost.

Variable cost:
Costs, which vary with the variation of the volume of production, are called variable cost,

Total cost = Fixed cost + Variable cost.

The designer should also consider the question of maximizing the profits subject to professional ethics and all legal and safety constraints. If we assume that the market dictates the sales price for a given design, the only way to maximize profit is to reduce cost. We may reduce fixed cost or variable cost or hopefully both.

Break Even Analysis:
Once we have designed and developed a product and set it up for production and distribution, a large sum of money has already been spent. These are our fixed cost (F.C.). If we do not produce anything the revenue will be zero and thus we operate at loss. Now if we produce (say) 50% of the installed capacity, we incur variable cost (V.C.) in proportion to this production value and earn revenue accordingly. The total cost (T.C.) against a certain volume of production will be the fixed cost, plus the variable cost at that level. The shapes and slopes of the total cost and revenue functions will be as shown in the Fig. 5 below.

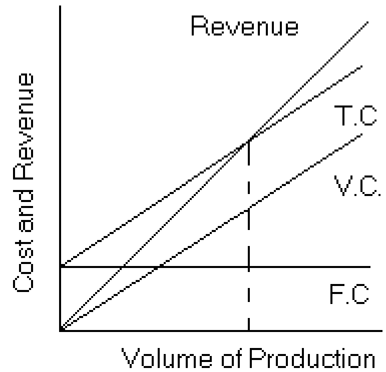


Fig.5: Break-Even Analysis

If we go on increasing the volume of production, the two variables, total cost (T.C.) and revenue will also increase, both at different rates. At a certain volume of production, total cost becomes equal to revenue. This point is called the BEAK EVEN POINT. Before this point, total cost is greater than the revenue and hence the farm operates at loss. Beyond his point total cost is less then the revenue and hence the farm earns profit. An acceptable design must have a Break Even Point (B. E. P.) below the expected sales volume point. If we expect to sell at about 80% capacity, the break-even point should be below that level.

Quality of Design:
The consumer pays for the design of the product and expects some standard of performance (quality) from the product. Thus it is in the interest of both the manufacture and designer to make an estimate of the overall performance of the product as seen by the consumer. Of the physically realizable and economically feasible design concept, the concept chosen for the development should be one which promises to give the right mix of performance and cost for the consumer.

There are usually many factors or attributes, which a customer looks for in a product. Safety, ease of use, maintainability, cost and appearance are only some of the things that one looks for in a product.

Utility:
Since a customer evaluates a product on a number of dimensions such as cost, safety, ease of use etc., it is essential that combining all these dimensions should evolve a common scale of measurement. One such is the utility scale, which is based on the personal preference of the evaluator, and as such is highly subjective. The utility of a product on a particular quality dimension measures the usefulness of that particular characteristic of that product. Thus the utility of a product on, say adaptability dimension, represents the judgment about how much important the adaptability is for the evaluator. Thus it is a measure of the contribution of the given level of adaptability to the overall usefulness of the product.

The overall utility of a product is the sum of utility of each of the quality dimensions. The individual utility ratings can be added up because each measures the usefulness of a product with respect to a particular quality. The overall usefulness should just be the sum total of these various utilities.

Quality	Bulb ‘A’	Bulb ‘B’
Life	4	5
Light emission	3	2.5

In the above example, since the total utility of bulb ‘B’ is more than the total utility of bulb ‘A’, bulb ‘B’ is considered to be of high utility.

It may be noted that to be able to add up the utility in the above manner we are explicitly making the assumption that one unit of utility of the light emission is replaceable with one unit of utility on the life. Thus we are perfectly willing to reduce life by one utility unit if the high emission increases by one utility unit and vice-versa. This property of utility scale may be termed as “INDIFFERENCE”

Another point to be noted is that the utility scale is not a proportional scale. A life of 400 hours would not necessarily have twice the utility of a 200-hour life. Also the increase in the utility when the life increases from 200 to 400 hours may be quite different from that when it increases from 400 to 600 hours.

In many cases the utility curves can be approximated by a logarithmic curve. The utility increases at a diminishing rate as the quality increases.

