Previous Page

be able to remove and replace a given package without having to remove and replace other packages in the process, or requiring an extensive amount of alignment and adjustment in the process.

3. In breaking down the system into subsystems, a configuration should be selected in which the "communications" between the subsystems is minimized. In other words, whereas the *internal* complexity in design may be high, the *external* complexity should be low. Breaking the system down into packages in which there are high rates of information exchange between these packages should be avoided.

An overall objective is to break the system down into elements so that only a very few critical events can influence or change the inner workings of the various packages that make up the overall system architecture. Accomplishing this objective should also facilitate the process of introducing new technology changes into the system for upgrading purposes and for the accomplishment of any system maintenance that may be required throughout the life cycle.[15]

Although the results of "partitioning" may constitute what is presented in Figure 2.21, the process for accomplishing it is better illustrated in Figure 2.22. System functions are identified, broken down into subfunctions, and grouped into three equipment units: Unit A, Unit B, and Unit C. The design should be such that any one of the three units can be removed and replaced without impacting the other units. In other words, there should be a minimum of interaction effects between the three units.[16]

2.8.2 Allocation of System-Level Requirements to the Subsystem Level and Below

With the identification of system elements, the next step is to *allocate* or *apportion* the requirements specified for the system down to the level desired to provide a meaningful *input* to design. This involves a top-down distribution of the quantitative and qualitative criteria developed through the QFD analysis described in Section 2.6. From the prioritized technical performance measures (TPMs), such as those identified in Figure 2.10, the designer needs to select and specify specific "design-to" requirements for each of the major elements of the system. For example, referring to Figure 2.22, what should be specified for each Unit A, Unit B, and Unit C in order to meet the system-level requirements in Figure 2.10?

The challenge is to first assign the appropriate factors at the unit level, considering complexity and utilizing historical experience and field data where available, prorating from the top down. Then synthesize these factors at the unit level and deter-

[15]The "open-architecture" approach to design is highly dependent on the functional packaging of system components and in meeting these objectives as stated.

[16]Attaining this objective is critical, particularly in view of today's trends pertaining to the increasing utilization of commercial off-the-shelf (COTS) items and extensive amount of outsourcing in the purchase and acquisition of major subsystems and large-scale components. The question is, Can we acquire and integrate a variety of COTS items, with a minimum of interaction effects among these items, and without destroying the overall system configuration (architecture) in the process?

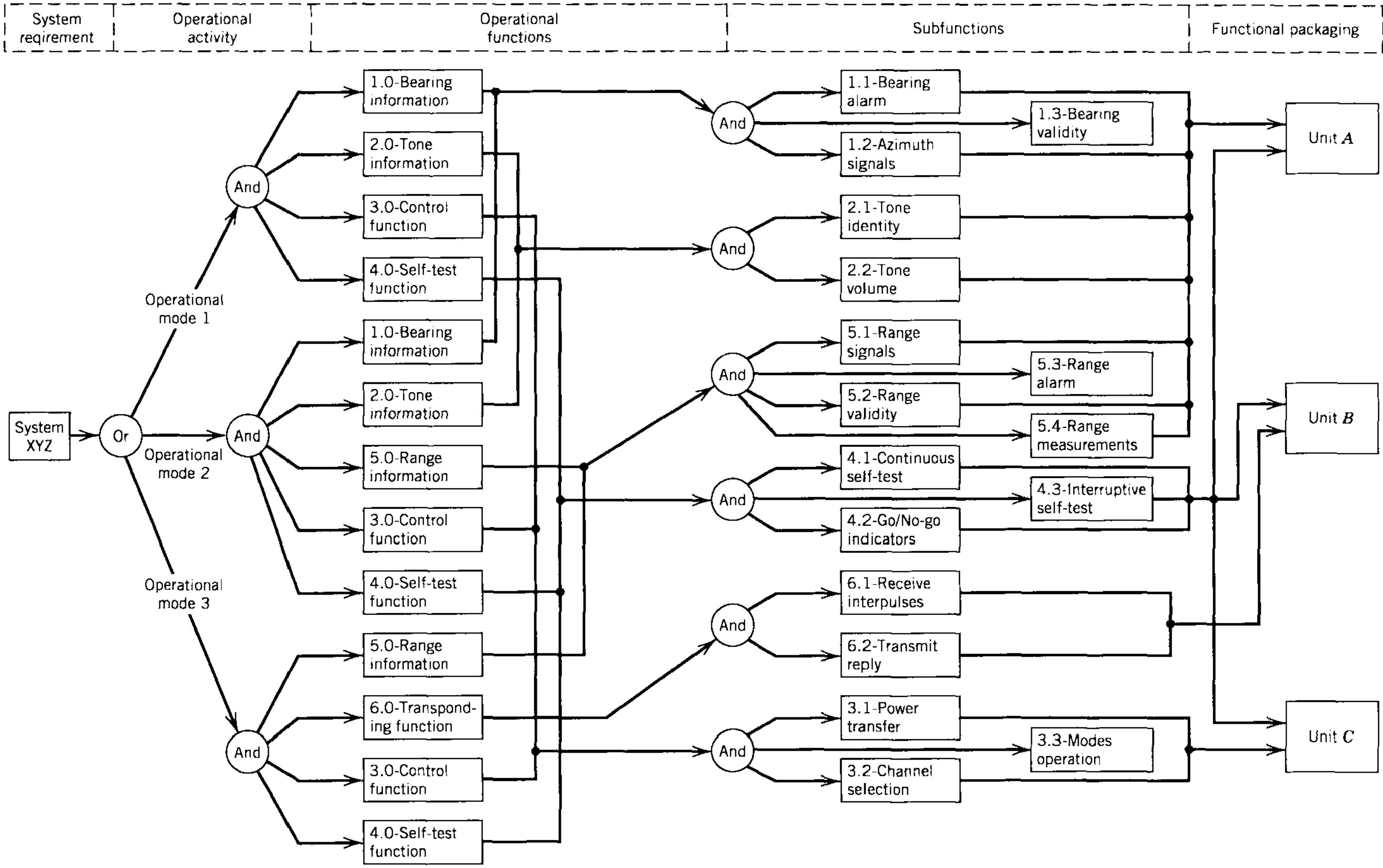

Figure 2.22 Abbreviated functional analysis leading to system packaging.

mine whether they are realistic and that, when combined, they will support the requirements for the system. There may be times when a given requirement for one of the units will be too stringent, considering the available technology and possible sources of supply. In such cases, the specific design-to criteria for the unit may be changed (less restrictive), which, in turn, will require a tightening of a requirement for one or more of the other units. In other words, there may be both a top-down and a horizontal process in which trade-off studies are accomplished in arriving at a final recommended solution. There may be several iterations of this process before the specific requirements for the applicable major system elements are defined.

Figure 2.23 shows the results of an allocation (in this instance to four units). Utilizing an "objective-tree" approach (illustrated in Figure 2.7), the designer established the appropriate metrics for the system, then the metrics at the next lower level, and so on. There should be a "traceability" of requirements from the top down and, although the measures vary somewhat at each level, those identified at the lower levels must directly support the requirements for the overall system. Further, the depth to which requirements are specified is somewhat dependent on the priorities (i.e., the "importance" factors) identified in Figure 2.10. If there is a highly critical requirement from the perspective of the consumer, the allocation may be accomplished to the assembly

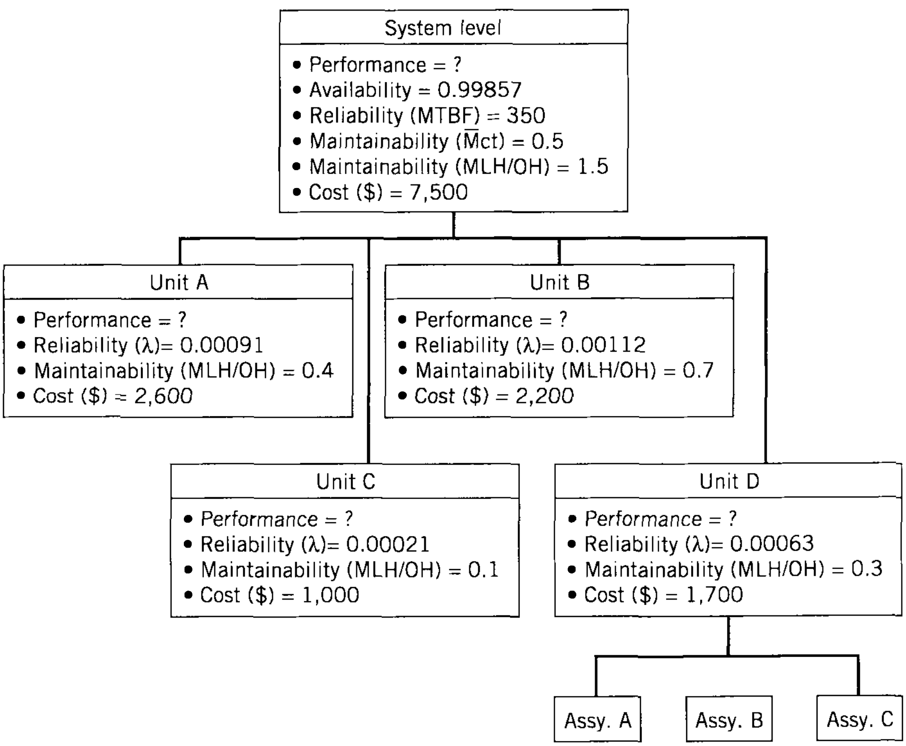

Figure 2.23 Allocation of system requirements.

level in Figure 2.23. On the other hand, if the allocation is accomplished unnecessarily to a very detailed level, the designer may be unduly constrained relative to what can be accomplished through the trade-off analysis and evaluation process.

