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ability and maintainability plan (interface requirements); supportability analysis plan; supply support plan; test and support equipment plan; personnel training plan; technical data plan; packaging, handling, storage, and transportation plan; facilities plan; distribution and user support plan (customer service); postproduction support plan; information systems plan; and system retirement plan.

The ILSP includes a description of logistics concepts, research results, and acquisition strategy; logistics organization, supplier requirements, and organizational interfaces; a listing of program tasks, task schedules, major milestones, and applicable policies and procedures; projected resource requirements; and areas of program risk. Basically, the ILSP must cover all of the applicable logistics and related activities identified by forward and reverse flows in Figure 1.20. The ILSP must tie directly into the System Engineering Management Plan (SEMP), particularly in regard to those tasks dealing with logistics engineering (see Figure 1.26; the SEMP is covered further in Chapter 6).

2. *Logistics engineering.* Logistics engineering commences with the definition of specific design-to requirements evolving from the development of system operational requirements, the maintenance concept, and the identification and prioritization of technical performance measures (refer to Sections 2.4, 2.5, and 2.6). These requirements are further delineated through the accomplishment of the functional analysis and requirements allocation process (refer to Sections 2.7 and 2.8). From this point on, there are requirements pertaining to the day-to-day design participation process, including the initial establishment of design-to criteria, conductance of trade-off analyses, accomplishment of a supportability analysis (SA), review of supplier activities, participation in formal design reviews, participation in test and evaluation (validation) activities, and so on. In essence, the area of logistics and system support must be represented and included as a "member" of the design team and must be involved in the ongoing design integration activities (refer to Sections 2.9, 2.10, and 2.11).

3. *Performance-based logistics (PBL) and associated design-to requirements.* As indicated in Section 2.6, a QFD analysis approach is utilized to aid in the identification and prioritization of specific quantitative design-to goals for the system; an example identifying the results of such an analysis is presented in Figure 2.10. Although the factors (requirements) included in the table primarily pertain to the prime mission-related elements of the system and its design for supportability, there is a need to further delineate these requirements down to the maintenance and support infrastructure (conveyed in the illustration presented in Figure 2.9). Although the specific requirements will vary for each system, Figure 3.32 provides an example of some of the measures/metrics that may apply to each of the major elements of support. If one is to ultimately realize the objectives that have been emphasized throughout this text, specific design-to requirements (established from the beginning) must be applied to *all* of the elements of the system, not limited to just those elements that are directly involved in accomplishing a given mission scenario.[45]

[45]PBL is addressed in DOD 5000.2-R, *Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs* (Washington, DC: Office of the Secretary of Defense, April 5, 2002), Section C2.8.3.

Maintenance and Support Infrastructure
- Effectiveness (Reliability) of Support Capability
- Logistics Responsiveness (Response Times)
- Efficiency of Support (Cost per Support Action)

Supply Support
- Spares/Repair Parts Demand Rates(s)
- Mean Time Between Replacement (MTBR)
- Spares/Repair Parts Processing Time
- Inventory Item Location Time
- Probability of System Success with Spares
- Probability of Spares Availability
- Inventory Stockage Level(s)
- Inventory Turnover Rate(s)
- Economic Order Quantity (EOQ)
- Cost/Supply Support Action

Test, Meas., Handling, and Support Equip.
- Utilization Rate (Period of Usage)
- Utilization Time (Test Station Processing Time)
- Availability of Equipment
- Reliability (MTBF, λ)
- Maintainability (MTBM, $\overline{M}ct$, $\overline{M}pt$, MDT)
- Calibration Rate and Cycle Time
- Cost/Test Action
- Cost/Hour of Utilization

Maintenance Facilities
- Number of Items Processed/Period
- Item Process Times(s)
- Item Turnaround Time (TAT)
- Waiting Line (Length of Queue)
- Materials Consumption Rate
- Utility Consumption/Maintenance Action
- Utility Consumption/Period
- Cost/Maintenance Action

Maintenance and Support Personnel
- Personnel Quantities and Skill Levels
- Personnel Attrition Rate (Turnover Rate)
- Maintenance Labor Hours/Maint. Action
- Personnel Error Rate(s)
- Cost/Person/Organization

Training and Training Support
- Quantity of Personnel Trained/Period
- Number of Personnel Training Days/Period
- Frequency and Duration of Training
- Training Program Input/Output Factors
- Training Data/Student
- Training Equipment/Program
- Training Software/Program
- Cost/Person Trained

Packaging, Handling, Stor., and Trans.
- Transportation Mode, Route, Distance, Frequency, Time, and Cost
- Packaging Materials/Items Shipped
- Container Utilization Rate
- Effectiveness of Transportation (Reliability)
- Successful Delivery Rate
- Package Damage Rate

Computer Resources
- Software Reliability/Maintainability
- Software Complexity (Lang./Code Level)
- Number of Software Modules/Syst. Element
- Cost/Element of Software

Technical Data/Information Systems
- Number of Data items/System
- Data Format and Capacity
- Data Access Time(s)
- Database Size
- Information Processing Time
- Change Implementation Time

Figure 3.32 Selected technical performance measures for the support infrastructure.

4. *Supportability analysis (SA).* A supportability analysis is an ongoing iterative analytical process, included within the context of the overall system analysis activity, with the basic objectives of initially *influencing design* and subsequently *determining logistic support resource requirements,* based on an assumed design configuration. In Figure 3.33, these objectives are best accomplished through the integration and application of various analytical techniques/methods utilized to ensure that logistics and supportability requirements are considered in the design process. Basically, the SA (which is inherent within the system engineering process):

a. Aids in the initial establishment of PBL metrics and supportability requirements during conceptual design through the evaluation of system operational requirements, alternative technology applications, and alternative logistics and maintenance support concepts. Through the development and prioritization of system requirements, design criteria are established for the logistics and maintenance support infrastructure and are included in the appropriate specifications.

b. Aids in the evaluation of alternative system, or equipment/software, design configurations (e.g., alternative material applications, repair policies, packaging schemes, diagnostic routines, and the selection of components). This includes the ongoing process of synthesis, analysis, and design optimization, utilizing trade-off studies to arrive at a recommended approach for supportability.

c. Aids in the evaluation of a given design configuration (whether "final" or "interim") to determine the specific logistic support resource requirements for that configuration. Resource requirements include personnel quantities and skill levels, training, spares/repair parts and related inventories, test and support equip-

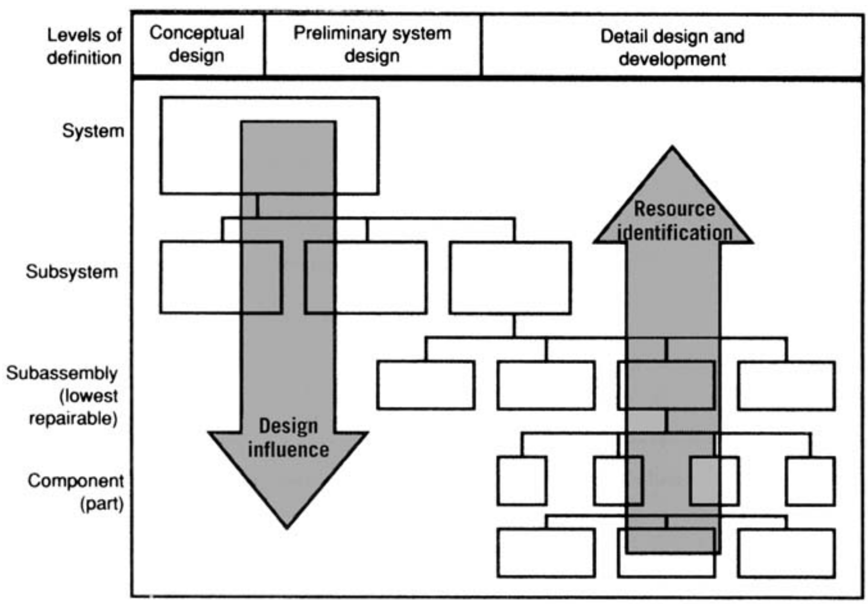

Figure 3.33 Supportability analysis emphasis. *Source:* Adapted from AMC Pamphlet 700-22, USAMC Material Readiness Support Activity, Lexington, KY.

ment, packaging and transportation, facilities, maintenance software, and data/information. The maintenance task analysis (MTA), supplemented through the utilization of other models, constitutes the database for the determination of these requirements (refer to Appendix B, Case Study B.4).

d. Aids in the ultimate measurement and evaluation (i.e., assessment) of an operating system being utilized by the consumer in the user's environment. Field data are collected, analyzed, and utilized to update the SA, which was initially based on design data. The objective is to determine the *true* effectiveness of the system, the *true* effectiveness of the logistics and maintenance support infrastructure, and so on, and to provide the appropriate feedback and any feasible recommended changes for system improvement (refer to Section 2.11.5 covering system modifications).