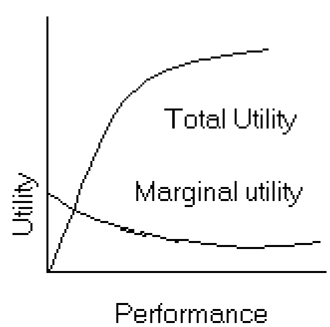


Fig.6: Utility Curves

Using Utility for Design Selection:

Instead of measuring the various quality dimensions on the same scale, different scale for each dimension should be used. First, a scale for usefulness on each quality dimension is constructed separately then these scales are weighed to obtain a composite number. For each characteristic we rate the various design on a 0 to 10 scale, 10 representing the perfect imaginable quality and 0 representing the quality, which is barely acceptable. It is to be noted that only those design concepts, which promise a quality above the minimum specification, have any utility at all. These represent only preferences. The next step is to obtain the actual utilities by multiplying these preference measures by the relative importance of the characteristics. For this the first step is to assign weight. These, too, depend on the subjective evaluation of how important a particular dimension is. The weights are so chosen that the total comes out to be one.

Example 1: Selection of safety device for passengers

Quality Dimension	Design Options		Weightage
	Seat Belt	Air Bag	
Protection	6	9	0.45
Reliability	9	5	0.15
Adaptibility	4	9	0.10
Cost	9.5	4	0.30

Now utility (Seat belt) = $6 \times 0.45 + 9 \times 0.15 + 4 \times 0.10 + 9.5 \times 0.3 = 7.3$
Utility (Air bag) = $9 \times 0.45 + 5 \times 0.15 + 9 \times 0.10 + 4 \times 0.3 = 6.9$
Seat belt is preferred.

Ex 2 To select the suitable material from four different types of materials.

Table 1. Properties of material

Material	Weight Kg/m2	Cost in arbitrary Units	Thermal Resistance	Transmission Loss in db
A	7.0	51	1.12	97
B	18.2	40.6	4.08	106
C	19.6	2.8	9.09	101
D	22.4	53.5	5.40	106

First step is to convert it to a preference scale. The preference scale should be logarithmic. Set zero to minimum quality and 9 to max quality or assume song other level as max and min quality

Using the formula –

P = A log (Quality under consideration /the quality level for which 0 value has set)

(i) Weight

Set 0 to 28 kg/m2

and set 9 to 7.00 kg/m2

9 = A l0g 7/28   A = - 14.9

r = - 14.9 log (Quality/28)

(ii) Cost:

Set 0 to 60

and 9 to 2.8

P = 6.9 log (Cost / 60)

(iii) Thermal resistance: -

Set 0 to 0.9 $\times$ 10-5

and 9 to 9.09 $\times$ 10-5

P = 9 log (Thermal resistance / 9.09 $\times$10-5)

(iv) Transmission loss is already in log scale so a new log transmission is not required

set 0 to 90 db

and set 9 to 106 db

P = 0.562 (Transmission)

Preference Table

Material	Weight	Cost	Thermal resistance	Transmission lose
A	9.0	7.4	0.9	4.0
B	2.6	1.2	5.9	9.0
C	2.3	9.0	9.0	6.2
D	1.4	1.4	7.0	9.0

Preference Table

Material	Weight	Cost	Thermal	Transmission loss
A	9.0	7.4	0.9	4.0
B	2.6	1.2	5.9	9.0
C	2.3	9.0	9.0	6.2
D	1.4	1.4	7.0	9.0
Weight age	0.4	0.3	0.15	0.15

U (A) = 9 $\times$ 0.4 + 7.4 $\times$ 0.3 + 0.9 $\times$ 0.15 + 4.0 $\times$ 0.15 = U (B) = 2.6 $\times$ 0.4 + 1.2 $\times$ 0.3 + 5.9 $\times$ 0.15 + 9.0 $\times$ 0.15 = U © = 2.3 $\times$ 0.4 + 9.0 $\times$ 0.3 + 9.0 $\times$ 0.15 + 6.2 $\times$ 0.15 = U (D) = 1.4 $\times$ 0.4 + 1.4 $\times$ 0.3 + 7.0 $\times$ 0.15 + 9.0 $\times$0.15 =

Material A is selected.

Ex.3 Decision making under conditions of chance variations (utility analysis under risk.)
Ex: To decide whether to provide hood to Motor cycles.