The allocation process constitutes a top-down specification of design requirements to the depth necessary to provide *input criteria* for the appropriate system elements. Highly complex new designs will require a greater degree of coverage than would be necessary in utilizing commercial off-the-shelf (COTS) items. The results of the allocation process should be incorporated in the appropriate "specification" identified in Figure 1.12. If the requirements are not properly specified from the top down, the results can be costly in terms of possible *overdesign, underdesign,* or both. The risks may be high if the requirements are not addressed from the beginning.[17]

2.8.3 Traceability of Requirements (Top-Down/Bottom-Up)

In the system engineering process and evolution of requirements illustrated in Figure 1.12, there are a series of specifications developed to cover various design-to requirements, starting with the system level and including its various components. In Figure 1.12, a generic classification has been identified, commencing with the System Specification—Type "A," the top-level specification, and including various lower-level specifications (Types "B", "C", "D", and "E") covering new developments, the procurement of off-the-shelf products, processes, and materials. These generic categories of specifications are described in detail in Chapter 3 (Section 3.2); however, the important issue in this section is to ensure that (1) the proper *requirements* that have been defined for the system are included in the *system specification,* (2) the requirements for the various elements or components of the system that have been developed through the allocation process are included in the appropriate lower-level specification (i.e., *"B", "C", "D", or "E" specification* as applicable), and (3) that there is a complete "traceability" of requirements from the system specification and on down. In Figure 2.24, which illustrates a partial "specification tree" for a typical project, such requirements must evolve from the top down and, at the same time, the combined requirements included in the lower-level specifications must support the requirements for the system as stated in the system specification. In other words, the *requirements* for the system and its components must be properly reflected through a good set of specifications. This is particularly important in view of the "outsourcing" and the large number of suppliers (from all over the world) that are likely to be responsible for the development and production of various system components.

2.9 SYSTEM SYNTHESIS, ANALYSIS, AND DESIGN OPTIMIZATION

Synthesis refers to the combining and structuring of components in such a way as to represent a feasible system configuration. The requirements for a system have been established, some preliminary trade-off studies have been completed, and a baseline

[17]The allocation of reliability, maintainability, human, economic, and related factors is discussed further in Chapter 3.

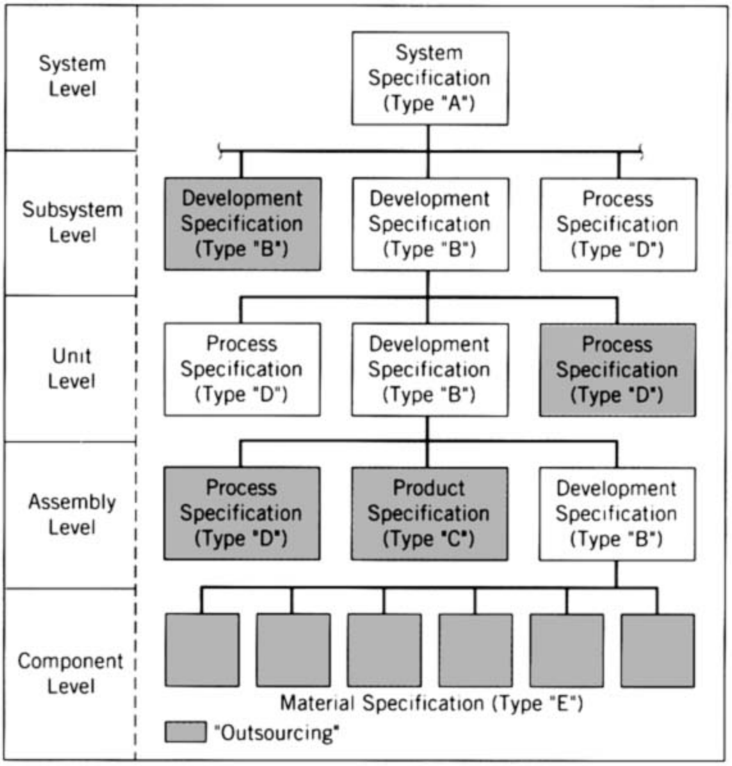

Figure 2.24 Specification tree (partial).

configuration must be developed to demonstrate the concepts discussed earlier. Synthesis is *design*. Initially, synthesis is employed to develop preliminary concepts and to establish basic relationships among the various components of the system. Later, when sufficient functional definition and decomposition have occurred, synthesis is used to further define the "HOWs" in response to the "WHAT" requirements. Synthesis involves the selection of a configuration that can be representative of the form the system will ultimately take, although a final configuration is certainly not to be assumed at this point.[18]

The synthesis process usually leads to the definition of several possible alternative design approaches, which will be the subject of further analysis, evaluation, refinement, and optimization. As these alternatives are initially structured, it is essential

[18]According to Sage and Armstrong, "synthesis" is the "step which involves searching for, or hypothesizing, a set of alternative courses of action or options. Each alternative must be described in sufficient detail to permit analysis of the impacts of implementation and subsequent evaluation and interpretation with respect to the objectives. As part of this step, we identify a number of potential alternatives and associated alternatives measures." A. P. Sage and J. E. Armstrong, *Introduction to Systems Engineering* (New York: John Wiley & Sons, Inc., 2000), p. 55.

that the appropriate technical performance parameters and associated measures be properly aligned to the applicable components of the system. For instance, technical performance parameters may include factors such as weight, size, speed, capacity, accuracy, security, volume, range, processing time, reliability, maintainability, and others as applicable. These parameters, or measures, must be prioritized and aligned to the appropriate elements of the system (e.g., equipment, unit or assembly, item of software, etc., as conveyed through the requirements allocation process described in Section 2.8).

In defining the initial requirements for the system, the technical performance measures (TPMs) are established based on their relationship and criticality to the accomplishment of the planned system mission; that is, the impact that a given factor has on cost-effectiveness, system effectiveness, and/or performance. These applicable TPMs are prioritized, and their relationships are presented in the form of design considerations, which, in turn, may be shown in the form of a hierarchical tree, as illustrated in Figure 2.25. The ranking of TPMs (and supporting design considerations), which will be built into the program management and review structure, will likely vary from one system to the next. A top-level measure for one system may be "reliability," whereas "availability" may be of greater importance in another example. In any event, the appropriate measures must be established, prioritized, and included in the specifications accordingly. As the design progresses, these measures will be used for the purposes of analysis and evaluation.[19]

Given a number of alternatives, the evaluation procedure progresses through the general steps illustrated in Figure 2.26 and described as follows:

1. *Definition of analysis goals:* An initial step requires the clarification of objectives, the identification of possible alternative solutions to the problem at hand, and a description of the analysis approach to be employed. Relative to alternatives, all possible candidates must be initially considered; however, the more alternatives considered, the more complex the analysis process becomes. Thus, it is desirable to first list *all* possible candidates to ensure against inadvertent omissions, and then eliminate those candidates that are clearly unattractive, leaving only a few for evaluation. Those few candidates are then evaluated with the intent of selecting a preferred approach.

2. *Selection and weighting of evaluation parameters:* The criteria used in the evaluation process may vary considerably, depending on the stated problem, the system being evaluated, and the depth and complexity of the analysis. In Figure 2.25, the parameters of primary significance include cost, effectiveness, performance, availability, and so on. At the detail level, the order of parameters will be different. In any event, parameters are selected, weighted in terms of priority of importance, and tailored to the system being addressed.

[19]It is important to emphasize the *process* whereby requirements are defined and prioritized as a result of a QFD analysis, allocated to the appropriate elements of the system, and subsequently addressed throughout the design in proportion to their respective level(s) of importance. In addition, these high-priority design factors must be inherent within and receive the appropriate attention through the applicable program management and review structure.

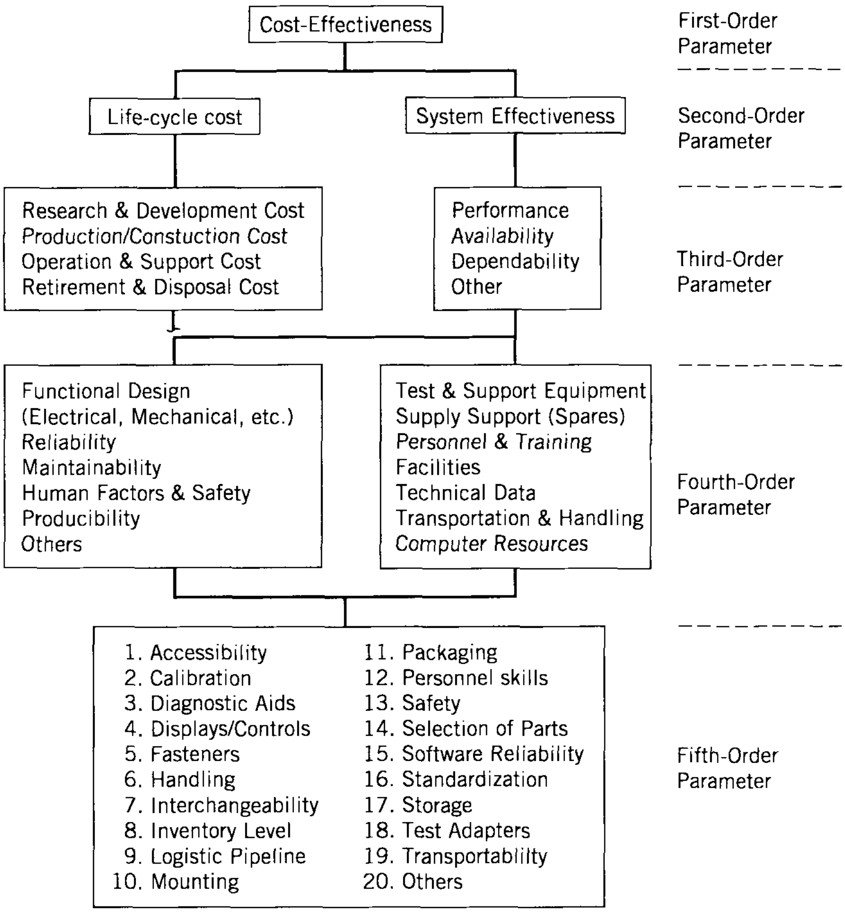

Figure 2.25 Order of evaluation parameters.