The SA includes the evaluation of many alternatives, following the basic analysis steps illustrated in Figure 2.26. Inherent within this activity is the utilization of such tools as the life-cycle cost analysis (LCCA); level-of-repair analysis (LORA); maintenance task analysis (MTA); reliability-centered maintenance (RCM) analysis; failure mode, effects, and criticality analysis (FMECA); testability and diagnostic analysis; and so on. In essence, the application of reliability and maintainability analysis techniques/methods are inherent in the completion of SA requirements. Further, such analytical techniques such as simulation, linear and dynamic programming, queuing analysis, accounting methods, and control theory may be employed in solving a wide variety of problems.[46]

5. *Sustaining system support.* Given that a system design configuration has been established, there is a series of logistics activities to be performed, including the selection of suppliers, provisioning and procurement of materials and services, movement of items through the production process, and the transportation and distribution of products to the consumer's operational sites. As the system is introduced and delivered to the ultimate user, there may be some customer service requirements in the form of training and assistance in the performance of operational and maintenance tasks. Subsequently, there are those activities necessary for the sustaining maintenance and support of the system throughout its planned life cycle. The system engineering role here is that of *assessment* (data collection, analysis, and feedback) and verification that the system is in compliance with the initially specified requirements. The ultimate objective is, of course, to ensure complete customer satisfaction.

In summary, Figure 3.34 is included to show the various logistics- and supportability-related activities in the context of the system life cycle. The major program phases and system-level activities are derived from the baseline presented in Figure 1.12 (Chapter 1).

[46]Many of the principles and concepts pertaining to the SA have been implemented in the past under such titles as *logistic support analysis* (LSA), *maintenance engineering analysis* (MEA), *maintenance level analysis* (MLA), *maintenance engineering analysis record* (MEAR), *maintenance analysis data* (MAD), and similar titles. Although the titles have changed through the years, the intent, objectives, and methods of implementation have basically remained the same.

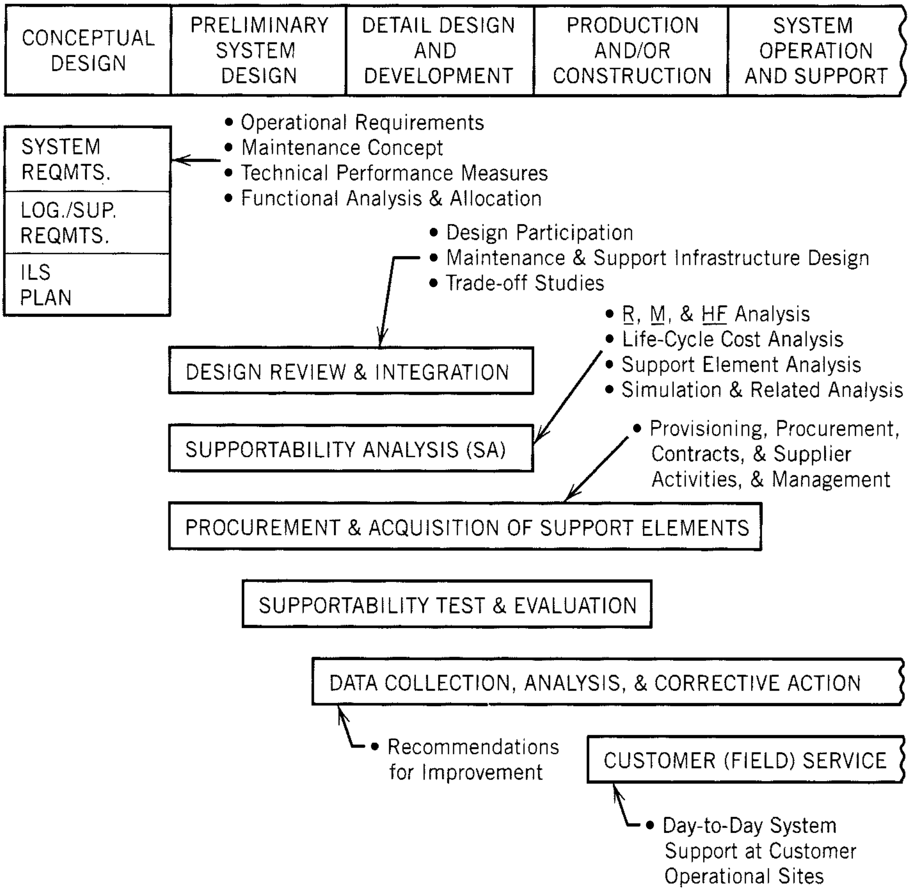

Figure 3.34 Logistics and supportability requirements in the system life cycle.

3.4.9 Disposability Engineering

Although *disposability* is certainly not a traditional engineering discipline in a pure academic sense, the subject area has received a great deal of emphasis in recent years. This is primarily due to (1) the ever-increasing unavailability of scarce resources in selected areas, requiring greater emphasis on conservation, and (2) the growing concern for the environment, and the disposal of obsolete material and its impact on the environment.

In regard to the system life cycle and its various phases illustrated in Figure 1.10, there is likely to be some waste during the production/construction process, and some items (products, components, and/or materials) may be discarded as a result; there will be items discarded throughout the system operational use phase as a result of maintenance; there will be some residual items that will be discarded during both the production/construction and operational use phases as a result of the incorporation of design changes; and there will be many items that will become obsolete when the system is ultimately retired from the inventory. The question is, What disposition can be assigned to these items as they are phased out of the inventory?

Given the objectives of eliminating waste, minimizing cost, and precluding negative impacts on the environment, it would be appropriate to design all nonrepairable system components and materials in such a way that, when designated as being obsolete, they can be recycled and reused for other purposes. Further, the process that is implemented for components that can be recycled and/or components that cannot be reused and require disposal, should not cause any degradation to the environment. In essence, the objectives, priorities, and process are conveyed in Figure 3.35.

The *design for disposability* has not been adequately considered (if at all) in the past. However, with the growing concern associated with dwindling resources and the environment worldwide, addressing this issue will become more important in the future and thus must be included as a design objective within the context of the system engineering process.

3.4.10 Quality Engineering[47]

In today's context, the word *quality* has come to mean more than it did in the past. Basically, it pertains to meeting or exceeding the requirements, expectations, and needs of the consumer (customer). The prime motivator is that of "survival" in a highly competitive international environment. In general, the availability of cost-effective, high-quality systems/products from international sources has been increasing, and competition is encouraging industries to do a better job in the design and production of systems and their components. As a result, the field of "quality," although not new, is undergoing a continual change in emphasis.

In the past, the fulfillment of quality objectives has primarily been accomplished in the production and/or construction phase of the life cycle through the implementation of formal quality control (QC) or quality assurance (QA) programs. Statistical process control (SPC) techniques, incoming and in-process inspection activities, closely monitored supplier control programs, periodic audits, and selective problem solving methods have been implemented with the objective of attaining a designated level of system quality. In addition, the advent of such techniques as "six sigma," applying "Baldridge" criteria for the purposes of evaluation, and the ever-increasing application and strengthening of ISO standards (e.g., ISO 9000 and ISO 14001) has aided in the maintenance of high-quality programs in many firms today. However, these efforts (although very effective in their application) have, for the most part,

[47]Selected references covering various facets of *quality, quality assurance, quality control,* and so on, are identified in the bibliography in Appendix A. Specifically, the reader is encouraged to review some of the writings of Crosby, Deming, and Juran to gain a better insight as to background, basic principles, and concepts. This section emphasizes some of the principles of *total quality management* (TQM); that is, total customer satisfaction, individual participation, continuous improvement, robust design, variability control, supplier integration, and management responsibility. More recently, emphasis in these areas has continued through the introduction of "Six Sigma" methods.