State of nature	Utilities		Chances of use Of motorcycle
	With hood (V1)	Without hood (V2)	
Very hot days	7	1	15%
Summer	1	6	35%
Rains	8	1	5%
Sunny winter days	3	7	30%
Cold winter evening	7	2	15%

Expected value of (V1) = $.15 \times 7 + 1 \times 0.35 + 8 \times 0.03 + 3 \times 0.5 + 7 \times 0.15 = 3.75$
E (V2) = $.15 \times 1 + 0.35 \times 6.\ 0.5 \times 1 + 0.30 \times 7 + 0.15 \times 2 = 4.7$
End case is considered (having maximum utility)

Development of Design:

The abstract design concept consisting of the outline, an idea from here and a mechanism from there expresses only a plausible relationship among elements which promises to fulfill the needs of the given problem. Then the feasibility study is carried out to estimate the chance of such a plausible relationship being converted to a physical reality. The development phase of the design process consists of putting the major elements of the concept together keeping in mind that the resulting product should satisfactorily perform the expected functions. The designer must build into the design – ease of use, maintenance, repair.

Design for Function:

The functional requirements get first preference in design. Sufficient technical background is necessary to design the system for function. Knowledge about the properties of the parts of the system is essential.

Designing for Production:

The question of how the product will be produced must be thought of at this stage. Designing the structure of a tall building must be accompanied by considerations of how it is going to be erected. A good designer always asks himself the question: can this be achieved with the available tools and skills?

Designing for Shipping Handling and Installing:

- Should be able to withstand shock during transit.
- Loading and unloading facilities.
- Facility to ship in an unassembled or partly assembled form.
- Carrying handles for portable equipment.
- Easier assembly, standard parts, requirement of less number of tools.
- Foolproof assembly: components should be so designed that it is impossible for the customer to assemble it in any but the correct manner.

Designing for Use:

The designer must remember that the product he develops is to be used by people. A well-designed product is one, which can be used by people readily. It is the product, which should be fitted to the person rather than the other way round. Designing for use essentially consists of ensuring that the points of friction between machine and man be rounded out is favor of man.

- Easily operated handles and levers.
- Easily readable meters.
- Proper positioning of control knobs and levers.
- Easy maneuverability.
- Less strenuous operations.

Designing for safety:

- Safe operations.
- Safety guards
- Signals indication danger
- Automatic control
- Locking devices
- Non-functioning with improper conditions.

Designing for maintenance:

All products whether big or small, need maintenance. It may be replacement of an electric fuse or services of an automobile or even the overhaul of an aircraft jet engine. There are in general two types of maintenance preventive and corrective. Preventive maintenance is carried out at a regular time interval before the part or component could develop the faults. Corrective maintenance or fault repair is undertaken whenever a fault arises.

In designing a product attention should be paid to designing it in such a way that the product could be maintained and repaired in the shortest possible downtime and with the skills normally available with the operator. Access panels for reaching the interiors, warning lights for fault condition as in engines, handles and rails for removal of heavy parts, plug in modular circuits as in television receivers, stainless steel for cooking pans, corrosion resistant coating and finishes are all examples of aids incorporated for ease in maintenance.

The Detailed Design:

In this last phase of the design process, a complete engineering description of the proposed system is evolved. This includes providing detail manufacturing instructions in the form of part drawings, assembly drawings and process instructions. Specifications of each part component or subsystem are defined so that a manufacturer knows exactly what has to be made and how.

Tolerance:

No machines, no matter how precise, and no worker, no matter how skilled, can produce two components that are exactly alike. A designer must recognize this fact while details should accordingly specify the range or tolerance within which the product will be acceptable.

Interchangeability

In deciding the dimensional tolerance, one must also keep in mind the need of interchangeability in mass produced parts. Interchangeability is needed to obtain maximum efficiency and least cost at the assembly stage. If the parts sere not interchangeable, additional effort would be needed for finding the part that fit together. Interchangeability means any of the mating parts should fit to any of its counter part.

Interchangeability is required to facilitate the consumers while baying spare parts for repair or maintenance.

Standardization:

It is done with a view to produce economically and to save in design effort. This is also required for ensuring the interchangeability of components or sub-systems of different manufactures. The designer must consult the factory standards, national standards and international standards in specifying the dimensions and quality of a product or a system.

Optmization:

There arise many situations where some conflicting requirements of performance exist. This means that while designing one must try to achieve the best possible combination of these conflicting requirements. The process of arriving at such balances is known as optimization.

Implementation & Testing:

The design process is incomplete till the first prototype has been manufactured and tested. Even the best considered detail design has to be modified to some extent to overcome the unexpected difficulty in construction, assembly or operations. The prototype is subjected to extensive test and the results obtained from these are utilized to modify the design suitably so that it meets the desired performance.