3. *Identification of data needs:* In evaluating a particular system configuration, it is necessary to consider operational requirements, the maintenance concept, major design features, production and/or construction plans, and anticipated system utilization and product support requirements. Fulfilling this need requires a variety of data, the scope of which depends on the type of evaluation being performed and the program phase during which the evaluation is accomplished. In the early stages of system development, available data are limited; thus, the analyst must depend on the use of various estimating relationships, projections based on past experience covering similar system configurations, and intuition. As the system development progresses, improved data are available (through analyses and predictions) and are used as an input to the evaluation effort. At this point it is important to initially determine the specific needs for data (i.e., type, quantity, and the time of need) and to identify possible data sources. The nature and validity of the data input for a given analysis can have a sig-

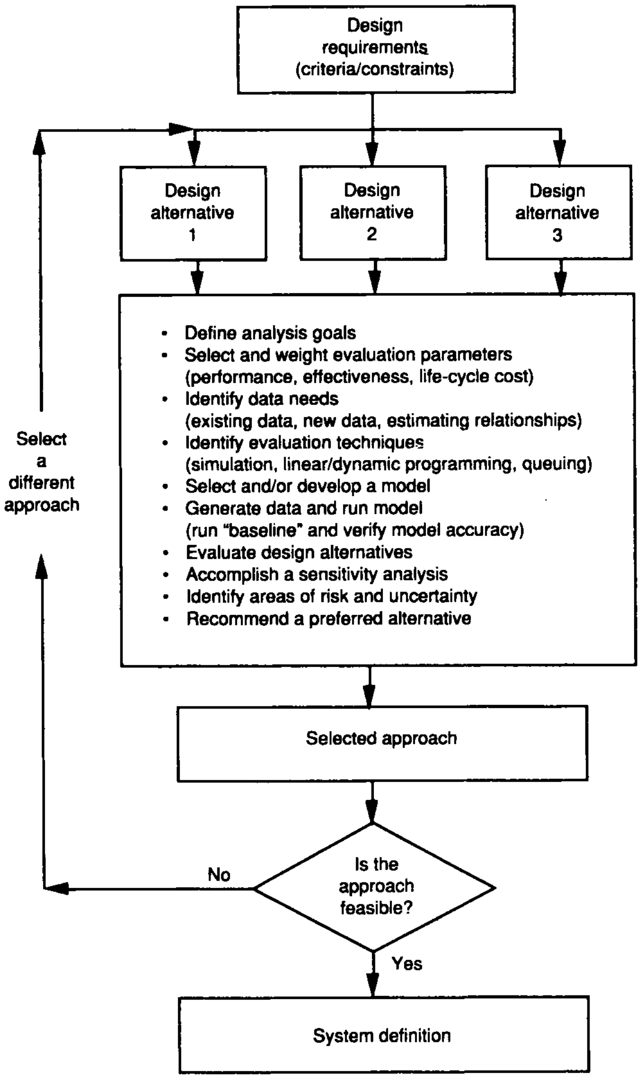

Figure 2.26 Evaluation of alternatives.

nificant impact on the risks associated with the decisions made based on the analysis results. Thus, one needs to accurately assess the situation as early as practicable.

4. *Identification of evaluation techniques:* Given a specific problem, it is necessary to determine the analytical approach to be used and the techniques that can be applied to facilitate the problem-solving process. Techniques may include the use of Monte Carlo simulation in the prediction of random events downstream in the life cycle, the use of linear programming in determining transportation resource requirements, the use of queuing theory in determining production and/or maintenance shop

requirements, the use of networking in establishing distribution needs, the use of accounting methods for life-cycle costing purposes, and so on. Assessing the problem itself and identifying the available tools that can possibly be used in attacking the problem are necessary prerequisites to the selection of a model.

5. *Selection and/or the development of a model:* The next step requires the combining of various analytical techniques into the form of a model, or a series of models, as illustrated in Figure 2.27. A model, as a tool used in problem solving, aids in the development of a simplified representation of the real world as it applies to the problem being solved. The model should (a) represent the dynamics of the system configuration being evaluated, (b) highlight those factors that are most relevant to the problem at hand, (c) be comprehensive by including *all* relevant factors and be reliable in terms of repeatability of results, (d) be simple enough in structure to enable its timely implementation in problem solving, (e) be designed so that the analyst can evaluate the applicable system configuration as an entity, analyze different components of the system on an individual basis, and then integrate the results into the whole, and (f) be designed to incorporate provisions for easy modification and/or expansion to permit the evaluation of additional factors as required. An important objective is to select and/or develop a tool that will help to evaluate the *overall* system configuration, as well as the *interrelations* of its various components. Models (and their applications) are discussed further in Chapter 4.[20]

6. *Generation of data and model application:* With the identification of analytical techniques and the model selection task accomplished, the next step is to "verify" or test the model to ensure that it is responsive to the analysis requirement. Does the model meet the stated objectives? Is it sensitive to the major parameters of the system configuration(s) being evaluated? Evaluation of the model can be accomplished through the selection of a *known* system entity and the subsequent comparison of analysis results with historical experience. Input parameters may be varied to ensure that the model design characteristics are sensitive to these variations and will ultimately reflect an accurate output as a result.

7. *Evaluation of design alternatives:* Each of the alternatives being considered is then evaluated using the techniques and the model selected. The required data are collected from various sources, such as existing data banks, predictions based on current design data, and/or gross projections using analogous and parametric estimating relationships. The required data, which may be taken from a wide variety of sources, must be applied in a consistent manner. The results are then evaluated in terms of the initially specified requirements for the system. Feasible alternatives are considered further. Figure 2.28 illustrates some considerations where possible feasible solutions fall within the desired shaded areas.

[20]There are many types of models, including physical models, symbolic models, abstract models, mathematical models, and so on. *Model,* as defined herein, refers primarily to a mathematical (or analytical) model. The development and application of various analytical methods are covered further in most texts on operations research. Two good references are (1) F. S. Hillier and G. J. Lieberman, *Introduction to Operations Research,* 6th ed. (New York: McGraw-Hill, 1995); and (2) H. A. Taha, *Operations Research: An Introduction,* 6th ed. (Upper Saddle River, NJ: Prentice-Hall, 1996).

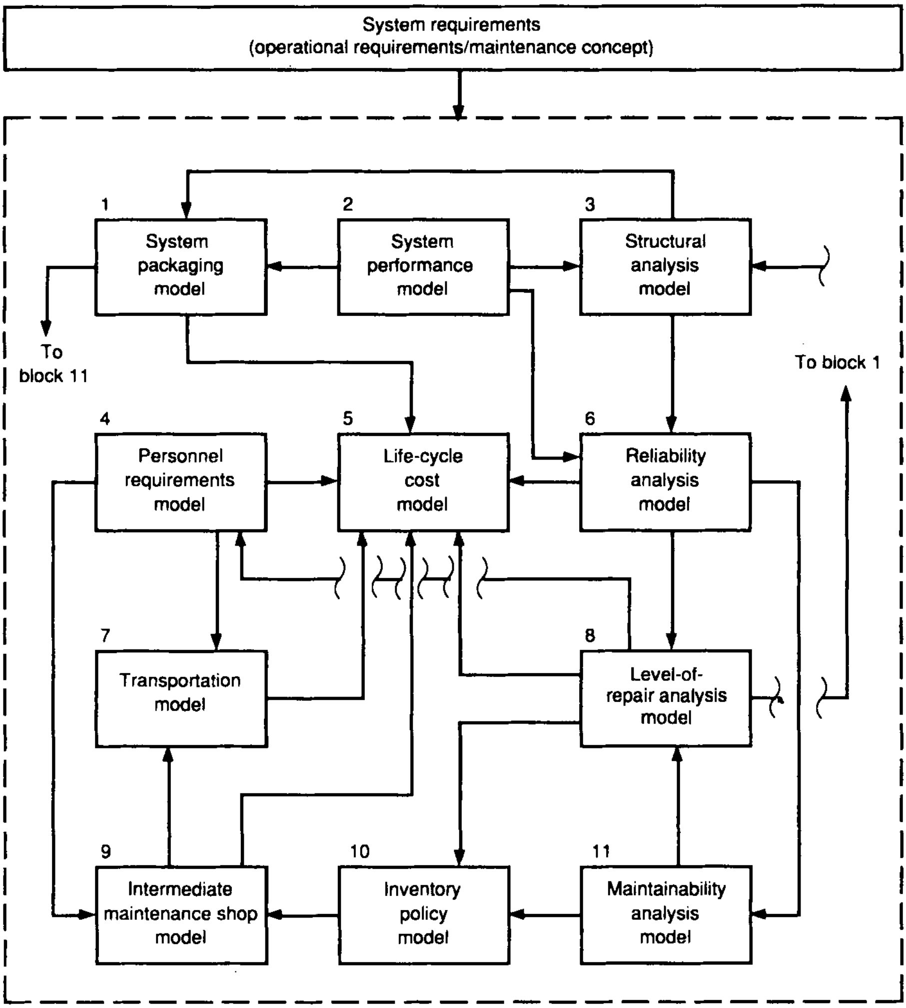

Figure 2.27 Example application of models.

