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Engineering Design: A Systems Approach

Krishna B. Misra

RAMS Consultants, Jaipur, India

Abstract: The purpose of this chapter is not to deal with all the aspects of design of an engineering system, but to discuss the design process using the systems approach, which the design department or section of a manufacturing concern, particularly in the electronics, aerospace, machine tool sector and the producers of consumer goods such as automobiles, office equipment, and household appliances and in many other areas, can use. For a manufacturer, the *research function* helps develop new products or useful design modifications to an existing product range and *development activity*, which is basically an engineering function aimed at converting the research concept into a viable product, is known as an R&D activity and sometimes it may be associated with design engineering as a project design and development function.

2.1 Introduction

The subject of system design has been dealt and discussed with in great detail ever since the dawn of the system age around 1940. The purpose of this chapter is to provide a broader outline of a scientific approach to the planning, design, development, manufacture and evaluation of engineering systems. It is basically aimed at realizing a coherent total system to achieve a specified objective subject to physical, environmental, state-of-the art techno-economic constraints. Any other approach may prove costly and untenable.

Historically, two approaches have been helpful in understanding the world around us. The first is called *reductionism* and is based on the assumption that everything can be reduced, decomposed, or disassembled to simple indivisible parts. Reductionism is basically an analytical approach and involves disassembling of what is to be explained down to independent and indivisible parts of which it is composed; and offers the explanation of the whole by aggregating the explanations of the behaviour of these indivisible parts.

The other approach is that of the *mechanism,* in which all phenomena are explained by using a cause and effect relationship. An event or a thing is considered to be the *cause* of another event or thing (called the *effect*) and a cause is sufficient to explain its effect and nothing else is required. It employs what is known as c*losed-system* thinking in which the search for causes is environment free and the laws for the phenomena are formulated in laboratories so as to exclude environmental effects. It is *mechanization* that brought about the *industrial revolution,* which in effect helped substitute men by machines in order reduce physical labour. However, with the decline of the machine age, a concept came into existence that heralded the dawn of the system age, which considers all objects and events, and all of their experiences, are parts of a larger whole. This concept is better known as *expansionism* and provides another way of viewing things around us; a way that is different from reductionism but compatible with it. However, this does not mean that there are no parts, but that focus is on the whole. It shifts the focus from ultimate elements to a whole with interrelated parts-to-systems.

2.1.1 Analytic Versus Synthetic Thinking

In the *analytic* approach that was associated with reductionism, an explanation of the whole was derived from explanations of its parts, whereas the systems approach has provided us with a *synthetic* mode of thinking and in this approach, one is more interested in putting things together rather than in tearing them apart analytically. In fact, *analytic thinking* can be considered as an *outside-in approach* whereas *synthetic thinking* is an *inside-out* approach of thinking.

The synthetic mode of thinking [1], when applied to physical problems is known as the *systems approach* and is based on the fact that even if each part of a system performs as well as possible, the system as a whole may not perform as well as possible. This follows from the observation that the sum of the functioning of the parts is quite often not equal to the functioning of the whole. Therefore, the synthetic mode seeks to overcome the often-observed predisposition to perfect details and ignore system outcomes.

All man-made artefacts, including products, equipment and processes are often termed *technical systems*. Engineering activities such as analysis and design for man-made or technical systems are not an end in them and may be viewed as means for satisfying human needs. Therefore, modern engineering has two aspects. One aspect addresses itself to materials and forces of nature whereas the other addresses itself to the needs of people. Successful accomplishment of engineering objectives requires a combination of technical specialties and expertise. Engineering in the systems approach necessarily has to be teamwork, where the involved individuals are aware of the relationships between the specialties, economic considerations, and ecological, political, and social factors. Today, engineering decisions require serious consideration of all these factors right in the early stage of system design and development as these decisions have a definite impact subsequently. Conversely, these factors usually impose constraints on the design process. Thus, technical aspects not only include the basic knowledge of the concerned specialties of engineering but also the knowledge of the context of the system being developed.

