Section 3

Design Process

3.1 Introduction

What is design? If you search the literature for an answer to that question, you will find about as many definitions as there are designs. Perhaps the reason is that the process of design is such a common human experience. Webster's dictionary says that to design is " to fashion after a plan," but that leaves out the essential fact that to design is to create something that has never been.

Thus, although engineers are not the only people who design things, it is true that the professional practice of engineering is largely concerned with design; it is frequently said that design is the essence of engineering. To design is to pull together something new or arrange existing things in a new way to satisfy a recognized need of society. An elegant word for "pulling together" is synthesis. We shall adopt the following formal definition of design: [1] "Design establishes and defines solutions to problems which have previously been solved in a different way."

Good design requires both analysis and synthesis. In order to design something we must be able to calculate as much as about the thing's behavior as possible by using the appropriate disciplines of science or engineering science and the necessary computational tools. Analysis usually involves the simplification of the real world through models. It is concerned with the separation of the problem into manageable parts, whereas synthesis is concerned with assembling the elements into a workable whole.

3.2 The Design Process

We frequently talk about "designing a system." By a system we mean the entire combination of hardware, information, and people necessary to accomplish some specified mission. A system may be an electric power distribution network for a region of the nation, a procedure for detecting flaws in welded pressure vessels, or a combination of production steps to produce automobile parts. A large system usually is divided into subsystems, which in turn are made up of components.

Examples of the operations might be 1) exploring the alternative systems that could satisfy the specified need, 2) formulating a mathematical model of the best system concept, 3) specifying specific parts to construct a component of a subsystem, and 4) selecting a material from which to manufacture a part. Each information that is expected of the trained professional and some of it very specific information that is needed to produce a successful outcome.

3.3 A Simplified Design Process

Once armed with the necessary information, the design engineer (or design team) carries out the design operation by using the appropriate technical knowledge and computational and/or experimental tools. At this stage it may be necessary to construct a mathematical model and conduct a simulation of the component's performance on a digital computer. Or it may be necessary to construct a full-size prototype model and test it to destruction at a proving ground. Whatever it is, the operation produces a design outcome that, again, may take many forms. It can be a ream of computer printout, a rough sketch with critical dimensions established, or a complete set of engineering drawings ready to go to the manufacturing department. At this stage the design outcome must be evaluated, often by a team of impartial experts, to decide whether it is adequate to meet the need. If so, the designer may of on to the next step. If the evaluation uncovers deficiencies, then the design operation must be repeated. The information from the first design is fed as input, together with new information that has been developed as a result of questions raised at the evaluation step. Each objective requires an evaluation, and it is common for the decision-making phase to involve repeated trials or iterations. The need to go back and try again should not be considered a personal failure or weakness. Design is a creative process, and all new creations of the mind are the result of trial and error. In fact, if it were possible to work a design straight through without iteration, the design would indeed be very routine. This iterative aspect of design may take some getting used to. You will have to persevere and work the problem out one way or the other.

The iterative nature of design provides an opportunity to improve the design on the basis of a preceding outcome. That, in turn, leads to the search for the best possible technical condition, e.g., maximum performance at minimum weight (or cost).

3.4 The Design Process Steps

To further illustrate the design process, we consider the process to consist of the following steps:

- Recognition of a need
- Definition of a problem
- Gathering of information
- Conceptualization
- Evaluation
- Communication of the design

The design process generally proceeds from top to bottom in the list just given, but it must be understood that in practice some of the steps will be carried out in a parallel and that feedback leading to iteration is a common fact of design.

3.5 Recognition of a Need

Needs are identified at many points in a business or agency. Most organizations have research or development components whose job it is to create ideas that are relevant to the needs of the organization. Needs may come from inputs of operating or service personnel or from customers through sales or marketing representatives. Other needs are generated by outside consultants, purchasing agents, government agencies, or trade associations or by the attitudes or decisions of the general public.

Needs usually arise from dissatisfaction with the existing situation or wanting one. They may be to reduce cost, increase reliability or performance.

3.6 Definition of a Problem

Probably the most critical step in the design process is the definition of the problem. The problem is not always what it seems to be at first glance. Because this step requires such a small part of the total time to create the final design, its importance is often overlooked.

It is advantageous to define the problem as broadly as possible. If the definition is broad, you will be less likely to overload unusual or unconventional solutions. Broad treatment of problems that previously were attacked in piecemeal fashion can have a big payoff. However, you should realize that the degree to which you can purse a broad problem formulation toward a final design will depend on factors often outside your control. Pursuit of a broad formulation may bring you into direct conflict with decisions already made by your employer or client, or it may lead you into areas of responsibility of other persons in the organization. In most cases the extent to which you are able to follow a broad problem formulation will depend on the importance of the problem, the limits on time and money that have been placed on the problem, and your own position in the organization.

One approach that you should not take is to consider the existing solution to the problem to be the problem itself. That approach immediately submerges you in the trees of the forest, and you will find yourself generating solutions to a problem that you have failed to define.

The definition of a problem should writing down a formal problem statement, which should express as specifically as possible what the design is intended to accomplish.