8. *Accomplishment of a sensitivity analysis:* In the performance of an analysis, there may be a few key system parameters about which the analyst is uncertain because of inadequate data input, poor prediction procedures, "pushing" the state of the art, and so on. There are several questions that must be addressed: How sensitive are the results of the analysis to possible variations of these uncertain input parameters? To what extent can certain input parameters be varied before the choice of alternatives shifts away from the initially selected approach? Experience shows that there are certain key input parameters in a life-cycle cost analysis, such as the reliability MTBF and the maintainability (mean corrective maintenance time, $\overline{M}ct$) that are con-

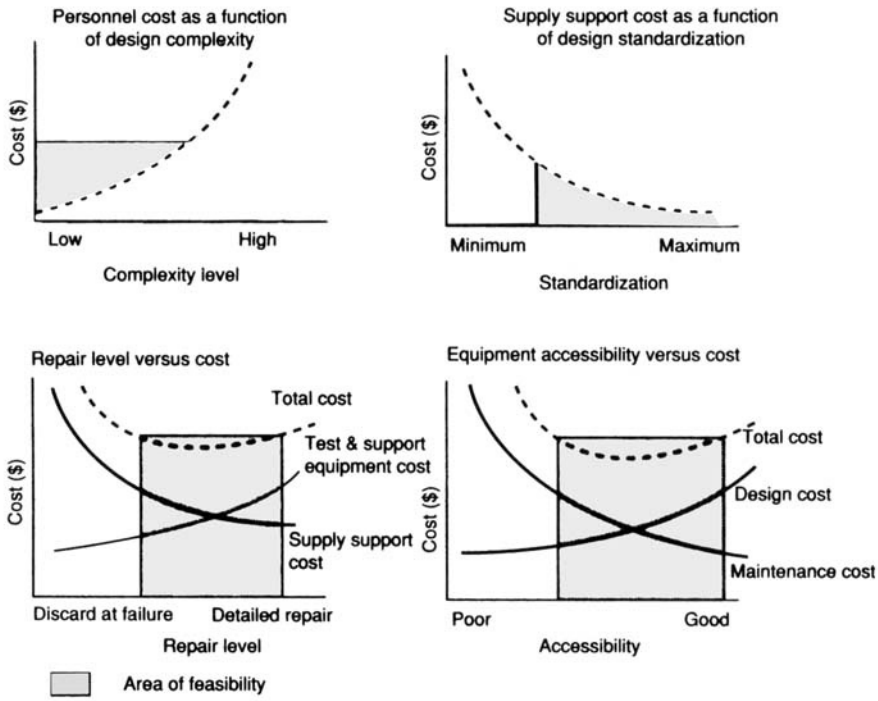

Figure 2.28 Example of evaluation results.

sidered to be critical in determining system maintenance and support costs. With good historical field data being very limited, there is a great deal of dependence on current prediction and estimating methods. Thus, with the objective of minimizing the risks associated with making an incorrect decision, the analyst may wish to vary the input MTBF and $\overline{\text{M}}$ct factors over a designated range of values (or a distribution) to see what impact this variation has on the output results. Does a relatively *small* variation of an input factor have a *large* impact on the results of the analysis? If so, then these parameters may be classified as being critical TPMs in the overall design review and evaluation process, monitored closely as design progresses, and an additional effort may be generated to modify the design for improvement and to improve the reliability and maintainability prediction methods. In essence, a sensitivity analysis is directed toward determining the relationships between design decisions and output results.

9. *Identification of risk and uncertainty:* The process of design evaluation leads to decisions having a significant impact on the future. The selection of evaluation criteria, the weighting of factors, the selection of the life cycle, the use of certain data sources and prediction methods, and the assumptions made in interpreting analysis results will obviously influence these decisions. Inherent within this process are the

aspects of "risk" and "uncertainty," because the future is, of course, unknown. Although these terms are often used jointly, *risk* actually implies the availability of discrete data in the form of a probability distribution around a certain parameter. *Uncertainty* implies a situation that may be probabilistic in nature, but one that is not supported by discrete data. Certain factors may be measurable in terms of risk or may be stated under conditions of uncertainty. The aspects of risk and uncertainty, as they apply to the system design and development process, must be integrated into the program risk management plan described in Chapter 6.

10. *Recommendation of preferred approach:* The final step in the evaluation process is the recommendation of a preferred alternative. The results of the analysis should be fully documented and made available to all applicable project design personnel. A statement of assumptions, a description of the evaluation procedure that was followed, a description of the various alternatives that were considered, and an identification of potential areas of risk and uncertainty should be included in this analysis report.

In Figure 1.12, the requirements for the system are established in conceptual design, functional analysis and the allocation of requirements are accomplished either late in conceptual design or at the start of preliminary design, and detail design is accomplished on a progressive basis from thereon. Throughout this overall series of steps, there is an ongoing effort involving synthesis, analysis, and design optimization. In the early stages of design, tradeoff studies may entail the evaluation of alternative operational profiles, technology applications, distribution schemes, or maintenance concepts. During early preliminary design, alternative methods for accomplishing a given function or alternative equipment packaging schemes may be the focus of the analysis. In detail design, the problems will be at a lower level in the overall hierarchical structure of the system.

In any event, the process illustrated in Figure 2.26 (and described herein) is applicable throughout the system design and development effort.[21] The only difference lies in the depth of analysis, the nature and type of data required, and the model used in accomplishing the analysis. For instance, one can perform a life-cycle cost analysis early in conceptual design, later in detail design, and as part of a system evaluation effort during the operational use phase. The same is true in accomplishing an FMECA, level-of-repair analysis, and so on. The process is the same in any case; however, the depth of analysis and the data requirements are different. The synthesis, analysis, and design optimization process must be tailored to the problem at hand. Too little effort will result in greater risks associated with decision making in design, and too much analysis effort may be expensive.[22]

[21]Although the emphasis here is primarily on the design and development of *new* systems, this process is equally applicable later in the life cycle in accomplishing system *validation* and/or *assessment* and in evaluating alternative ways in which a system can be improved/upgraded through modification.

[22]See Figure 1.14; one of the objectives in system engineering is to initiate and provide continuity in the application of various analytical methods/tools/models (i.e., an integrated "tool set") as one progresses from the system level of definition and on down to the development of the various system elements. There needs to be some type of "flow" process in this area as well.

2.10 DESIGN INTEGRATION

Design integration activities commence during the early stages of conceptual design and extend through system development, production and/or construction, distribution, operational use and sustaining support, and ultimate retirement and disposal (or recycling) of materials. As the requirements for a new system are established, the *design team* is formed, initially performing system-level design functions, as indicated in Figure 1.12. At this stage the design team may include only a small number of selected qualified individuals, with the objective of developing a comprehensive System Specification (Type "A"; refer to Figure 1.12). It is important that personnel with the appropriate backgrounds and experience be selected, and these individuals must be able to work together and effectively communicate on a day-to-day basis. The assignment of a large number of individual domain specialists, whose expertise lies in given technical fields, is not appropriate at this stage. The organization of design teams is discussed further in Chapter 7.

As system development progresses, the appropriate design specialists are added to the team. The objective, from a system engineering perspective, is to ensure that the right specialists are available at the time required and that their individual contributions are properly integrated into the whole. The selection of domain specialists is highly dependent on the requirements developed through the functional analysis and allocation process (refer to Sections 2.7 and 2.8). As the criteria for design will vary with the type of system and its mission, the emphasis in assigning those with the proper level of expertise to the team will be different from one project to the next. Figure 2.29 identifies some of the considerations that must be addressed through the design integration effort.

During the latter phases of the life cycle (i.e., production/construction, system utilization and support), the role of system engineering continues, but in the form of evaluation/validation and the introduction and processing of design changes as necessary. The requirement(s) for *change* may stem from some identified deficiency (i.e., the failure to meet an initially specified requirement), or may be established for the purposes of *continuous process improvement.* Each "engineering change proposal" (ECP) must be evaluated, not just in terms of performance issues alone, but in terms of reliability, maintainability, supportability or serviceability, producibility, disposability, and life-cycle cost as well. The design change and modification process is described further in Chapter 5.

Inherent in the established design team activity is the requirement for good communications on a day-to-day basis. Although the colocation of personnel in one geographical area (and "eyeball-to-eyeball" contact) is preferred, the trends toward outsourcing and decentralization often result in the introduction of many different suppliers located throughout the world.[23] Further, there are design activities being

[23]The term *outsourcing* refers to the practice of soliciting the support of product suppliers to accomplish selected packages of work externally from the producer or prime contractor. Experience indicates that there is a greater use of external suppliers today than in the past. This, in turn, provides some additional challenges relative to maintaining the proper level of communications across and throughout the project organization.