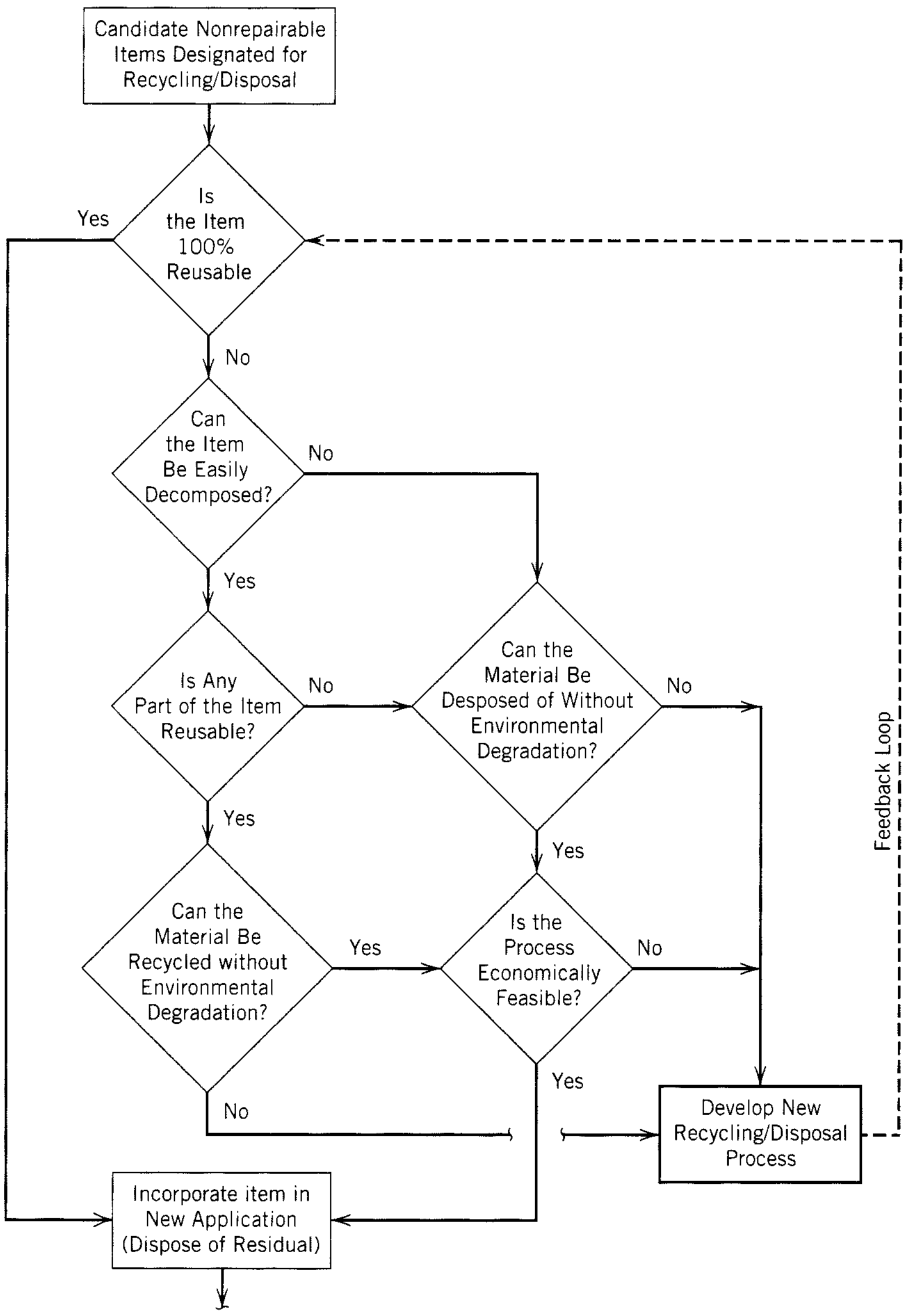

Figure 3.35 The material reuse/recycling/disposal process.

been accomplished "after the fact" and the overall results have been somewhat questionable.[48]

Recently, the aspect of "quality" has been viewed more from a top-down life-cycle perspective, and the concept of *total quality management* (TQM) has evolved. TQM can be described as a *total integrated management approach that addresses system/product quality during all phases of the life cycle and at each level in the overall system hierarchical structure.* It provides a before-the-fact orientation to quality, and it focuses on system design and development activities, as well as production, manufacturing, assembly and test, construction, product support, and related functions. TQM is a unification mechanism linking human capabilities to engineering, production, and support processes. It provides a balance between the "technical system" and the "social system." Specific characteristics of TQM include the following:

1. Total customer satisfaction is the primary objective, as compared with the practice of accomplishing as little as possible in conforming to the minimum requirements. The customer orientation is important (versus the "What can I get away with?" approach).
2. Emphasis is placed on the iterative practice of "continuous improvement" as applied to engineering, production and support processes, functions, and the like. The objective is to seek improvement on a day-to-day basis, as compared with the often-imposed last-minute single thrust initiated to force compliance with some standard. The Japanese practice this approach through the implementation of a process known as *kaizen.*
3. In support of item 2, an individual understanding of processes, the effects of variation, the application of process control methods, and so on, is required. If individual employees are to be productive relative to continuous improvement, they must be knowledgeable of various processes and their inherent characteristics. Variability must be minimized (if not eliminated).
4. TQM emphasizes a total organizational approach, involving every group in the organization and not just the quality control function. Individual employees must be motivated from within and should be recognized as being key contributors to meeting quality objectives.

Included within the broad spectrum of TQM are the very important aspects of engineering and the "design for quality"; that is, quality engineering. The projected life cycles illustrated in Figure 1.10 (Section 1.2.3) must be considered in *total.* A system is conceived, designed, produced, utilized, and supported throughout its planned life cycle. As part of the initial system design effort, consideration must be given to (1) the

[48]Three good references that include some discussion of the more recent quality-related methods/techniques, their applications, and results are (1) Y. Fasser, and D. Brettner, *Management for Quality in High-Technology Enterprises* (New York: John Wiley & Sons, Inc., 2002); (2) P. Swamidass, *Innovations in Competitive Manufacturing* (American Management Association (AMACOM), 2002); and (3) A. Gaal, *ISO 9001:2000 for Small Business: Implementing Process-Approach Quality Management* (St. Lucie Press (CRC Press), 2001).

design of the process that will be utilized to produce the system and (2) the design of the support configuration that will be utilized to provide the necessary ongoing maintenance and support for that system. As the interactions between these various facets of program activity are numerous, it is important that these areas be addressed on an integrated basis from the start.

These program relationships have been recognized through initiation of the concept of "concurrent engineering" (see Section 1.3.1), which is defined as "a systematic approach to the integrated, concurrent design of products and their related processes, including manufacture and support. This approach is intended to cause the developers, from the outset, to consider all elements of the product life cycle from conception through disposal, including quality, cost, schedule, and user requirements."[49] The objectives of concurrent engineering include (1) improving the quality and effectiveness of systems/products through a better integration of requirements and (2) reducing the system/product development cycle through a better integration of activities and processes. This, in turn, should result in a reduction in the total life-cycle cost for a given system.

From the perspective of this text, the primary thrust is *quality engineering* and its role as a part of the system engineering process. In a relationship similar to that expressed for logistics (refer to Section 3.4.8), there is the larger concern for TQM and there are some specific concerns associated with quality as it pertains to engineering design. The following activities are thus considered appropriate in regard to system engineering:

1. *Quality planning:* The development of a TQM plan (or equivalent) must be accomplished during conceptual design and updated during preliminary and detail design as required. Inherent within this overall plan are quality engineering activities including the (a) determination of engineering design requirements using a QFD, "house of quality," or equivalent approach (refer to Section 2.6); (b) evaluation and design of manufacturing and assembly processes in response to design technology decisions; (c) participation in the evaluation and selection of system components and supplier sources; (d) preparation of product, process, and material specifications as required (Types "C," "D," and "E"); (e) participation in on-site supplier reviews; and (f) participation in formal design reviews. These and related activities should also be included in the SEMP.[50]

2. *Quality in design:* This area of activity, viewed in the broad context, pertains to many of the issues discussed throughout the earlier sections of this chapter. Emphasis is directed toward design simplicity, flexibility, standardization, and so on. Of a

[49]IDA Report R-338, *The Role of Concurrent Engineering in Weapons System Acquisition* (Alexandria, VA: Institute for Defense Analysis, 1988).

[50]"House of quality" refers to a basic methodology used to implement a "quality function deployment" (QFD) program. QFD focuses on planning and communications, using a cross-functional team approach. It provides a framework for assessing product attributes and for transforming them into engineering design requirements. Refer to J. R. Hauser and D. Clausing, "The House of Quality," *Harvard Business Review* (May–June 1988): 63–73.

more specific nature are the concerns for "variability," whereby a reduction in the variation of the dimensions for specific component designs, or tolerances in process designs, will likely result in an overall improvement. Taguchi's general approach to "robust design" is to provide a design that is insensitive to the variations normally encountered in production and/or in operational use. The more robust the design, the less the support requirements, the lower the life-cycle cost, and the higher the degree of effectiveness. Overall design improvement is anticipated through a combination of careful component evaluation and selection, the appropriate use of statistical process control (SPC) methods, and application of experimental testing approaches, applied on a continuous basis.[51]

The subject of quality pertains to both the technical characteristics of design and the human aspects in the accomplishment of design activities. Not only is there a concern relative to the selection and application of components, but the successful fulfillment of quality objectives is highly dependent on the behavioral characteristics of those involved in the design process. A thorough understanding of customer requirements, good communications, a team approach, a willingness to accept the basic principles of TQM, and so on, are all necessary. In this respect, the objectives of quality engineering are inherent within the scope of system engineering.