2.2 The Concept of a System

The word "*system*" has a very wide connotation. Broadly speaking, we have a wide variety of systems around us. Several of them have been created by man to satisfy his needs while others exist in nature. *Natural systems* are those that came into existence through natural processes whereas *man-made systems* are those in which human beings intervene through components, attributes, or relationships. Examples of man-made systems are highways, railways, waterways, marine and air transport, space projects, chemical plants, nuclear plants, electrical power generation, distribution and utilization, housing and office complexes, mining and oil extraction, *etc*. Even in the context of nanotechnology [2], nanosystems are systems and the principles of system engineering naturally apply to them. Solid mechanics, system dynamics, mechanisms and control theory are all relevant to nanotechnology and all enable technologies in future. Therefore, the word system may connote anything ranging from simple, artificial or composite, physical systems to conceptual, static and dynamic systems or even organizational and information systems. However, man-made systems are invariably imbedded into the nature [3], therefore interfaces exist between man-made systems and natural systems, and man-made systems in turn influence natural systems.

2.2.1 Definition of a System

A system can be defined as an aggregation of parts or elements, connected in some form of interaction or interdependence to form a complex or unitary whole. In other words, *a system is a set of mutually related elements or parts assembled together in some specified order to perform an intended function*. Not only do we have systems that are assemblies of hardwired units but we also have abstract systems such as the education system, the social system, the monitory system, a scheme of procedures, *etc*. Not every set of items, facts, methods or procedures is a system. A random collection of items cannot be called a system because of the absence of purpose and unit's functional relationship. At most, it can be called a set of objects but not a system. This is a very broad definition and allows anything from a power system down to an incandescent lamp to be classified as a system provided a system must have an objective or a function to perform

2.2.2 Classification of Systems

In order to provide a better understanding of the systems that we shall be concerned with, it would not be out of place to mention here the broad classification of systems. Physical systems are those that manifest themselves in some physical form while conceptual systems are those, where the attributes of components are represented by symbols, ideas, plans, concepts and hypotheses. A physical system occupies physical space whereas conceptual systems are organizations of ideas. Conceptual systems often play an important role in the operations of physical systems in the real world. A static system has a structure without any activity whereas a dynamic system constitutes structural arrangement with some activity. Many systems may not be classified in this broad category because they may lack the notion used here. For example, a highway is a static system yet it constitutes of components, attributes and relation of dynamic systems.

A closed system is one that does not interact significantly with its environment and it exhibits the characteristics of equilibrium resulting from the internal rigidity that maintains the system in spite of influences from the environment. In contrast, an open system allows information, energy and matter to cross its boundaries. Open systems interact with their environment. They display steady state characteristics whereas in a dynamic interaction of systems, the elements adjust to the changes in the environment. Both closed and open systems exhibit the property of entropy, which may be defined as the degree of disorganization in a system and uses the term analogously to thermodynamics. Actually, entropy is the energy not available for work when energy transformation takes place from one form to the other.

In a large variety of natural or man-made systems, the inputs, processes and the outputs are described mostly in statistical terms and uncertainty exists in both the number of inputs and their distribution over time. Therefore, these features can be best described in terms of probability distributions and the system operation is known to be probabilistic.

Many of the existing systems today in the sphere of energy, transportation, information, computer communication, production, *etc.,* are all artificial or man-made. However, they can influence or be influenced by natural systems at the same time and can also be composite.

As far as this handbook is concerned, we shall deal exclusively with engineering systems. However, the system concepts and analyses presented here may be applicable to any other category of systems as well. The scope of engineering systems itself is so vast that no generalization is possible to handle such systems. However, one specific feature of engineering systems, unambiguously and strikingly, is that they are all man-made and both their elements and the system as a whole can be called products. Nevertheless, man's presence in an engineering system and his role in its functioning, may change from system to system. In any case, man shall always be regarded as an element of the system. Secondly, an engineering system must be trustworthy and dependable otherwise it cannot serve the purpose it was intended.