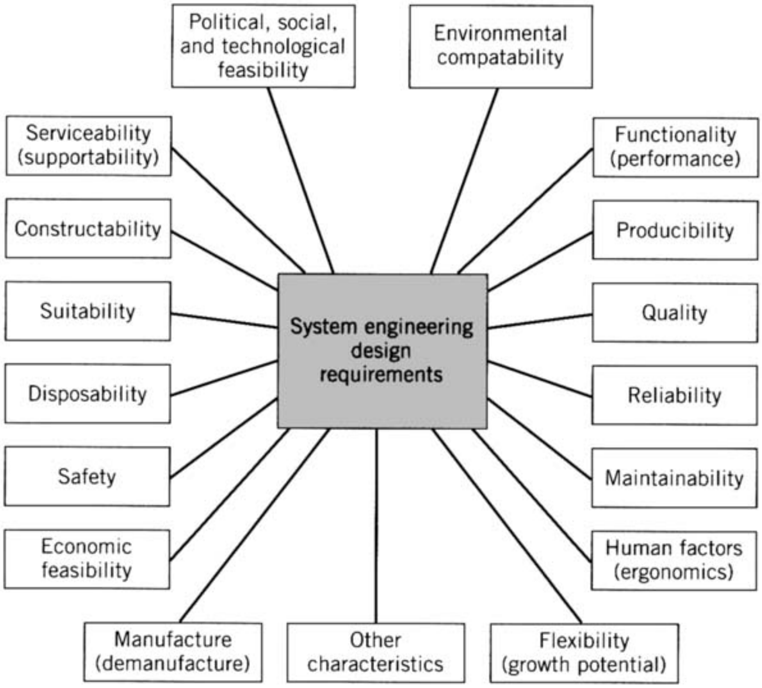

Figure 2.29 The integration of design requirements.

conducted at remote locations and being accomplished concurrently. Thus, the design team often becomes heavily dependent on the utilization of computer-aided tools, operating in a network such as illustrated in Figure 2.30.[24]

Successful implementation of the integrated computer-based network shown in Figure 2.30 is highly dependent on the structure of the design database. Such a database may include design drawings and layouts, the presentation of three-dimensional visual models, parts and materials lists, prediction and analysis results, supplier data, and whatever else is necessary to describe the system configuration as designed. The designer must be able to gain access to the database and provide input easily, and the results must be transmitted to other members of the design team accurately and in a timely manner. The data, usually presented in a digital format, must be available to all members of the design team concurrently. Instead of many different data items "flowing" back and forth between different members of the design team, between the producer (contractor) and consumer (customer), and so on, an integrated shared database structure is necessary, as illustrated in Figure 2.31. This, of course, should

[24]Included in this network is the proper mix of computer-aided design (CAD), computer-aided manufacturing (CAM), computer-integrated manufacturing (CIM), computer-aided support (CAS), and electronic commerce (EC) related tools utilized to varying degrees to accomplish design, production, and system support activities.

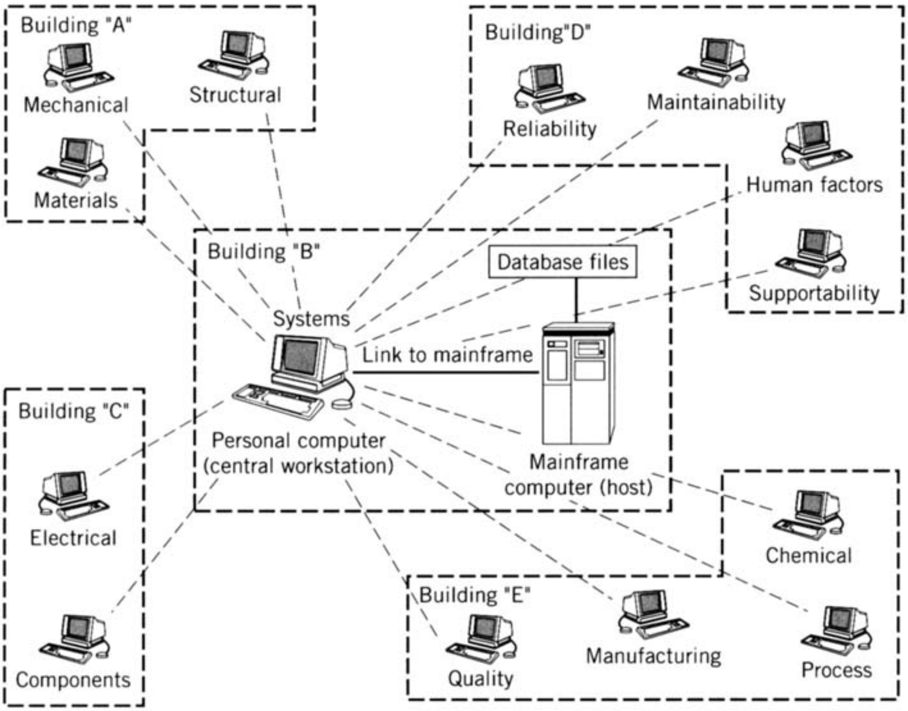

Figure 2.30 Design communication network.

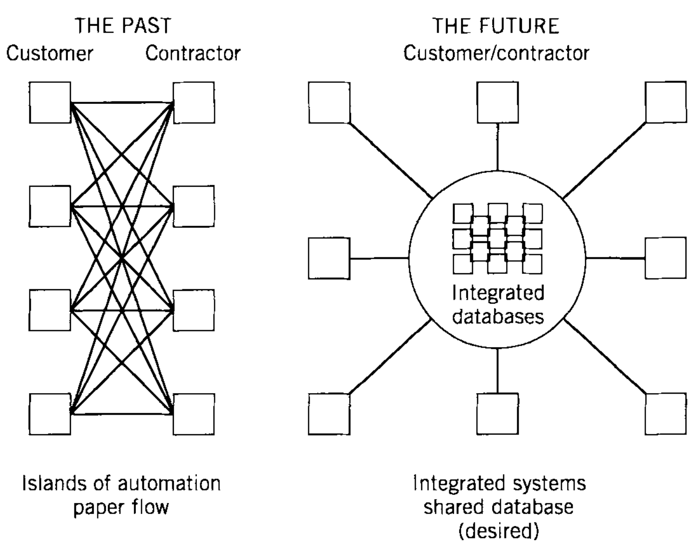

Figure 2.31 The data environment.

facilitate the process of communications, with every member of the design team having access to the same system description.[25]

2.11 SYSTEM TEST AND EVALUATION

As the system design and development activity progresses, there needs to be an ongoing measurement and evaluation (or validation) effort, as indicated in Figure 1.27. Realistically, a complete evaluation of the system, in terms of meeting the initially specified consumer requirements, cannot be accomplished until the system is produced and functioning in an operational environment. However, if problems occur and system modifications are necessary, the accomplishment of such an evaluation so far downstream in the life cycle may turn out to be quite costly. In essence, the earlier problems are detected and corrected, the better off the designer is in terms of both incorporating the required changes and the associated costs of modification.

In addressing the subject of evaluation, the objective is to acquire a high degree of confidence, as early in the life cycle as possible, that the system will ultimately perform as intended. Acquiring this confidence, through the accomplishment of laboratory and field testing involving a physical replica of the system (and/or its components), can be quite expensive. The resources required for testing are often quite extensive, and the necessary facilities, test equipment, personnel, and so on, may be difficult to schedule. Yet we know that a certain amount of formal testing is required in order to properly verify that system requirements have been met.

On the other hand, with a more comprehensive analysis effort and the use of prototyping, it may be possible to verify certain design concepts during the early stages of preliminary and detail design. With the advent of three-dimensional databases and the application of simulation techniques, the designer can now accomplish a great deal relative to the evaluation of system layouts, component relationships and interferences, human–machine interfaces, and so on. There are many functions that can now be accomplished with computerized simulation that formerly required a physical mock-up of the system, a preproduction prototype model, or both. The availability of computer-aided design (CAD), computer-aided manufacturing (CAM), computer-aided logistic support (CALS) methods, and related technologies has made it possible to accomplish much in the area of system evaluation relatively early in the system life cycle, when the incorporation of changes can be accomplished with minimum cost.[26]

In determining the need for test and evaluation, one commences with the initial

[25]With the advent of electronic commerce (EC) methods and new technologies on an almost continuing basis, it is anticipated that the nature of the *data environment* will be changing almost constantly. The objective here is to emphasize the need for good communications through the integration and effective transfer of design data among members of the design team, supporting organizations, and management.

[26]Through the years, the Department of Defense (DOD) has applied a number of different terms to cover the application of computer-aided methods to logistics. The term, *computer-aided logistic support* (CALS), is one, which, for the sake of convenience, is utilized periodically throughout this text. The purpose is to emphasize the importance of using electronic commerce (EC) processes in facilitating the accomplishment of logistics functions and in the processing of logistics information. Much of what has been included in CALS can be addressed within the spectrum of EC, which is much broader in scope.