3.4.11 Environmental Engineering

Although the previous sections in this chapter dealt primarily with some of the more tangible considerations in design, it is essential that one also address the aspect of *design for the environment* (DFE). "Environment," in this context, refers to the numerous external factors that must be dealt with in the overall system design and development process. In addition to the *technical* and *economic* factors discussed earlier (see Figure 1.24), one must deal with *ecological, political,* and *social* considerations as well. The system being developed must be compatible with, acceptable in, and ultimately must exist within an environment that addresses the many factors illustrated in Figure 3.36. A requirement within the spectrum of system engineering is to ensure that the system being developed will be socially acceptable, compatible with the political structure, technically and economically feasible, and will not cause any degradation to the environment overall.

Of particular interest here are the ecological considerations. *Ecology* generally pertains to the study of the relationships between various organisms and their environment. This includes consideration of plant, animal, and human populations in terms of rate of population growth, food habits, reproductive habits, and ultimate death. In other words, one is concerned with the conventional biological process as viewed in the broad context.

[51]Genichi Taguchi developed some mathematical techniques relative to the evaluation of design variables, with the objective of reducing variability through continuous process improvement. Refer to (1) Y. Fasser, and D. Brettner, *Management for Quality in High-Technology Enterprises* (New York: John Wiley & Sons, Inc., 2002), Section 13.2, pp. 245–248; and (2) P. J. Rose, *Taguchi Techniques for Quality Engineering* (New York: McGraw-Hill, 1988).

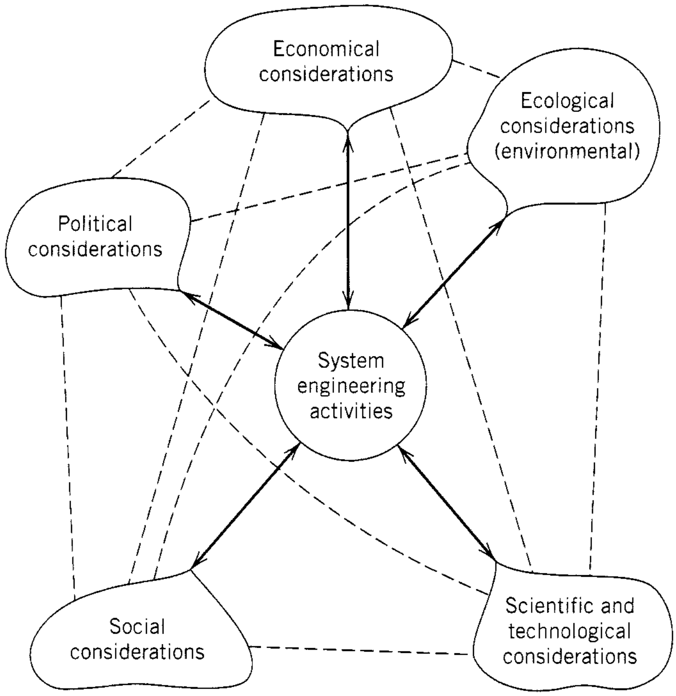

Figure 3.36 Environmental influences considered in system design and development.

In recent decades, the world population growth, combined with the many technological changes associated with our living standards, has resulted in greater consumption of our natural resources, thereby causing potential shortages which, in turn, have stimulated shifts toward establishing other means for accomplishing our objectives. Concurrently, the amount of waste has increased significantly. The net effects of this trend have been alterations to the basic biological process, and to some extent these alterations have been harmful. Of particular concern are those problems resulting from the following:

1. *Air pollution:* Any gaseous, liquid, toxic, or solid material suspended in air that can result in health hazards to humans. Air pollutants may fit into a number of categories: particulate matter (small particles of substances in air resulting from fuel combustion, incineration of waste materials, or industrial processes), sulfur oxides, carbon monoxide, nitrogen oxides, and hydrocarbons.
2. *Water pollution:* Any contaminating influence on a body of water brought about by the introduction of materials that will adversely affect the organisms living in that body of water (measure of dissolved oxygen content).
3. *Noise pollution:* The introduction of industrial noise, community noise, and/or domestic noise that will result in harmful effects on humans (e.g., loss of hearing).

4. *Radiation:* Any natural or human-made energy transmitted through space that will result in harmful effects on the humans.
5. *Solid waste:* Any garbage and/or refuse (e.g., paper, wood, cloth, metals, plastics, etc.) that will result in a health hazard. Roadside dumps, piles of industrial debris, junk car yards, and so on, are good examples of solid waste. Improper solid waste disposal may be a significant problem in view of the fact that flies, rats, and other disease-carrying pests are attracted to areas where there are solid wastes. In addition, there may be a significant impact on air pollution if windy conditions prevail or on water pollution if the solid waste is located near a lake, river, or stream.

Thus, in the development of systems and in the selection of components, the designer must be sure that the materials selected will not have a negative impact on any one (or more) of these ecological areas of concern, either when the system is operational and responding to a specific mission requirement or when the system is undergoing some form of maintenance. Throughout the utilization phase of the life cycle, there may be numerous instances when faulty components (residual material) will be removed and discarded in the accomplishment of system maintenance functions. Further, when obsolescence occurs and the system is ultimately retired from the inventory, there will be additional challenges relative to the disposal of its components. A prime objective is to design components so that they can be directly *reused* in similar applications where possible. If there are no opportunities for reuse, then the component should be designed so that it can be easily decomposed, with the residual elements being *recycled* and converted into materials that can be remanufactured for other purposes. In addition, the *recycling process* itself should not create any detrimental effects on the environment (see Figure 3.35).

In summary, all of the factors identified in Figure 3.36 need to be addressed in the design and development of systems, and on an integrated basis. The basic questions are, how will the introduction and operation of this new system capability impact the political, social, economical, and ecological infrastructure? How will the accomplishment of system maintenance and support activities influence this infrastructure? One can develop the best "technical" solution in the world, but it may not be feasible from a political perspective, or socially acceptable, or economically justifiable. An objective in system engineering is to achieve the proper balance among all of these factors.

3.4.12 Value/Cost Engineering (Life-Cycle Costing)[52]

The material presented thus far has primarily emphasized the *technical factors* associated with the system, as referenced in Figure 1.24. These factors, which include

[52]Value engineering, cost engineering, life-cycle costing, and related areas are covered further in (1) B. S. Blanchard and W. J. Fabrycly, *Systems Engineering and Analysis,* 3d ed. (Prentice-Hall, 1998); (2) G. J. Thuesen, and W. J. Fabrycky, *Engineering Economy,* 9th ed. (Prentice-Hall, 2001); and (3) Department of Defense Regulation 5000.2-R, "Mandatory Procedures for Major Defense Acquisition Programs (MDAPS) and Major Automated Information System (MAIS) Acquisition Programs" Washington, DC: DOD (latest edition). Additional references are noted in Appendix A, and the Life-Cycle Cost Analysis (LCCA) process is covered in detail in Appendix C.

performance, reliability, maintainability, human factors, supportability, and quality, represent only one side of the overall spectrum. The other side of the spectrum pertains to *economic factors,* and a proper balance between the two must be attained.

In the system evaluation process, these technical and economic factors are often combined in such a manner as to provide a measure of effectiveness (MOE) for a given system. Although these effectiveness figures of merit (FOMs) will vary from one application to the next, a few examples are noted:

$$\text{Effectiveness FOM} = \frac{\text{performance} \times \text{availability}}{\text{life-cycle cost}} \tag{3.24}$$

$$\text{Effectiveness FOM} = \frac{\text{system capacity}}{\text{revenues} - \text{cost}} \tag{3.25}$$

$$\text{Effectiveness FOM} = \frac{\text{life-cycle cost}}{\text{facility space}} \tag{3.26}$$

$$\text{Effectiveness FOM} = \frac{\text{supportablility}}{\text{life-cycle cost}} \tag{3.27}$$

Or other measures

In regard to the *economic* side of the balance, both *revenues* and *costs* must be considered, as conveyed in Figure 3.37, particularly in the commercial sector where the loss of revenues often represents a major segment of cost. However, the emphasis in this section is on cost; that is, the total cost of all activities throughout the system life cycle. *Life-cycle cost* (LCC) includes the consideration of *all* future costs associated with research and development (i.e., design), construction and/or production, distribution, system operation, maintenance and support, retirement, and material disposal and/or recycling. It involves the costs of all technical and management activities throughout the system life cycle; that is, producer activities, contractor and supplier activities, and consumer or user activities. In addition, costs are often related to "functions" accomplished over the long term, as compared with the rather short-term perspective conveyed through the traditional accounting structure for most organizations. With this in mind, one may pose the following questions:

1. Do you know the costs associated with each of the functions being accomplished within your company or organization?
2. Do you know what functions constitute the high-cost contributors over the long term? For a given system, what are the high-cost elements? What are the high-cost drivers?
3. Are you aware of the cause-and-effect relationships and the criticalities as they relate to the accomplishment of a give mission (or operational scenario)?
4. Can you identify the high-risk areas or elements of the system in question?