2.3 Characterization of a System

Most of the engineering systems today belong to the category of *complex* systems. Although such a distinction between simple and complex systems is totally arbitrary, the degree of complexity of a system relates to the number of elements, their physical dimensions, multiplicity of links or connections of the constituent elements within the system, multiple functions, *etc*. The complexity of a system can be best defined based on the complexity of its structure and the functions performed by the system.

2.3.1 System Hierarchy

A system is a top-down approach and has basically three levels of hierarchy [4], *i.e., systems, subsystems* and *components*. In such a hierarchy, a *component* is defined as the lowest level of hierarchy in a system and is a basic functional unit of a system. Components, in the system definition should be regarded as those units of the system, which can be assumed indivisible in context of the problem being considered at hand. Sometimes we may use the word *element* (the fundamental unit) to mean a component. The assembly of components connected to produce a functional unit is designated as a *subsystem*. It is the next higher level of hierarchy in a system, after the component. Finally, an assembly of subsystems connected functionally to achieve an objective is called a *system*. It is the highest level of hierarchy in the concept of a system.

Sometimes terms like *element*, *product*, *unit*, *equipment, etc*., are also used interchangeably to mean a system, a subsystem or even a component depending upon the context of level of system hierarchy.

2.3.2 System Elements

Regardless of the level of hierarchy of a system, it always comprises *items*, *attributes* and *relationships* to accomplish a function, where:

- *Items* are the operational parts of a system consisting of input, process and output;
- *Attributes* are the properties of the items or components of a system that are discernible,
- *Relationships* are the links between items and attributes.

Therefore, a system can be considered as a set of interrelated items or units working together to accomplish some common objective, purpose or goal. The purposeful action performed by a system is called as its *function*. Once the objective of a system is defined, system items can be selected to provide the intended output for each specified set of inputs. The objective also makes it possible to establish a measure of effectiveness, which indicates how well the system will perform.

A system usually involves transformation of material, energy or information, which in turn involves *input*, *process* and *output*. In fact, a system that converts material, energy or information involves structural components, operating components and flow components. Standard components are usually the static parts.

A system has [5] its limits and boundaries. Any thing outside the boundaries of a system is called its *environmen*t and no system can ever remain isolated from it. Materials, energy or information must pass through the boundaries as an *input* to the system whereas material, energy or information that passes from the system to the environment is called its *output*. However, the constraints imposed on the system limit its operation and define the boundary within which it has to operate. In turn, the system imposes constraints on the operation of its subsystems and consequently on its components. Therefore, at all levels of the system hierarchy, there are inputs and outputs. The output of one item can be input to another. Inputs can be physical entities like materials, stresses or even information.

2.3.3 System Inputs and Outputs

An input to a system can be defined as any stimulus, or any factor whose change will invoke some kind of response from the system.

Usually, we have three groups of inputs, namely,

- *Component parameters,*
- *Operating condition parameters,*
- *External inputs.*

The component parameters are those variables that are generally determined by the hardware design, whereas the operating condition parameters determine the state of the system in terms of operating conditions and environmental parameters, and the external inputs are the inputs, such as power supply voltage, input signal voltage, *etc*.

An input applied to the system will result in a response, which depends on the system condition and the input. This result is called the output of the system. Here again, we may have the following subdivisions:

- Primary outputs,
- Secondary outputs.

For example, primary outputs could be the power output of an amplifier or the output voltage of a stabilized power supply, whereas the secondary outputs may be regarded as the power dissipated in components, the voltage across a capacitor, noise or vibrations generated, *etc*.

2.4 Design Characteristics

Engineering design is a function that usually employs established practices to produce hardware specifications for the solution of a given problem. The design should be *functional* and must be one which, when translated into hardware, will satisfactorily perform the functions for which it was designed. The design should be *reliable*, which means when the design is translated into hardware, it must not only function but also continue to meet the full-range functional requirements over the required period of time throughout the specified range of environments. If the system is maintainable and its maintenance is anticipated, the design must provide adequately for *maintainability.*

The design must be *producible* and should be economically produced by the available production facilities and supplies. The design must be *timely* and should be completed and released within the established time schedule, which may be established either by a contract, or by the deadlines dictated by compulsions of change of model, or by competitors. The design must be *competitive* and *saleable*. However, the factors involved in saleability vary widely and may include *cost*, *special features*, *appearance*, and several other factors.