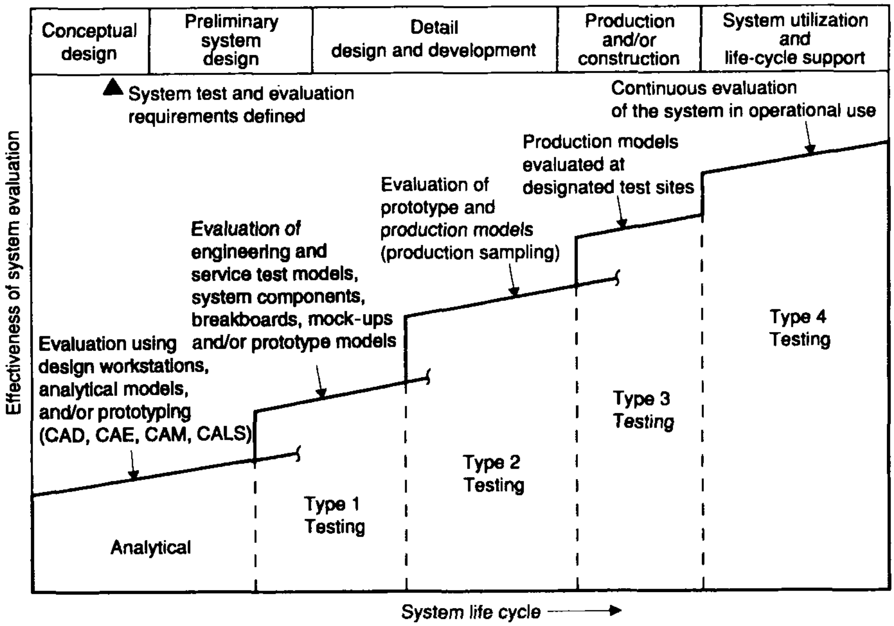

Figure 2.32 Stages of system evaluation during the life cycle.

specification of system requirements in conceptual design. As specific technical performance measures (TPMs) are established, it is necessary to determine the methods by which compliance with these factors will be verified. How will these TPMs be measured, and what resources are necessary to accomplish this? Responses to this question may entail using simulation and related analytical methods, using an engineering model for test and evaluation purposes, testing a production model, evaluating an operational configuration in the consumer's environment, or a combination of these. In essence, one needs to review the requirements for the system, determine the methods that can be used in the evaluation effort and the anticipated effectiveness of these methods, and develop a comprehensive plan for an overall integrated test and evaluation effort (i.e., Test and Evaluation Master Plan; refer to Figure 1.26). Figure 2.32 illustrates suggested categories of testing as they may apply in system evaluation.[27]

2.11.1 Categories of Test and Evaluation

In Figure 2.32, the first category is "Analytical," which pertains to certain design evaluations that can be conducted early in the system life cycle using computerized techniques such as CAD, CAM, CALS, simulation, rapid prototyping, and related approaches. With the availability of a wide variety of models, three-dimensional databases, and so on, the design engineer is now able to simulate human–equipment inter-

[27]The categories of test and evaluation may vary by type of system and/or by functional organization. These categories have been selected as a point of reference for discussion throughout this text.

faces, equipment packaging schemes, the hierarchical structures of systems, and activity/task sequences. In addition, through the utilization of these technologies, the design engineer is able to do a better job of predicting, forecasting, and accomplishing sensitivity/contingency analyses with the objective of reducing future risks. In other words, a great deal can be now accomplished in system evaluation that, in the past, could not be realized until equipment became available in the latter phases of detail design and development.

"Type 1 testing" refers primarily to the evaluation of system components in the laboratory using engineering breadboards, bench test models, service test models, rapid prototyping, and the like. These tests are designed primarily with the intent of verifying certain performance and physical characteristics and are developmental by nature. The test models used operate functionally, but do not by any means represent production equipment or software. Such testing is usually performed in the producer/supplier's laboratory facility by engineering technicians using "jury-rigged" test fixtures and engineering notes for procedures. It is during this initial phase of testing that design concepts and technology applications are validated and changes can be initiated on a minimum-cost basis.

"Type 2 testing" includes formal tests and demonstrations accomplished during the latter stages of the detail design and development phase when preproduction prototype equipment and software are available. Prototype equipment is similar to production equipment (that which will be delivered for operational use), but is not necessarily fully qualified at this point. A test program in this area may constitute a series of individual tests, tailored to the need, including the following:[28]

1. *Environmental qualification:* Temperature cycling, shock and vibration, humidity, sand and dust, salt spray, acoustic noise, explosion-proofing, and electromagnetic interference.
2. *Reliability qualification:* Sequential testing, life testing, environmental stress screening (ESS), and test, analyze, and fix (TAAF).
3. *Maintainability demonstration:* Verification of maintenance tasks, task times and sequences, maintenance personnel quantities and skill levels, degree of testability and diagnostic provisions, prime equipment–test equipment interfaces, maintenance procedures, and maintenance facilities.
4. *Support equipment compatibility:* Verification of the compatibility among the prime equipment, test and support equipment, and ground handling equipment.
5. *Technical data verification:* The verification (and validation) of operating procedures, maintenance procedures, and supporting data.
6. *Personnel test and evaluation:* Verification to ensure compatibility between the human and equipment, the personnel quantities and skill levels required, and training needs.

[28]"Qualified" equipment refers to the production configuration that has been verified through the *successful completion* of environmental qualification tests (e.g., temperature cycling, shock and vibration), reliability qualification, maintainability demonstration, and supportability compatibility tests. Type 2 testing primarily refers to that activity associated with the qualification of a system.

7. *Software compatibility:* Verification that software meets the system requirements, that there is compatibility between software and hardware, and that the appropriate quality provisions have been incorporated. This includes computer software unit (CSU) and computer software configuration item (CSCI) testing, as reflected in Figure 1.13.

Another facet of testing in this category is production sampling tests, used when multiple quantities of an item are being produced. Although the system (and its components) may have successfully passed the initial qualification tests, there must be some assurance that the *same* level of quality has been maintained throughout the production process. The process is usually dynamic by nature, conditions change, and there is no guarantee that the characteristics that have been built into the design will be retained throughout production. Thus, sample systems/components may be selected (based on a percentage of the total produced), and qualification tests may be conducted on a recurring basis. The results are measured and evaluated in terms of whether improvement or degradation has occurred.

"Type 3 testing" includes the completion of formal tests at designated field test sites by user personnel over an extended period of time. These tests are usually conducted after initial system qualification and prior to the completion of the production/construction phase. Operating personnel, operational test and support equipment, operational spares, applicable computer software, and validated operating and maintenance procedures are used. This is the first time that *all* elements of the system (i.e., prime equipment, software, and the elements of support) are operated and evaluated on an integrated basis. A series of simulated operational exercises are usually conducted, and the system is evaluated in terms of performance, effectiveness, compatibility between the prime mission-oriented segments of the system and the elements of support, and so on. Although Type 3 testing does not completely represent a fully operational situation, the tests can be designed to provide a close approximation.

"Type 4 testing," conducted during the system operational use and life-cycle support phase, includes formal tests that are sometimes conducted to acquire specific information relative to some area of operation or support. The purpose is to gain further knowledge of the system in the user environment, or of user operations in the field. It may be desirable to vary the mission profile or the system utilization rate to determine the impact on total system effectiveness, or it may be feasible to evaluate several alternative maintenance support policies to see whether system operational availability can be improved. Type 4 testing is accomplished at one or more user operational sites, in a realistic environment, by operator and maintenance personnel, and is supported through the normal maintenance and logistics capability. This is actually the first time that we will really know the true capability of the system.

2.11.2 Integrated Test Planning

Test planning starts in the conceptual design phase when system requirements are initially established. If a requirement is to be specified, there must be a way to evaluate and validate the system at a later point in time to ensure that the requirement has been met. Thus, considerations for test and evaluation are intuitive from the beginning.

In Figure 1.26, initial test planning is included in a Test and Evaluation Master Plan (TEMP), prepared in the conceptual design phase. The document includes the requirements for test and evaluation, the categories of test, the procedures for accomplishing testing, the resources required, and associated planning information (i.e., tasks, schedules, organizational responsibilities, and cost).[29]

One of the key objectives of this plan, and of particular significance for system engineering, is the *complete integration* of the various test requirements for the overall system. By referring to the content of Type 2 testing (Section 2.11.1), individual requirements may be specified for environmental qualification, reliability qualification, maintainability demonstration, software functionality, and so on. These requirements, stemming from a series of "stand-alone" specifications, may be overlapping in some instances, and conflicting in other cases. Further, not all system configurations should be subjected to the same test requirements. In situations where there are new design technology applications, more up-front evaluation may be desirable, and the requirements for Type 1 testing may be different from those in a situation involving the use of well-known state-of-the-art design methods. In other words, in areas where the potential technical risks are high, a more extensive evaluation effort early in the system life cycle may be feasible.

In any event, the TEMP represents a significant input relative to meeting the objectives of system engineering. Not only must one understand the system requirements overall, but knowledge of the functional relationships among the various components of the system is necessary. In addition, those involved in test planning must be familiar with the objectives of each specific test requirement, such as reliability qualification, maintainability demonstration, and so on. A total integrated approach to test and evaluation is essential, particularly when considering the costs associated with testing activities.

2.11.3 Preparation for Test and Evaluation

Prior to the start of formal testing, an appropriate period of time is designated for the purposes of test preparation. During this time, the proper conditions must be established to ensure effective results. These conditions will vary, of course, depending on the category of testing being undertaken.

During the early phases of design and development, as analytical evaluations and Type 1 testing are accomplished, the extent of test preparation is minimal. On the other hand, the accomplishment of Type 2 and Type 3 testing, in which the conditions are designed to simulate realistic consumer operations to the maximum extent possible, will likely require a rather extensive preparation effort. To promote a realistic environment, the following factors must be addressed:

[29]In the defense sector, a TEMP is required for most large programs and includes the planning and implementation of procedures for Development Test and Evaluation (DT&E) and Operational Test and Evaluation (OT&E). DT&E basically equates to the Analytical, Type 1, and Type 2 testing described in Section 2.11.1, and OT&E is equivalent to Type 3 and Type 4 testing.