3.7 Gathering of Information

Perhaps the greatest frustration you will encounter when you embark n your first design problem will be due to the dearth or plethora of information. No longer will your responsibility stop with the knowledge contained in a few chapters of a text. Your assigned problem may be in a technical area in which you have no previous background, and you may not have even a single basic reference on the subject. At the other extreme you may be presented with a mountain of reports of previous work and your task will be keeping from drowning in paper. Whatever the situation, the immediate task is to identify the needed pieced of information and find or develop that information.

The following are some of the problems connected with obtaining information:

- Where can I find it?
- How can I get it?
- How credible and accurate is the information?
- How should the information be interpreted for my specific need?
- When do I have enough information?
- What decisions result from the information?

3.8 Conceptualization

The conceptualization step is to determine the elements, mechanisms, processes, or configurations that in some combination or other result in a design that satisfies the need. It is the key step for employing inventiveness and creativity.

Very often the conceptualization step involves the formulation of a model which maybe either of the two general types: analytical and experimental. In most of your engineering courses the emphasis has been on the development of analytical models based on physical principles, but experimental models are no less important.

A vital aspect of the conceptualization step is synthesis. Synthesis is the process of taking the elements of the concept and arranging them in the proper order, sized and dimensioned in the proper way. Synthesis is a creative process and is present in every design.

3.9 Evaluation

The evaluation step involves a thorough analysis of the design. The term evaluation is used more in the sense of weighing and judging than in the sense of grading. Typically the evaluation step may involve detailed calculation, often computer calculation, of the performance of the design by using an analytical model. In other cases the evaluation may involve extensive simulated service testing of an experimental model or perhaps a full-sized prototype.

An important consideration at every step in the design, but especially as the design nears completion, is checking. In general, there are two types of checks that can be made: mathematical checks and engineering-sense checks. Mathematical checks are concerned with checking the arithmetic and the equations used in the analytical model. Incidentally, the frequency of careless math errors is a good reason why you should adopt the practice of making all your design calculations in a bound notebook. In that way you won't be missing a vital calculation when you are forced by an error to go back and check things out. Just draw a line through the part in error and continue. It is of special importance to ensure that every equation is dimensionally consistent.

3.10 Communication of the Design

It must always be kept in mind that the purpose of the design is to satisfy the needs of a customer or client. Therefore, the finalized design must be properly communicated, or it may lose much of its impact or significance. The communication is usually by oral presentation to the sponsor as well as by a written design report. Detailed engineering drawings, computer programs, and working models are frequently part of the "deliverables" to the customer. It hardly needs to be emphasized that communication is not a one-time thing to be carried out at the end of the project. In a well-run design project there is continual oral and written dialog between the project manager and the customer.

3.11 Design Drawings

Engineering drawings are vital for communicating the design. Although at one time it could be assumed that most engineering graduates were proficient in engineering drawing, today the education of an engineer provides limited exposure to the subject. Clearly, the time devoted to engineering drawing in the present education of an engineer is not commensurate with the practical importance of the subject. Every engineer, who deals more than casually with design should be well grounded in the elements of orthographic projection, be able to read the language of engineering drawings fluently, and be able to produce an acceptable sketch that can be converted by a draftsman into an engineering drawing.

Engineering drawings also often contain instructions on 1) the surface roughness or surface treatment of the part, 2) the required heat treatment, and 3) the inspection or testing of the part. When the information is too detailed or voluminous, the drawing has a reference to a specification or standard that will supply the needed information.

Different kind of engineering drawings are used for various purposes. A detail drawing gives a complete description of the shape of a part using up to three orthographic views and possibly one or more section views. It provides all of the information for producing the part. The detail drawing specifies the material finished dimensions, surface finish, and any special processing (such as heating treating). Usually a separate drawing is made for each component. Such a drawing normally will include a parts list that identifies component part numbers, part names, and the required number of pieces. Schematic drawings show the manner in which components are connected together, as in a piping system or electronic control system. The components are shown in symbolic form in this type of drawing.

Three aspects of engineering drawing that are often overlooked in an introduction to the subject but are vital in design practice are dimensions, tolerance, and specification of surface finish. Careful attention to those aspects of engineering drawing can greatly improve the cost and quality of a design.

3.12 Tolerances

Tolerances must be placed on the dimensions of a part to limit the permissible variations in size because it is impossible to manufacture a part exactly to given dimensions. A small tolerance results in greater ease of interchangeability of parts, but it also greatly adds to the cost of manufacture.

Tolerances can be expressed in either of two ways. A bilateral tolerance is specified as a plus or minus deviation from a basic dimension, e.g., 2.000±0.004 in. This system is being replaced by the unilateral tolerance, in which the deviation in one direction from the basic dimension is given. For example,

2.000+0.008 or 5.005+0.000

-0.000 -0.005

In the case of bilateral tolerance, the dimension of the part would be permitted to vary between 1.996 and 2.004 in for a total tolerance of 0.008 in. If unilateral tolerances have the advantages that they are easier to check on drawings and that a change in the tolerance can be made with the least disturbance to other dimensions.