As far as possible, a designer should employ proven design techniques. When design objectives cannot be met by proven and familiar design practices, the designer is expected to employ new methods, borrow design techniques from other industries, or use available new *state-of-the-art* materials and processes. Since designers are generally supposed to be creative, it is often difficult for them to resist trying something new even though a technique of proven effectiveness and reliability exists. It is the responsibility of management to establish a system that makes it easier for a designer to use proven design than to try unproven design. Also as all system objectives cannot be met to the fullest extent in a design, the designer should be encouraged to attempt a trade-off between the set of important objectives.

By specifying unusually tight tolerances or use of exotic materials, a designer may be able to increase reliability but generally at the expense of producibility. Sometimes, a designer may be tempted to take chances with lowered reliability design without demonstrating its ability to function under the worst scenario of environment and ageing, so that the design is released on schedule. Some of these compromises and trade-offs are unavoidable. The management has the necessary information and responsibility to make decisions in this respect. However, the designer must disclose the fact that trade-offs have been made and the reasons for making these decisions to the reliability section and to the management.

To accomplish a system design, the design management must set clear-cut design objectives. These design objectives may be either imposed by the user or by the general management, or they may be developed within the design organization for submission to and acceptance (with or without modification) by the general management.

The design process necessitates a very high degree of creativeness, technological insight, and flexibility. At the initial stage, several activities like brainstorming, consultations, literature search, interviewing, systems engineering, and so on, are carried out. In the feasibility study, a designer must apply his mind and all his experience and creativity him in proposing a number of plausible solutions. Once the feasibility study has been completed, the design has advanced to a point where a number of *alternative solutions are available for further study*. This marks the beginning of *the preliminary design phase*.

The first step in the preliminary design phase likewise depends upon the designer, who is to choose for further study the most promising configuration or topology from the feasibility analysis. Having done this, the rest of the preliminary design is carried out without changing the system configuration or topology. The designer has to choose the specifications and component parameters such that the best possible alternative within the limitations of a fixed topology results, duly considering component parameter variations and conditions of use including environmental effects.

The last phase of the design process is the *detailed design phase*, which brings the design to detailed part specifications, assembly drawings, testing of prototypes, *etc*. Following this phase, we come to the point where we may be planning for production and subsequently follow up with other stages such as distribution, utilized servicing, and retirement of the product of system.

2.5 Engineering Design

Basically, there are two main approaches in engineering design, *viz.,* the bottom-up and top-down approaches. In the case of bottom-up design, physical realizability in terms of known elements is assured, whereas the top-down design process ends with the system elements as its functional entities. Their physical realizability may not be guaranteed. In the top-down approach, the requirements are always satisfied at every step of the design process because it is an inherent part of the methodology, whereas in the bottom-up approach the methodology provides no assurance that that finally would happen.

2.5.1 Bottom-up Approach

Traditional engineering design is basically a *bottom-up approach*, where one starts with a set of known elements and creates a product or a system by *synthesizing* a set of specific system elements. It is also very rare that the functional requirements are met right in the first instance unless the system is quite simple. After determining the system's performance and deviations from what is desired, these elements and/or their configuration may be changed again and again till the desired performance is assured and the system objective is met. The process is known as the *bottom-up process* and is iterative in nature. Of course, the number of iterations naturally would depend on the complexity of the system being designed and the experience and creativity of a designer.