1. *Selection of test item:* The system (and its components) selected for test should represent the most up-to-date design or production configuration, incorporating all of the latest approved engineering changes.
2. *Selection of test site:* The system should be tested in an environment that will be characteristic for user operations; that is, arctic or tropics, flat or mountainous terrain, airborne or ground. The test site selected should simulate these conditions to the maximum extent possible.
3. *Testing procedures:* The fulfillment of test objectives usually involves the accomplishment of both operator and maintenance tasks, and the completion of these tasks should follow formal approved procedures (e.g., validated technical manuals). The recommended task sequences must be followed to ensure proper system operation.
4. *Test personnel:* This includes (a) the individuals who will actually operate and maintain the system throughout the test and (b) the supporting engineers, technicians, data recorders, analysts, and administrators who provide assistance in conducting the overall test program. Personnel selected for the first category should be representative of user (or consumer) requirements in terms of the recommended quantities and skill levels.
5. *Test and support equipment/software:* The accomplishment of system operational and maintenance tasks may require the use of ground-handling equipment, test equipment, software, and/or a combination thereof. Only those items that have been approved for operation should be used.
6. *Supply support:* This includes all spares, repair parts, consumables, and supporting inventories that are necessary for the completion of system test and evaluation. Again, a realistic configuration, projected in a real-world environment, is desired.
7. *Test facilities and resources:* The conductance of system testing may require the use of special facilities, test chambers, capital equipment, environmental controls, special instrumentation, and associated resources (e.g., heat, water, air-conditioning, power, telephone). These facilities and resources must be properly identified and scheduled.

In summary, the nature of the test preparation function is highly dependent on the overall objectives of the test and evaluation effort. Whatever the requirements may dictate, these considerations are important to the successful completion of these objectives.

2.11.4 Test Performance, Data Collection, Analysis, and Validation

With the necessary preparations in place, the next step is to commence with the formal test and evaluation of the system. The system (or elements thereof) is operated and supported in a designated manner, as defined in the TEMP. Throughout this process, data are collected and analyzed, and the results are compared with the initially specified requirements. With the system in operational status (either "real" or "simulated"), the following questions arise:

1. How well did the system actually perform, and did it accomplish its mission objective?
2. What is the *true* effectiveness of the system?
3. What is the *true* effectiveness of the system support capability?
4. Does the system meet all of the requirements as covered through the specified technical performance measures (TPMs)?
5. Does the system meet all consumer requirements?

A response to these questions requires a formalized data-information feedback capability with the appropriate output in a timely manner. A data subsystem must be developed and implemented with the goal of achieving certain objectives, and these objectives must relate to these questions.

The process associated with formal testing, data collection, analysis, and evaluation is presented in Figure 2.33. Testing is conducted, data are collected and evaluated, and decisions are made as to whether the system configuration (at this stage) meets the requirements. If not, problem areas are identified and recommendations are initiated for corrective action.

The final step in this overall evaluation effort is the preparation of a final test report. The report should reference the initial test planning document (i.e., the TEMP), describe all test conditions and the procedures followed in conducting the test, identify data sources and the results of the analysis, and include any recommendations for corrective action and/or improvement. Because this phase of activity is rather extensive and represents a critical milestone in the life cycle, the generation of a good comprehensive test report is essential to establish a good historical baseline.

2.11.5 System Modifications

The introduction of a change in an item of equipment, a software program, a procedure, or an element of support will likely affect many different components of the system. Equipment changes will likely affect software, spare parts, test equipment, technical data, and possibly certain production processes. Procedural changes will affect personnel and training requirements. Software changes may impact hardware and technical data. A change in any given component of a system will likely have an impact (of some kind) on most, if not all, of the other major components of that system.

Recommendations for changes, evolving from test and evaluation, must be dealt with on an individual basis. Each proposed change must be evaluated in terms of its impact on the other elements of the system, and on life-cycle cost, prior to a decision on whether to incorporate the change. The feasibility of incorporating the change will depend on the extensiveness of the change, its impact on the system in terms of its ability to perform the designated mission, and the cost of change implementation.

If a change is to be incorporated, the necessary change control procedures described in Chapter 5 must be implemented. This includes consideration of the time

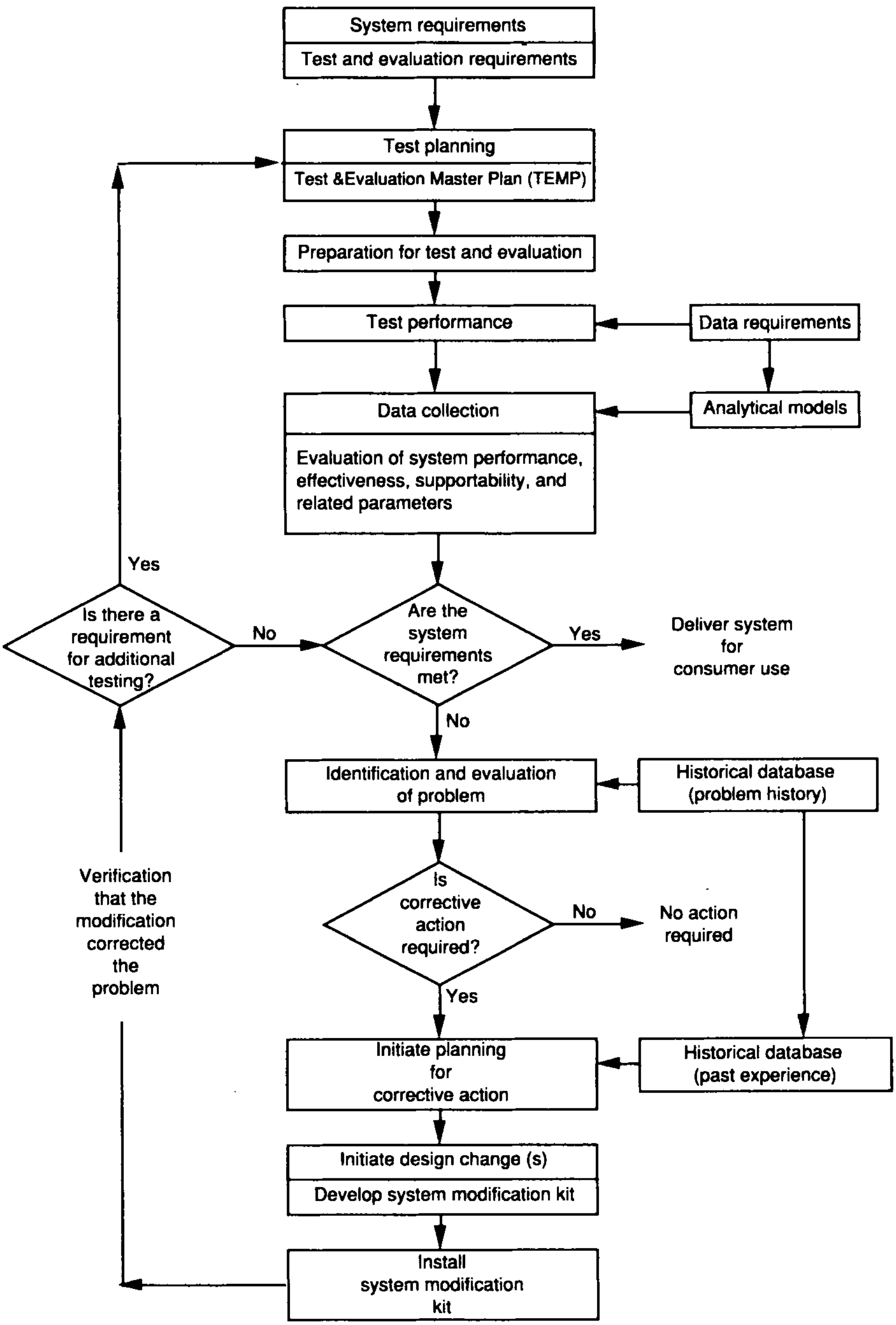

Figure 2.33 System evaluation and corrective-action loop.

when the change is to be incorporated, the appropriate serial-numbered item(s) affected in a given production quantity, the requirements for retrofitting on earlier serial-numbered items, the development and "proofing" of the change modification kits, the geographic location where the modification kits are to be installed, and the requirements for system checkout and verification following the incorporation of the change. A plan should be developed for each approved change being implemented.

2.12 PRODUCTION AND/OR CONSTRUCTION

The earlier sections of this chapter have addressed primarily the design and development of systems and emphasized the importance of system engineering as an integral and inherent activity therein. From this point, the system structure may assume several different forms, as illustrated in Figure 1.10. For a one-of-a-kind ground satellite tracking station (for example), the next phase in the system life cycle may involve *construction,* followed by the operational utilization of the tracking station in accomplishing its designated mission throughout its planned life cycle. For a system with many similar elements to be distributed throughout the world, the next phase will include *production,* followed by the utilization of these elements for the specified life cycle. In either case, the design and development of the system has been accomplished and the required performance and effectiveness characteristics have been verified (validated) through system test and evaluation (described in Section 2.11).

Given such verification, the challenge is to ensure that the system, its configuration, and its performance and effectiveness characteristics are *maintained* throughout the construction and/or production process. In the construction of a one-of-a-kind configuration, the introduction of poor quality (either through poor workmanship or through the use of substandard materials) in the building of a facility (for example) would certainly be degrading and have a negative impact on the system relative to the performance of its intended mission. In the production of multiple quantities of an item, even if the initial design has been verified through test and evaluation, there is no guarantee that subsequent models of the item being produced will exhibit the same characteristics. The production line is highly *dynamic,* and the lack of maintaining proper tolerances and the introduction of variances in manufacturing processes can significantly affect the output results. The question is, Does the system that has been constructed and/or produced have the same inherent characteristics as the configuration that was designed and validated through system test and evaluation?[30]

Because an objective in system engineering is to facilitate the design and development of a system that will respond to customer requirements in a timely and effective manner, it is important not only that the final design configuration be ideal and well documented, but that the resultant output from the construction/production pro-

[30]There has been a great deal of emphasis in recent years on the issue of *quality* (e.g., total quality management, the implementation of six-sigma practices, the application of Taguchi methods, and so on). Much of this stems from experience indicating that although the design of a system may be good initially, a great deal of degradation can be introduced through the subsequent phases of the life cycle unless the practice of good "quality control" is maintained from the beginning. Refer to Appendix A for some excellent references on quality and quality control.

cess be reflective and representative of what has been designed. Initially, this will involve an early emphasis on *design for constructability and producibility* (see Figure 2.29) and, later, the ongoing *evaluation* and *assessment* of construction and/or production activities. The system engineering process must encompass not only the initial design and development activities, but the follow-on assessment and feedback capabilities as well. Otherwise, one will never really know just how good the design/construction/production interfaces are and whether corrective action or improvement is needed.