The answers to these and related questions are not easily attained. Yet individual design and management decisions are often based on some smaller aspect of cost

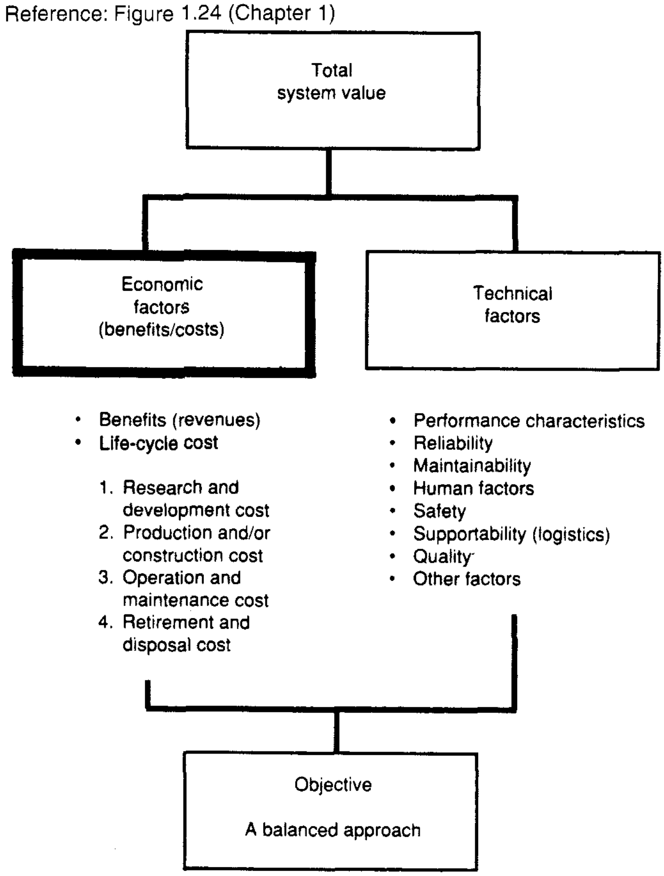

Figure 3.37 System evaluation factors.

(e.g., initial purchase price or acquisition cost) without first assessing the consequences of these decisions in terms of of *total* cost. As conveyed in Section 1.2 (Chapter 1), many of the decisions made in the early stages of system design will have a large impact on the costs of downstream activities such as production, operations, maintenance and support, and retirement and material disposal. Although some of these early decisions may be necessary, the decision maker is remiss unless they are made in the context of total life-cycle cost. *Full-cost visibility* is essential if the risks associated with the decision-making process are to be properly assessed.

Life-cycle cost analyses, in one form or another, are performed throughout system design and development, during construction/production, and/or for the purposes of assessment while the system is being utilized in the field. The completion of such an effort generally requires that one follow certain steps, such as those presented in Figure 3.38.

In Figure 3.38, one of the first steps in the process is to describe the system in *functional* terms, and then to construct a functional flow diagram covering all of the

1. Describe the system configuration being evaluated in functional terms, and identify the appropriate technical performance measures (TPMs) or applicable "metrics" for the system.
2. Describe the system life cycle and identify the major activities in each phase as applicable (system design and development, construction and/or production, utilization, maintenance and support. retirement and disposal).
3. Develop a work breakdown structure (WBS), or cost breakdown structure (CBS), covering all activities and work packages throughout the life cycle.
4. Estimate the appropriate costs for each category in the WBS (or CBS,), using activity-based costing (ABC) methods, or equivalent.
5. Develop a computer-based model to facilitate the life-cycle cost analysis process.
6. Develop a cost profile for the "baseline" system configuration being evaluated.
7. Develop a cost summary, identifying the high-cost contributors (i.e., high cost "drivers").
8. Determine the "cause-and-effect" relationships, and identify the "causes" for the high-cost areas.
9. Conduct a sensitivity analysis to determine the effects of input factors on the analysis results. and identify the high-risk areas
10. Construct a Pareto diagram and rank the high-cost areas in terms of relative importance and requiring immediate management attention.
11. Identify feasible alternatives (potential areas for the improvement), construct a life-cycle cost profile for each, and construct a break-even analysis showing the point in time when a given alternative assumes a point in preference.
12. Recommend a preferred approach, and develop a plan for system modification and improvement (this may entail a modification of equipment or software, a facility change, and/or a change in some process). This constitutes an ongoing iterative approach for continuous process improvement.

Figure 3.38 The basic steps in a life-cycle cost analysis.

activities in the system life cycle, evolving from the identification of need through retirement and material disposal (refer to Section 2.7). Given this requirement, it is necessary to develop a *cost breakdown structure* (CBS), such as shown in Figure 3.39. The CBS constitutes a vehicle for including all costs and is broken down to the depth required to provide the appropriate level of visibility for determining the costs of various functions, processes, and/or elements of the system over time. The CBS serves as a structure that will allow for the initial allocation of cost targets in a "design-to-cost" application (refer to Figure 2.23) and for the subsequent collection of costs in a "life-cycle cost analysis." Costs are estimated for each year in the system life cycle, inflationary and other influencing factors are included, costs profiles are developed, and costs are summarized by category in the CBS. The high-cost contributors are noted, cause-and-effect relationships are established, a sensitivity analysis is performed, feasible alternatives are evaluated, and recommendations are made based on the results.

A life-cycle cost analysis may serve many purposes, and the possible applications are varied, as conveyed in Figure 3.40. Of particular note is the use of LCC analysis in the evaluation of different design configurations in the early stages of system development, the evaluation of different commercial off-the-shelf (COTS) alternatives, and the evaluation of an existing system configuration with the objective of identifying the high-cost contributors leading to possible recommendations for product/process improvement. In each application, the steps identified in Figure 3.38 and the process illustrated in Figure 3.41 are followed.