2.5.2 Top-down Approach

A more general methodology to engineering design is provided using the systems approach, which is actually based on a *top-down approach* to the design. There are two main features of the top-down process. First, the process is applicable to any part of the system. Starting with the system as a whole, repeated application of this process to various levels of system hierarchy will result in partitioning of the system into smaller and smaller *elements*, better known as *subsystems* and *components*. Second, the process is self-consistent. External properties of the whole system, as described by the inputs and outputs and relations between parts, must be reproduced by the external properties of the set of interacting elements.

The top-down approach also recognizes that general functions are available in transforming inputs into outputs and a designer abstracts from the particular case to the underlying generic case, and represents the genetic case by several interacting functional elements. The use of functional elements is the essential feature of the systems approach compared with systems integration in convention design. A particular functional element is applicable to a whole class of systems. Consequently, only a few such elements are required to realize many real systems.

Lastly, it may be emphasized that a systems approach is not intended to replace bottom-up design totally. Every end product incorporates physical objects working together to meet the desired objective. At any point in the design process there must be a transition from the functional to the physical. Thus almost all engineering designs may gainfully employ both methodologies. However, the first to be employed is supposed to be the systems approach, which will reduce the system complexity by decomposing it into its constituent elements and then bottom-up design can be used to realize the design elements physically.

2.5.3 Differences Between Two Approaches

The systems approach lays emphasis on the following aspects of engineering design:

1. The systems approach views the system as a whole, whereas conventional engineering designs have always covered the design of various system components but the necessary overview and understanding of how these system components effectively fit together is not outright obvious.
2. Emphasis in the past was primarily placed on the design and system acquisition activities, without considering their impact on production, operations, maintenance, support, and disposal. If one is to adequately identify the risks associated with the upfront decision-making process, these should be based on life-cycle considerations. The systems approach considers a *life-cycle orientation* that views all phases of the system's life, *i.e.,* system design and development, production and/or construction, distribution, operation, maintenance and support, retirement, phase-out, and disposal.
3. In the systems approach, emphasis is put on providing the initial *definition of system requirements* and on the specific design criteria followed by analysis to ensure the effectiveness of early decision making in the entire design process. The actual system requirements are well defined and specified, and the tractability of these requirements right from the system level downwards are transparent. In fact, in earlier designs, this type of early analysis in many new systems was always practically non-existent. The lack of defining such an early "baseline" often resulted in greater design efforts downstream, which subsequently often resulted in expensive system modifications.
4. *The systems approach necessitates an interdisciplinary team approach* throughout the design and development process. This ensures that all design objectives are addressed in an effective and efficient way.

Last but not least, the systems approach involves the use of appropriate technologies and management principles in a synergetic manner and its application requires a focus on the process, along with a *thought process* that should lead to better system designs.

2.6 The System Design Process

To design a system is to synthesize it. This requires selecting known elements and putting them into a new configuration. A design alternative is an arrangement to realize the system objective. Evaluation is a prediction of how good the design alternative would be if it were accepted for implementation. System design evaluation generally precedes the system analysis, which in turn, is preceded by synthesis. In fact analysis, evaluation and synthesis are followed in a cyclic order till the objective of system design is met. In order to make system design cost-effective and competitive, system design evaluation should be carried out as an essential technical activity within the design process. However, it should not be pursued in isolation. System design evaluation should necessarily be carried out regularly as an assurance of continuous design improvement. As one proceeds from the top-down approach in the early phases of system design and development, there is also a follow-on "bottom-up" procedure at the same time. During the latter phases of the preliminary and detail design and development phase, subsystems or components are combined, assembled, and integrated into the specified system configuration. This, in turn, leads to the iterative process of system evaluation. Inherent within the systems engineering process is always a provision for constant feedback and necessary corrective action.