2.13 SYSTEM OPERATIONAL USE AND SUSTAINING SUPPORT

As indicated in Figure 1.10, system engineering is *life-cycle* oriented. Given that a system has been properly designed and validated, constructed/produced, and installed at the user's operational site(s), the objective is to ensure that the resultant product will perform as intended and does indeed meet all of the customer requirements as initially defined. From this point, there are several key activities to include:

1. *Sustaining maintenance and support.* Throughout the system operational use phase, both scheduled and unscheduled maintenance will be required either to maintain the system in full operational status or to restore it to that status in the event of failure. It is essential that the proper maintenance actions be accomplished effectively and efficiently as required, and that the quality of the system not be degraded in the process.[31]

2. *Incorporating new technologies and modifications for improvement.* With the increasing trends toward "evolutionary" system development and the incorporation of new technologies for the purposes of system "upgrading," on an almost continuous basis, care must be taken to ensure that the system is not degraded in the process. As stated in Section 2.11.5, proposed system modifications must be evaluated from a total life-cycle perspective, a plan for incorporation must be prepared, and the follow-on installation process must be of high quality (refer to the process shown in Figure 2.33).[32]

A major system engineering objective throughout the system operational use phase is that of *assessment,* to ensure that the system continues to perform as desired by the customer (user). The accomplishment of this objective is heavily dependent on the availability and implementation of a good *data collection, analysis, and feedback information capability.* The goal is twofold:

[31]Poor maintenance practices (sloppy workmanship, the use of low-quality replacement parts, not utilizing the proper tools or following the proper procedures, the absence of follow-on quality inspections, and so on) can significantly degrade the system so that it will not be capable of performing its mission as intended.

[32]In the current environment (Section 1.1), one of the trends noted is the extension of the life cycle of many systems in use today, while at the same time the life cycles for many technologies are becoming shorter. This trend, combined with the emphasis on "evolutionary" design, leads to the conclusion that a system is likely to see many changes (modifications) as it evolves through its life cycle. Unless these changes are closely monitored for quality, and good configuration management and control practices are maintained in the process, there is a great possibility that an extensive amount of system degradation will occur with time.

1. To collect and provide data on a continuing basis, covering the operations and support of the system as it performs its various mission scenarios throughout the planned life cycle. The purpose is to *assess* the actual performance and effectiveness of the system and its various elements (including the mission-related elements of the system and its maintenance and support infrastructure) and to ensure that all requirements are being met. Such an assessment may lead to the necessity for corrective action in the event of a problem.

2. To collect and provide data (covering an existing system in the field) for historical purposes and for feedback into the design process. Our engineering growth and potential for the future certainly depends on our ability to capture experiences of the past and subsequently to apply the results in terms of *what to do* and *what not to do* for a new forthcoming design.[33]

The type and format of data may vary from one system to the next. It is important to collect both *success* data and *maintenance* data. "Success data" refers to information covering system operations and utilization on a continuing basis. *How is the system doing on a day-to-day basis?* "Maintenance data" refers to information covering the various scheduled and unscheduled maintenance actions that occur throughout the life cycle. Maintenance event reports should reference the system and its operational status at the time a failure occurs (should this be the case). It is not uncommon to find that we do not pay much attention to what occurs in the field as long as things are going well. However, our reaction is often quite different when there are reported problems and "panic" occurs.[34]

In any event, the role of system engineering throughout the system use and sustaining support phase is continuous and very important. One may initially perceive that the application of system engineering principles and concepts during the design and development effort has been successful. However, the proof depends on what happens later.

2.14 SYSTEM RETIREMENT AND MATERIAL RECYCLING/DISPOSAL

With the concern for environmental impacts as they exist today, consideration must be given not only to the acquisition and utilization of a system throughout its intended life cycle, but also to the requirements associated with system retirement and the appropriate disposal of its components. There are many systems in use today that, upon becoming obsolete, will be costly to phase out of the inventory. This may also be true

[33]For the most part, and for many new system design efforts, we do a very poor job of capturing the experiences from earlier and similar systems that have been in operation in the past. This is due primarily to the fact that we do not have a good data collection and feedback capability in place. Hence, we tend to introduce the same problems over and over again as we evolve through new system developments, which, in turn, often results in costly modifications later on.

[34]One approach to a data collection, analysis, and system evaluation capability is described in B. S. Blanchard, *Logistics Engineering and Management*, 5th ed. (Upper Saddle River, NJ: Prentice-Hall, 1998), Section 7.3, pp. 329–334.

for obsolete components that are replaced as a result of system modifications and the incorporation of new technologies for the purposes of system upgrading. Although some system components can be appropriately recycled, with the resulting materials made available for other uses, there are a number of other components that cannot be consumed without causing a detrimental impact on the environment.

Relative to the role of system engineering, program objectives must address the retirement and material recycling/disposal phase of the life cycle as well as the earlier phases. The *design for disposability* and/or the *design for the environment* should be covered in defining the criteria for analyses and early design decisions. In addition, there is a follow-on requirement for *assessment* as this phase evolves and the system and all of its elements are retired from operational use.

2.15 SUMMARY

A number of terms and definitions are introduced in Chapter 1; the purpose of this chapter is to relate these to the system life cycle. Further, a baseline must be established to provide a frame of reference for the discussion of individual design disciplines, design methods, and the activities associated with system engineering.

The *system engineering process,* discussed throughout this chapter, is presented in the form of an overview. In the subsequent chapters of this text, the concepts introduced here are amplified to a much greater degree. However, the material in this chapter is a necessary prerequisite to the information presented later.

QUESTIONS AND PROBLEMS

1. Identify the basic steps in the system engineering process, and describe some of the *inputs* and *outputs* associated with each step.
2. What is the purpose of *feasibility analysis?* What information is desired from such an analysis?
3. Why is the definition of system *operational requirements* important? What is included?
4. Why is the definition of the system *maintenance concept* important? What is included? How does the maintenance concept relate to the *maintenance plan?*
5. Identify a specific problem you wish to solve through the design and development of a new system. For your system:
   (a) Describe the current deficiency and identify the *need* for the new system.
   (b) Perform an abbreviated feasibility analysis and discuss the various alternative technical approaches you may wish to consider in designing the new system.
   (c) Define the basic operational requirements for the new system.

(d) Define the maintenance concept for the new system.
(e) Identify the critical technical performance measures (TPMs), based on the defined operational requirements and maintenance concept. Describe the process leading from the identification of TPMs to the identification of specific design characteristics.

6. What is meant by "quality function deployment" (QFD)? What are some of the benefits that can be derived from its application?

7. Identify a new system requirement and apply the QFD process (or something of an equivalent nature) in defining the specific characteristics that should be included in the design (demonstrate the application by applying QFD to a real situation).

8. Describe how the QFD process can be beneficially applied in fulfilling the objectives of system engineering.

9. What is meant by *functional analysis?* When should it be performed (if at all)? Why is it important in system engineering? What purpose(s) does it serve?

10. For the system selected in Problem 5, perform a functional analysis. Construct a functional block diagram showing three levels of *operational* functions. From one of the blocks in the operational functional flow diagram, show two levels of *maintenance* functions. Show how the operational functions and the maintenance functions relate.

11. Select one block from the operational functional diagram and one block from the maintenance functional diagram in Problem 10, and show inputs-outputs and how specific resource requirements are identified (e.g., hardware, software, people, facilities, data, etc.). Show an example by documenting the resource requirements using a format similar to that presented in Figure 2.20.

12. Why are the identification and description of system-level *functional interfaces* important? What can happen if these interfaces are not well defined?

13. Identify some applications of functional analysis.

14. Describe what is meant by *allocation* or *partitioning*. What is its purpose? To what depth should it be applied? How can the process of allocation influence system design?

15. For the system configuration described in Problem 5, show a breakdown of the system into its subsystems and lower-level elements. Perform an allocation of requirements specified through the TPMs at the system level to the next level below.

16. What are the basic steps involved in *system analysis?* Construct a basic flow diagram illustrating the process, showing the steps, and including feedback provisions.

17. Describe what is meant by *synthesis*. How do the functions of *analysis, synthesis,* and *evaluation* relate to each other?

18. What is a *model?* Identify some of the basic characteristics of a model. List some of the benefits associated with the usage of mathematical models in system analysis. What are some of the problems/concerns?

19. What is meant by *sensitivity analysis?* What are some of the objectives of performing a sensitivity analysis? Benefits?

20. In your opinion, what are some of the major problems in implementing the process described in Figure 2.26? Identify at least three areas of concern.

21. What are some of the challenges associated with the day-to-day design process that must be addressed for successful implementation of the system engineering process?

22. How is a system *validated* in terms of compliance with the initially specified requirements?

23. How are test requirements determined?

24. Select of a system of your choice and develop a comprehensive outline for a test and evaluation plan. Identify the categories of test, and describe the *inputs* and *outputs* for each category.

25. Describe some of the considerations associated with the initiation of design changes resulting from test and evaluation.

26. Describe the process associated with the initiation and implementation of design changes. What considerations must be incorporated to enhance the implementation of the system engineering process?

27. Why is system engineering important in the production/construction phase? Operational use and maintenance and support phase? Retirement and disposal phase?