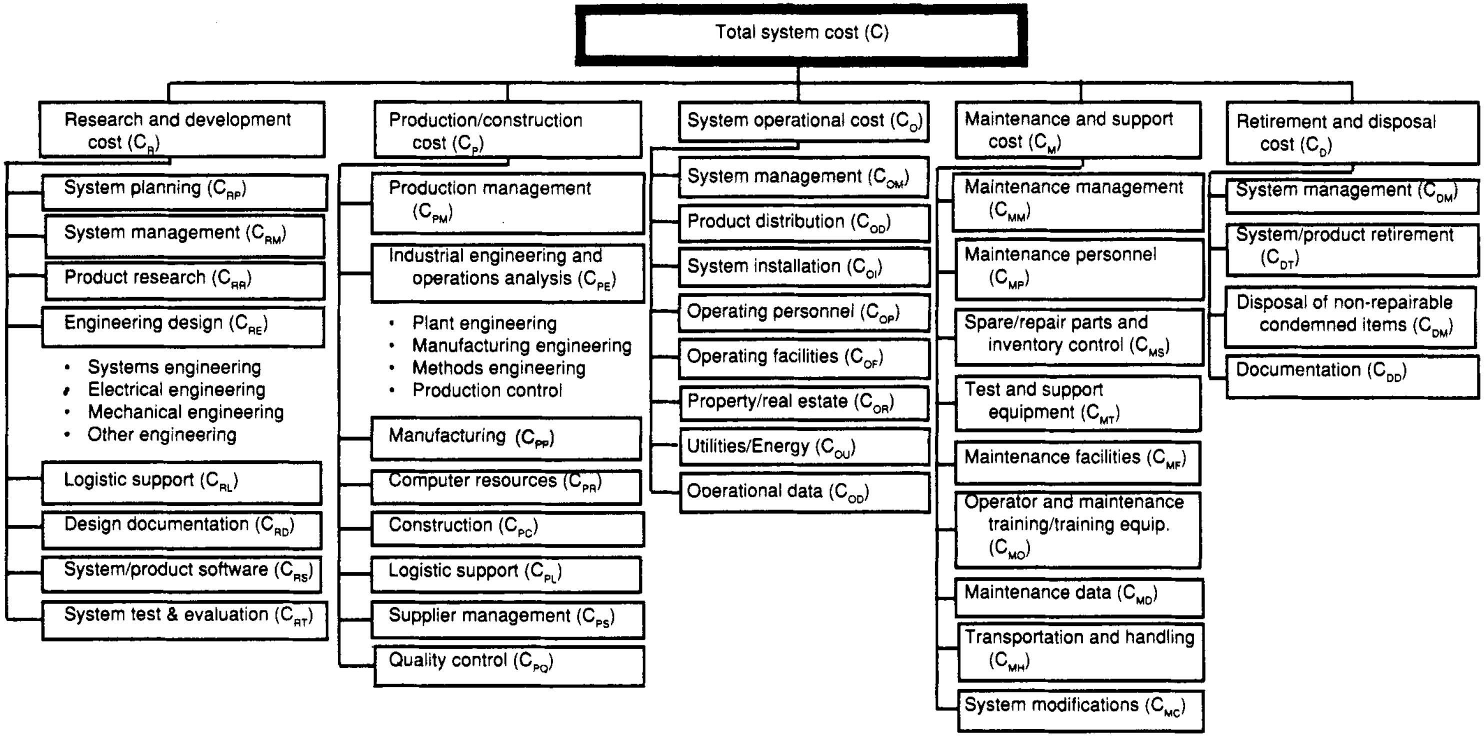

Figure 3.39 Sample cost breakdown structure (CBS).

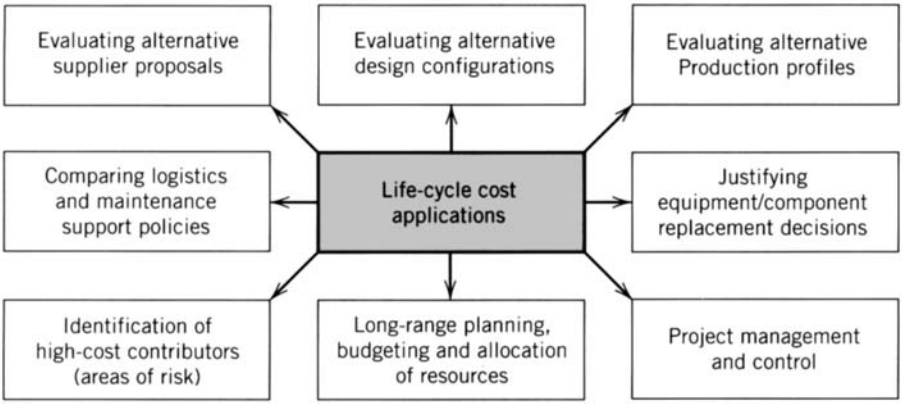

Figure 3.40 Life-cycle cost applications.

Figure 3.42 provides an example of LCC analysis applications in the system design and development process. Cost targets may be established initially in conceptual design through the development of TPMs (refer to Section 2.6). Trade-off studies are performed during the preliminary and detail design phases to support design and procurement decisions. During the latter stages of detail design and throughout the construction/production and system utilization phases, LCC analyses may be conducted for assessment of the overall cost-effectiveness of the system. Computer-based models are used to facilitate the analysis process (as shown in Figure 2.27). Figure 3.43 shows the LCC analysis as it may be applied throughout the system life cycle. For a more in-depth discussion of life-cycle costing, the analysis process, and its benefits, refer to Appendix C.

3.5 SUMMARY

Inherent within the system engineering process described in Chapter 2 are the requirements for reliability, maintainability, supportability, quality, and the like. A few design disciplines such as these have been selected for discussion in Section 3.4 of this chapter. In each instance, there are certain steps that are followed in order to meet the objectives as specified. Initially, the requirements for reliability, maintainability, and so on, must be established in defining operational requirements and the maintenance concept for the system. Functional analyses and the allocation of these requirements are necessary to identify input criteria for design. Analyses and trade-off studies are accomplished in the design optimization process. Finally, the initially specified requirements are verified through system test and evaluation. These steps, which are characteristic in each instance, are illustrated in Figure 3.44.

Although the design disciplines in this chapter have been introduced as separate individual requirements, there is a certain degree of interdependence among them. Maintainability requirements are based on reliability, supportability requirements are dependent on reliability and maintainability data, safety factors are based on human

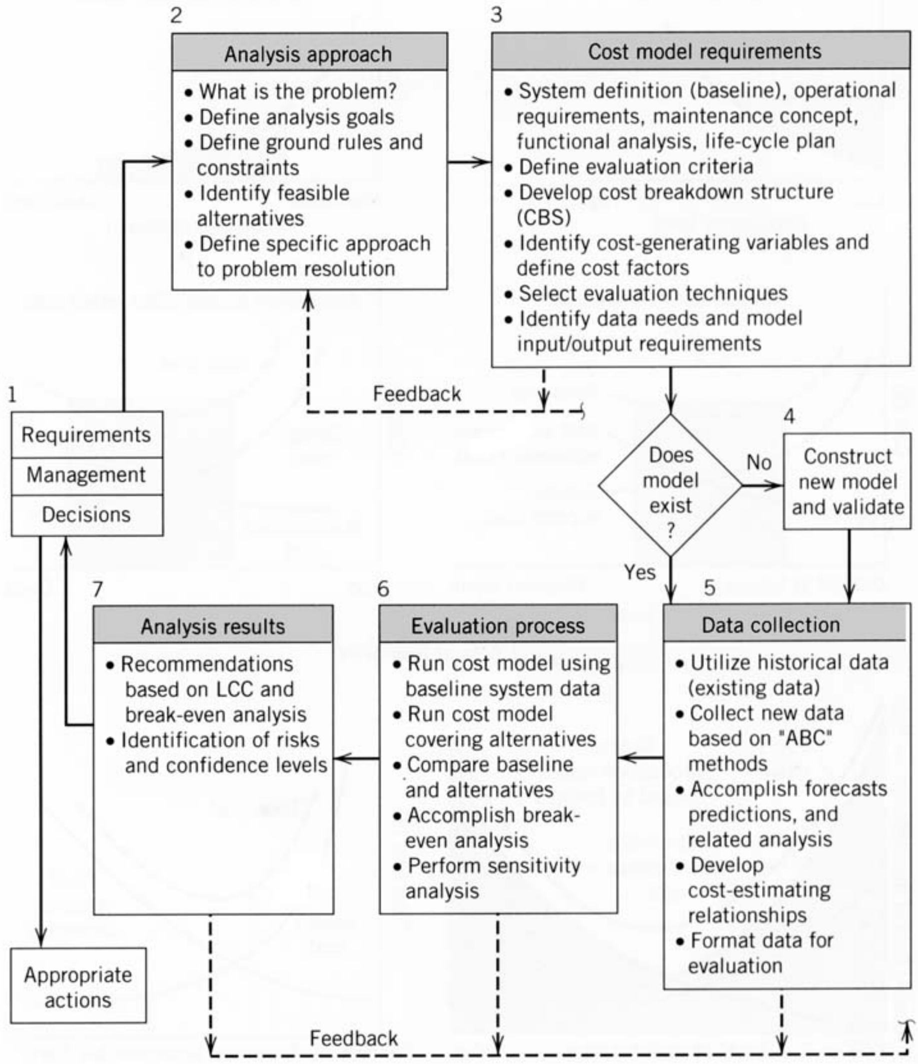

Figure 3.41 Life-cycle cost analysis process.

factors, and so on. These disciplines not only build on the basic design (i.e., electrical design, mechanical design, etc.), but they build on each other. An attempt is made to show these relationships through the order of material presentation in Section 3.4.

Finally, with the objectives of system engineering in mind, it is essential that the appropriate level of communications be established among these disciplines. This communication must be reflected throughout the individual respective program plans, and there must be a free exchange of design-related data in order to fulfill the various analyses and design support functions. The necessity to integrate these activities into a total effective engineering design effort is a major aspect of system engineering.