2.6.1 Main Steps of Design Process

The designer's approach to design is basically the same whether it is design of a component or a part, a subsystem, or a system, and the difference lies only in in the degree with which the task is carried out. The following is the sequence of steps that are commonly executed during the design:

1. Develop one or more design concepts that satisfy the design objective.
2. Carry out the feasibility analysis of the various possible design concepts using personal experience or by theoretical analysis and simulation, or by experimentation and testing, or by combinations of these.
3. Choose the design concept that meets all of the design objectives. Apportion reliability or any other performance goal requirements at all levels down to the part level of system hierarchy.
4. Prepare preliminary specifications and drawings.
5. Based on preliminary drawings and specifications, pass on the design for fabrication and production and procurement of development hardware to be used for feasibility and evaluation testing of the hardware.
6. Plan qualification test requirements and participate in planning production test and inspection requirements.
7. Participate in the preparation of prototype and qualification testing, taking whatever corrective design action is found to be necessary.
8. Prepare the final design. It is at this point that the review of set of designed objectives is necessary.
9. Review and approve those portions of the design that are not created by the design section.
10. Release the completed design, after ensuring that the objectives of design and other required approvals, for manufacturing or fabrication or for the user's disposition as applicable, have been achieved.

The designer has several tasks to perform even after the design is released. Two of these functions, design-configuration control and design-change control, are closely related. All design-change requests must be fully and carefully reviewed for impact on design objectives such as inherent reliability as well as for other impacts. As the design approaches completion, design-change control must come under the direct control of top management, because it is difficult to stop most design organizations from making changes. Design-configuration control relates to the control of requirements for a specific model type of hardware, serial number or production block.

There are two approaches for executing the first two phases of the design, *viz.,* the feasibility study and the preliminary system design and the most common and realistic approach based on the foregoing practice of design is outlined in Figure 2.1(a), where the configuration is fixed at the discretion of the designer and formal optimization is subsequently applied only to this design. While choosing the most promising design from the feasibility study, a designer usually makes some rough calculation of the expected performance of the system. Needless to say, a comparison of designs can only be valid if each design has been optimized according to the same criterion. If the designs are acceptable, there is no point in comparing an optimized design to one that has not been optimized, as there is little to gain by comparing two non-optimized designs.

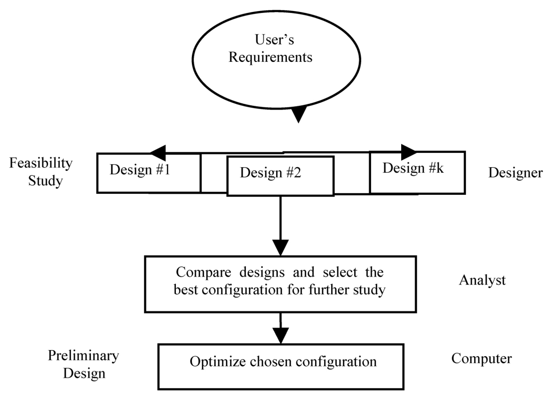

Figure 2.1(a). Common practice for system design

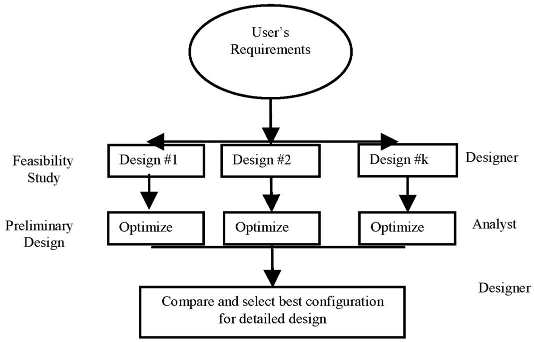

Figure 2.1(b). Ideal process for system design

Figure 2.1(b) shows the idealized structure for the first two phases of the design process. It would be unrealistic to consider this structure at all, if the design were not achieved through a computer optimization. It is, however, necessary to appreciate that the optimization of different design configurations can be quite time consuming; the designer must in each case prepare the specific actions for consideration.

It should be mentioned here that in either case the final design configuration is realized through the interaction of designer and analyst and very often we will need to do some iterations as the results of the preliminary design may sometimes provide ideas for minor changes in the design configuration.