The American National Standards Institute (ANSI) has established eight classed of fit that specify the amount of allowance and the tolerance on the hole size *d* is the basic dimension, because most holes are produced by using produced to a nonstandard dimension. Consider a basic hole size of 2.000 in and a class (medium) fit.

Allowance $0.009(2)^{2/3}=0.0014$ in

Tolerance $\pm 0.0008(2)^{2/3}=0.0010$ in

Hole

Maximum dimension 2.001 in

Minimum dimension 2.000 in

Shaft

Maximum dimension 2.000- 0.0014=1.9986 in

Minimum dimension 1.9986-0.001=1.9976 in

Therefore, the maximum clearance between shaft and hole is

2.0010-1.9976=0.0034 in

And the minimum clearance between shaft hole is

2.00-1.9986=0.0014 in

3.13 Dimensions

The engineering drawing provides the manufacturing department with the information necessary for producing the part. Therefore, it is important that the dimensions of the part be clear and complete. The dimensions given should be sufficient in number to make it unnecessary for shop personnel to perform involved calculations for setting up the production equipment. On the other hand, too many dimensions can cause problems by resulting in ambiguity and leaving the manufacturing department with a choice.

3.14 Computer-Aided Engineering

The advent of plentiful computing is having a major impact on how engineering is practiced. While engineers were one of the first professional groups to adapt the computer to their needs, the early applications chiefly were computational intensive ones.

The greatest impact of computer-aided engineering to date has been in engineering graphics. The automation of drafting in two dimensions (CAD) has become commonplace. Such geometric modeling capabilities tie in nicely with analysis capabilities introduced through extensive use of finite element modeling (FEM). This makes possible interactive simulations in such problems as stress analysis, kinematics of mechanical linkages, and numerically controlled tool path generation for machining operations. The computer extends the designer's capability in several ways. First, by organizing and handling time-consuming and repetitive operations, it frees the designer to concentrate on more complex design situations. Second, it allows the designer to analyze complex problems faster and more completely. Both of these factors make it possible to carry out more iterations of design. Finally, through a computer-based information system the designer can share more information sooner with people in the company, like purchasing agent, tool and die designers, manufacturing engineers, and process planners, who need the design information. The link between computer-aided design (CAD) and computer-aided manufacturing (CAM) is particularly important, and often difficult to achieve.

3.15 Computer-Aided Design

The widespread use and decreasing cost of the computer have brought about a revolution in the practice of engineering design. There are two different aspects to this fantastic change in design practice.

- Through on-line interaction with the computer in real time, the designer is able to utilize the computer and its graphics input-output devices to perform many of the routine aspects of design at far greater speed and lower cost. For example, the designer is able to draw objects on a graphics display terminal and, by utilizing computer software, portray the object in a three- dimensional view, and oblique view, or in any cross section.
- By employing computer software codes based on the finite-element method, the designers are able to perform powerful analytical procedures. The actual structural members under analysis can be displayed graphically. Graphical simulation, such as how a structure deforms under load, and be observed. The interactive mode of communication with the computer through the graphics terminal permits easy iteration procedures and design optimization.

The development of the finite-element method (FEM) coupled with computer analysis has created a new and powerful tool for the analysis of engineering problems. Now the analysis can be performed on a complex shape with the actual loads rather than use a simplified geometry and/or loads for which a solution is available.

3.16 Design Review

The design review is a vital aspect of the design process. It provides an opportunity for specialists from different disciplines to interact with generalists to ask critical questions and exchange vital information. A design review is a retrospective study of the design up to that point in time. It provides a systematic method for identifying problems with the design, aids in determining possible courses of action, and initiates action to correct the problem areas.

To accomplish these objectives the review team should consist of representatives from design, manufacturing, marketing, purchasing, quality control, reliability engineering, and field service. The chairman of the review team is normally a chief engineer of project manger with broad technical background and broad knowledge of the company's products. In order to ensure freedom from bias the chairman of the design review team should not have direct responsibility for the design under review.

Depending on the size and criticality of the project, full-scale design reviews should be held at three or four times in the life of the project. The first review should be held when concept feasibility has been established. The problem definition and initial specifications should be critically examined with respect to the needs of the marketplace. If the feasibility study has been done by the research laboratory, them this review is especially critical to pass on information to the engineering group. Sometimes an intermediate design review is conducted before the detail drawings have been completed. This review would look critically at the interfaces between the specialty design teams, e.g. mechanical, electronics, materials, and begin to discuss tooling and packaging. A design review after the detail drawings are complete will ensure that the dis8ign is ready for prototype testing. A review after the completion of prototype testing is critical to ensure that there are no loose ends to the project. The purpose of this review is to fine-tune the design prior to authorizing full-scale production. This review focuses on achieving the performance, producibility, cost, and reliability goals. There may also need to be a final acceptance review prior to handing the project over to the customer.

It is helpful to prepare a checklist for the design review. The major headings should consist of:

1. Design requirements
2. Functional requirements
3. Environmental requirements
4. Manufacturing requirements
5. Reliability-related requirements

For each item under these headings answer yes or no as to whether the condition has been fulfilled by the design.