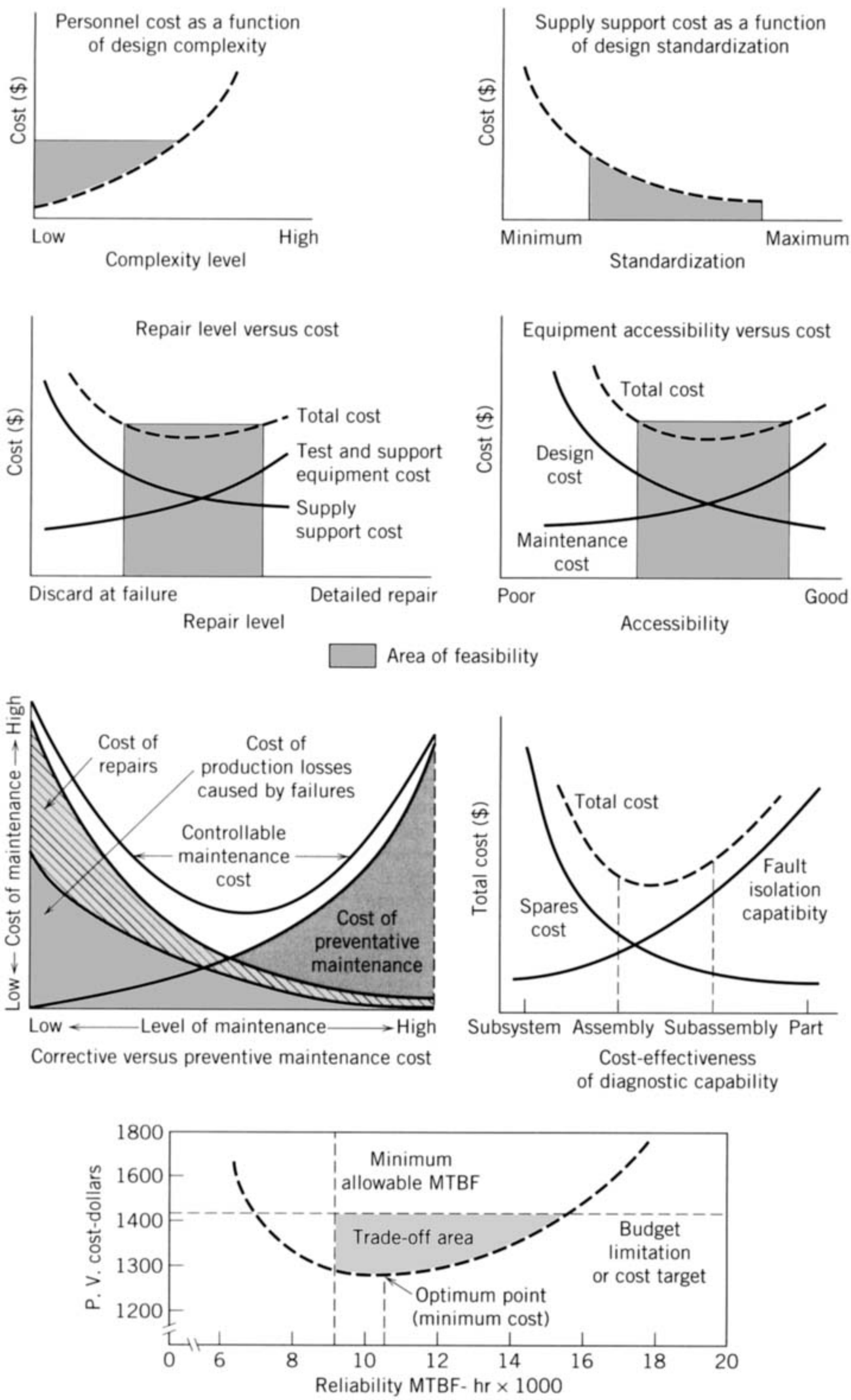

Figure 3.42 Examples of cost-effectiveness analysis applications.

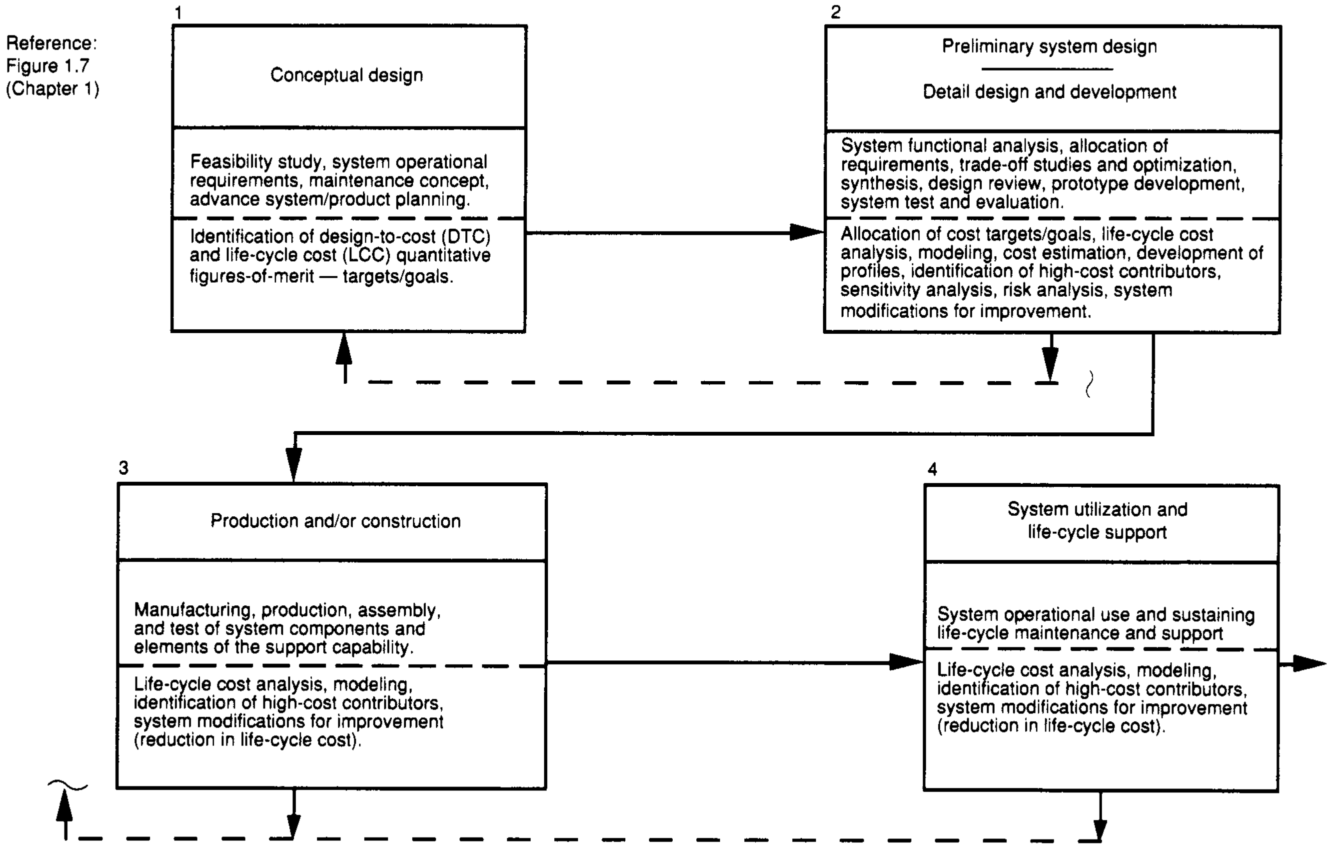

Figure 3.43 Considerations of value/cost in the system life cycle.

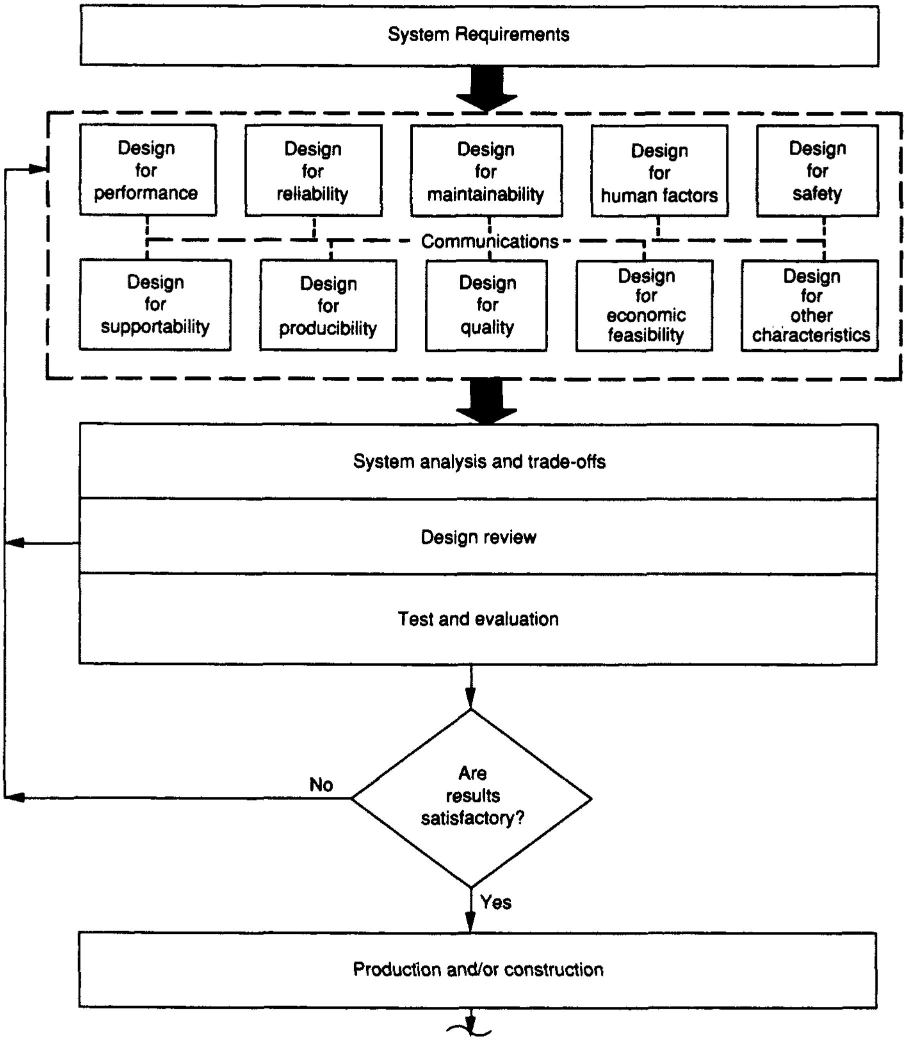

Figure 3.44 The design process.