2.6.2 Phases of System Design

Basically, any system design [6] evolves through the following phases of development:

- Conceptual Design
- Preliminary System Design
- Detail Design and Development
- System Test and Evaluation

2.6.2.1 Conceptual Design

This is the first phase in a system design and development process. Conceptual design is the foundation on which the life-cycle phases of the remaining stages of system design, *viz.,* preliminary system design, detail design and development, and system test and evaluation, are based.

Conceptual design evolves from:

- Functional definition of the system based on an identified need of the system and the requirements of the customer.
- Establishment of design criteria.

Therefore, system design is a process that starts with the need and definition of user requirements to a fully developed system configuration that is ready for production and delivery for subsequent use. To identify need, we must identify the deficiencies in the present design involving the customer if necessary; in fact, the customer should be associated with the design team throughout the design from start to end.

Once we have established the need, it is necessary to identify a possible design approach that can be pursued to meet that need and we can assess various approaches in terms of performance, effectiveness, maintenance, logistic support and economic criteria and select the best alternative. At this stage the possible technology can also be selected and the operational requirements of the system in terms of deployment, mission profile, utilization, environment of use and performance and effectiveness related parameters, *etc.,* can be developed. Maintenance and logistic support [7] for the system can also be designed at this stage. Having accomplished this, system specifications can be developed and a review of the conceptual design can be undertaken.

2.6.2.2 Preliminary System Design

This phase of design translates the system level requirements obtained from the conceptual design phase into subsystem level requirements and below for developing a system configuration. It also extends functional analysis and requirements allocation from the baseline, to the depth that is needed to identify specific requirements for hardware, software, man-power, facilities, logistic support, and other related resources. Subsystem functional analysis is basically an iterative process and decomposes requirements from the system level to the subsystem level and if desired to the components level if it is necessary to describe functional interfaces and identifying resource needs adequately. These resources may be in the form of hardware, software, people, facilities, data, or their combinations. Also allocation of resources along with statement of maximum or minimum specifications of all important parameters is done in this phase. A system design review is again undertaken to ensure that the overall requirements are being met and the results of the functional analysis and allocation process, the trade-off studies, the design approach selected, *etc*., are reviewed for compliance with the initially set requirements. All deviations are recorded, and the necessary corrective measures as considered appropriate are initiated. Results from this phase support detail design and development.

2.6.2.3 Detail Design and Development

The design requirements at this stage are derived from the system specifications and evolve through applicable lower-levels specifications. These specifications include appropriate design-dependent parameters, technical performance measures and associated design-to criteria for characteristics that must be incorporated into the design of system, subsystems and components. This is achieved by the requirements allocation process. Design requirements for each system element are specified through the process of allocation and the identification of detailed performance and effectiveness parameters for each element in the functional analysis *(i.e.,* input–output factors, metrics, *etc*.). Given this information, a designer can decide whether to meet the requirement by an item that is commercially available and for which multiple suppliers are available or by modifying an existing commercially available item off-the-shelf or by designing, developing and producing a new item to meet the specific requirement. Detail design documentation is an essential part of detail design phase and generates a database for the purpose of information processing, storage and retrieval so that it can be used during the testing and is also available for future designs. At this stage, the design may be evaluated through the fabrication of a prototype model or using a physical working model. Detail design review is undertaken generally after the detail design has been completed, but before the release of firm design data to initiate production and/or fabrication. The objective is to establish a good "*product baseline*". Such a review is conducted to verify the adequacy and producibility of the design. The design is then "frozen" at this point, and manufacturing methods, schedules and costs are re-evaluated for final approval and the product or system design may go for testing and evaluation. This baseline design should also be evaluated for environmental impact, social acceptability, *etc*.

2.6.3 Design Evaluation

The objective of design evaluation is to establish the *baseline* against which a particular design configuration can be evaluated. The whole idea of evaluation is that the functions that the system must perform to satisfy a specific user need should be assessed along with the expectations in terms of effectiveness, costs, time, frequency and any other factors. However, the functional requirements starting at the *system level* are ultimately expected to determine the characteristics that should be incorporated within the design of the system and its subsystems and components. The ultimate objective is to assess requirements at each level of system hierarchy in terms of hardware, software, facilities, people and data.

System evaluation is a continuous process and is undertaken starting with the conceptual design, and extends to the operational use and support phase, and concludes only when the system is retired. The objective of system evaluation is to determine (through a combination of prediction, analysis and measurement activities) true system characteristics and to ensure that the system successfully fulfils its intended purpose or mission.

2.6.4 Testing Designs

The test plan for testing a system may vary depending on the system requirements; however, a general outline of test plan is expected to include the following:

- The definition and schedule of all test equipment and details of organization, administration, and control responsibilities.
- The definition of test conditions including maintenance and logistic support.
- The description of test plans for each type of testing.
- A description of the formal test phase.
- The description of conditions and provisions for the retest phase.
- The test documentation.

The basic test plan serves as a valuable reference and indicates what is to be accomplished, the requirements for testing, the schedule for the processing of equipment and materials for test support, and data collection and reporting methods and so on. All this information is useful in developing an information feedback subsystem, in providing historical data that may be useful in the design and development of new systems in future of the same type or having similar function.

Also testing is done at each stage of design to ensure that the design is progressing in the intended direction and goal. For example, *feasibility testing* is done by the designer to prove the design concept and to choose the most promising concept from several possible design concepts. *Evaluation testing* is done to test early hardware in the operating and environmental conditions for which it was designed. Test procedures and test results are documented. Hardware, test equipment, and test procedures can be modified, if conditions require this. *Qualification testing* is done for formal proofing of the design against the design specifications. Corrective design action in the form of hardware redesign is taken if test results indicate the necessity for such design modifications.

2.6.5 Final Design Documentation

As is common with engineering design, the final design documentation usually includes the following:

- *Specifications:* These list the performance requirements, specify environmental conditions, establish system performance goals, and specify the basic logistic requirements.
- *Drawings:* These include coordination drawings, correlation drawings, production drawings procurement drawings, and drawings of special test equipments.
- *Parameters:* These documents detail the functional parameters with their tolerances starting at the operational-use end and working backwards to the supplier. Tolerances are tightened at each major step so that there is room for some functional parameters drift or degradation with time and transportation. These adjusted tolerances are called “funnels of tolerance”, with the small end of the funnel at the suppliers and the large end of the funnel at the users.

The design section usually produces the design documentation in consultation and approval of the product assurance department.

2.7 User Interaction

As we have seen in the earlier sections, the design begins with the specifications of more-or-less well-defined system requirements, and “users requirements”, which made the basis of a search for acceptable design solutions in a feasibility study acceptable in terms of both physical and economic soundness.

The user must be kept fully informed of the system limitations and the conditions of use for which it was intended. However, these must be agreed upon between the designer and the user. If the user has some special requirements to meet, they must be defined, in the system’s specifications, the exact conditions under which the system is intended to operate. Furthermore, the user must ensure that the system is subsequently operated within those conditions for the sake of the safety of the system. It is also necessary during system operation to invest in a sound user-training program and back it up with the assessment of actual conditions of use. This is expected to assist the designer to anticipate actual environments and adverse conditions during system operation, so that the designer makes due allowance for them and the possibility of failure is not overlooked. On the other hand, the designer can take the initiative to apprise the user of the conditions and environments of use that the designer expects the system may happen be operated in and the user must be given every opportunity to match this use of the system to the designer's anticipation.

The designer must receive adequate feedback of the in-service behaviour of the system design from the user. This feedback of field experience will let the designer know about the possible deficiencies in the existing design, so that remedial measures can be taken. It will also help designer to remove those deficiencies from future system designs.

In short, matching of the design to the requirements of the user in its intended environment requires intense and good communication between the designer and the user.

2.8 Conclusions

This chapter has discussed the basic design procedure generally followed for engineering systems design. It is observed that the systems approach is convenient and tractable as compared to the bottom-up approach that was commonly followed earlier. This will become more apparent from the subsequent chapters presented in this handbook.

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