QUESTIONS AND PROBLEMS

1. Describe the steps involved in defining the quantitative and qualitative design criteria for a system.

2. Select a system of your choice and develop a detailed outline of a Type "A" Specification for this system.

3. Define "reliability." Provide an example of some reliability measures/metrics for a typical system, and describe the bases for these.

4. One hundred (100) parts were tested for 10 hours, and 10 failures occurred during the test. The times when the failures occurred are 1, 3, 6, 2, 3, 6, 8, 9, 2, and 1 hour, respectively. What is the failure rate?

5. Field data have indicated that Unit "A" has a failure rate of 0.0004 failure per hour. Calculate the reliability of the unit for a 150-hour mission.

6. A system consists of four subassemblies connected in series. The individual subassembly reliabilities are A = 0.98, B = 0.85, C = 0.90, and D = 0.88. Determine the overall system reliability.

7. A system consists of three subsystems in parallel. Subsystem "A" has a reliability of 0.98, Subsystem "B" has a reliability of 0.85, and Subsystem "C" has a reliability of 0.88. Calculate the overall system reliability.

8. In Figure 3.45, the component reliabilities are A = 0.95, B = 0.97, C = 0.92, D = 0.94, E = 0.90, and F = 0.88. Determine the overall network reliability.

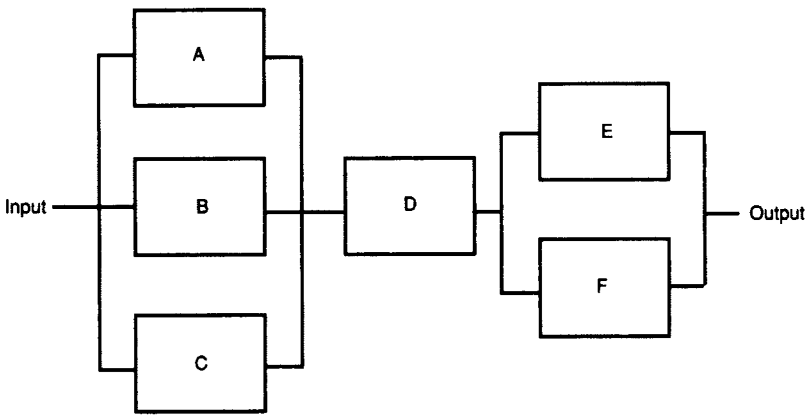

Figure 3.45 Problem 8 network.

9. Develop the overall reliability expression (R_n) for the network shown in Figure 3.46.

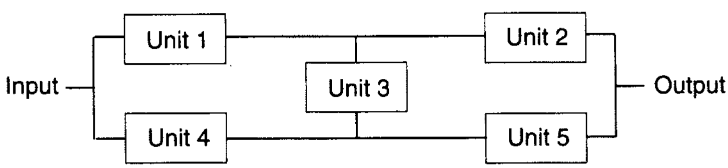

Figure 3.46 Problem 9 network.

10. There are a variety of tools/techniques that can effectively be utilized in the design process to help meet the objectives of reliability engineering. Briefly describe the objective and the application of each of the following (what is it? how and when can it be applied? what are the anticipated results?): *reliability modeling, reliability allocation, reliability prediction, FMECA, FTA, RCM.*

11. Define "maintainability." Provide an example of some maintainability measures/metrics for a typical system and describe the bases for these.

12. The corrective maintenance task times in Figure 3.47 were observed.

(a) What is the range of observations?
(b) Using a class interval width of 4, determine the number of class intervals. Plot the data and construct a curve. What type of distribution is indicated by the curve?
(c) What is the $\overline{\text{M}}\text{ct}$?
(d) What is the geometric mean of the repair times?
(e) What is the standard deviation of the sample data?
(f) What is the $\overline{\text{M}}_{\text{max}}$ value (assume 90%)?

Task time (min)	*Frequency*	*Task time (min)*	*Frequency*
41	2	37	4
39	3	25	10
47	2	35	5
36	5	31	7
23	13	13	3
27	10	11	2
33	6	15	8
17	12	29	8
19	12	21	14

Figure 3.47 Problem 12 data.

13. There are a variety of tools/techniques that can be effectively utilized in the design process to help meet the objectives of maintainability engineering. Briefly describe the objective and the application of each of the following (what is it? how and when can it be applied? what are the anticipated results?): *maintenance concept, maintainability allocation, maintainability analysis, maintainability prediction, FMECA (as it applies to maintainability), LORA, MTA.*

14. Calculate as many of the following parameters as you can with the given information: Determine

A_i	MTBM
A_a	MTBF
A_o	$\bar{M}$
$\overline{M}ct$	$MTTR_g$
M_{max}	

Given:
$\lambda = 0.004$
Total operation time = 10,000 hours
Mean downtime = 50 hours
Total number of maintenance actions = 50
Mean preventive maintenance time = 6 hours
Mean logistics plus administrative time = 30 hours

15. Define "human factors." Provide an example of some human measures/metrics for a typical system and describe the bases for these.

16. Identify and briefly describe some of the characteristics that must be considered in the design for the human.

17. Describe the objective and application of each of the following (what is it? how and when can it be applied? what are the anticipated results?): *functional analysis and allocation, operator task analysis, error analysis, OSD.*

18. Describe the steps involved in defining the requirements for personnel training. What is included?

19. Describe the steps involved in defining the requirements for system safety and system security. What are the relationships between the two? Identify and briefly describe some of the tools that are utilized in helping to meet the objectives of safety and security engineering.

20. Define "logistics." What is meant by "supply chain management" (SCM)? Describe how the two relate to each other (if at all). What are the elements of logistics? Briefly describe each. What is meant by "logistics engineering"? Define "supportability?"

21. Describe some of the measures/metrics of logistics, and describe how they might be applied for a typical system.

22. What is the "supportability analysis"? What are the "input" requirements, and what is the expected "output" in terms of type of information and application?

23. How are the requirements for software determined? What are some of the measures/metrics for software? How is software reliability measured? How is software maintainability measured?

24. Define "TQM." What is meant by "SPC"? Describe quality engineering. How does it relate to system engineering?

25. Describe concurrent engineering. How does it relate to system engineering?

26. Describe what is meant by "agile manufacturing," "lean production," and "enterprise resource planning (ERP)."

27. What is meant by "disposability engineering" and "environmental engineering"? How do they relate to each other? How do they differ?

28. Describe what is meant by "total productive maintenance" (TPM). How can it be measured?

29. Define "life-cycle cost" (LCC). How does LCC relate to value? How are economic factors considered in the system design process?

30. Describe the steps involved in accomplishing a life-cycle cost analysis (LCCA).

31. What is the "CBS"? What is included/excluded? How does the CBS relate to the functional analysis?

32. Describe some of the more commonly used cost estimating methods. Under what conditions should they be applied?

33. What is "activity-based costing" (ABC)? Why is it important (if at all)?

34. What is meant by "cost estimating relationships" (CERs)? How are they determined?

35. In the evaluation of alternative design configurations, an individual cost profile is developed for each. These individual profiles must be reviewed and evaluated in terms of some form of "equivalence." Briefly describe the steps you would follow in accomplishing such.

36. Calculate the anticipated life-cycle cost for your personal automobile.

36. Select a system of your choice, and accomplish a life-cycle cost analysis (LCCA) in accordance with the steps identified in Figure 3.38 and the process described in Appendix C.

37. Why is the accomplishment of life-cycle costing important? Please explain.