INSTRUCTOR'S GUIDE TO PROBLEM SOLUTIONS

For

SYSTEMS ENGINEERING AND ANALYSIS

Fifth Edition

By

Benjamin S. Blanchard
Wolter J. Fabrycky

FOREWORD

There are exactly 500 end-of-chapter questions, problems, and exercises for student response and solution in this textbook. These are included to emphasize the application of systems engineering concepts, principles, and methods and to provide practice in systems analysis.

The responses presented are suggestive rather than complete. There may be subjectivity inherent in some of the solution procedures. In these cases, problems may be interpreted differently but correctly by different people. Other problems may be solved in different ways, with the numerical result being essentially the same for all correct procedures. Further, many of the approaches and solutions are based on the personal experience of the authors which is likely to be different for other individuals. While the solutions given have been found to be simple and easily understood by most people, it is assumed that the instructor will view differences accordingly and enlarge upon them based on his or her own experience.

We would greatly appreciate any feedback and advice that you may wish to offer about the questions, problems, and exercises and their solutions. The validity and completeness of these exercises relative to the textbook material is of keen interest to us. We seek to continuously improve both the presented material in the book as well as the questions and problems derived there from. In this regard we wish to thank Alan L. Fabrycky for his dedicated editorial assistance in the preparation of this Instructor's Guide.

This is a good opportunity for us to thank you for choosing *Systems Engineering and Analysis, the Thirtieth Anniversary Edition*, for use in your course. We wish you the very best in your teaching and in promoting the benefits of this emerging engineering interdiscipline.

Benjamin S. Blanchard
160 Slate Creek Drive NW
Christiansburg, VA 24073
Telephone (540) 394-3311
Email **bsblanch@vt.edu**

Wolter J. Fabrycky
1200 Lakewood Drive NW
Blacksburg, VA 24060
Telephone (540) 552-1957
Email **fab@vt.edu**

TABLE OF CONTENTS

Part I Introduction to Systems

Chapter 1 Systems Science and Engineering 1
Chapter 2 Bringing Systems Into Being 7

Part II The System Design Process

Chapter 3 Conceptual System Design 12
Chapter 4 Preliminary System Design 21
Chapter 5 Detail Design and Development 28
Chapter 6 System Test, Evaluation, and Validation 34

Part III Systems Analysis and Design Evaluation

Chapter 7 Alternatives and Models in Decision Making 40
Chapter 8 Models for Economic Evaluation 48
Chapter 9 Optimization in Design and Operations 55
Chapter 10 Queuing Theory and Analysis 66
Chapter 11 Control Concepts and Methods 72

Part IV Design for Operational Feasibility

Chapter 12 Design for Reliability 77
Chapter 13 Design for Maintainability 86
Chapter 14 Design for Usability (Human Factors) 99
Chapter 15 Design for Logistics and Supportability 106
Chapter 16 Design for Producibility, Disposability, and Sustainability . 115
Chapter 17 Design for Affordability (Life-Cycle Costing) 120

Part V Systems Engineering Management

Chapter 18 Systems Engineering Planning and Organization 140
Chapter 19 Program Management, Control, and Evaluation 151

CHAPTER 1

SYSTEMS SCIENCE AND ENGINEERING

1) A river system (Mississippi) is an *assemblage* of a watershed, tributaries, and river banks that conveys water from the continental U.S. to the Gulf of Mexico. A municipal transportation system (Chicago) is an *assemblage* of trains, buses, subways, etc. that transports people among many city locations. A system of organization and management (Matrix) is based on *a morphology and procedure,* coordinating both line and support functions. An automobile manufacturer is a *combination* of factories, organizations, dealerships, etc., that delivers automobiles and related support services. A home is an *assemblage* of land, structure, utilities, furnishings, and people that provides a supportive place to live for one or more families. Reference: Section 1.1 and Footnote 1 (pages 3-4).

2) The major *components* of a home are listed in Answer 1 above. *Attributes* include acreage, terrain, square footage, utility capacities, styles of decorating and furnishing, personalities, and philosophies. *Relationships* include layout, allocation of space to people, and approaches to living together. Reference: Section 1.1.1 (page 3).

3) A chemica1 processing plant is composed of *structural* components (building, tanks, piping), *operating* components (pumps, valves, controls), and *flow* components (chemical constituents, energy, information). Reference: Section 1.1.1 (page 4).

4) An *air transportation system* is composed of aircraft and numerous supporting facilities, equipment, and personnel, each of which is a *subsystem*. An aircraft itself is composed of lower–level subsystems (fuselage, wings, and engines) and these subsystems are further composed of subsystems. For example, the engine is composed of the compressor rotor, pump, pod, etc. Finally, the compressor rotor is composed of components such as the shaft and rotor blades. Reference: Section 1.1.2 (page 4).

5) The *boundaries* of a dam system can be limited to the physical dam. Alternatively, the human-modified river system, which now has a lake, can be considered a part of the dam system. The related road system, for which the dam now provides a bridge over the river, can be included. The region's tourism service system, for which the dam system now provides an array of additional services, can be included. Reference: Section 1.1.2 (page 5).

6) A *physical system* such as a watershed has components which manifest themselves in space and time, whereas a *conceptual system* such as a work breakdown structure has no physical manifestations. It is only a plan for action. Reference: Section 1.2.2 (pages 6-7).

7) A *static system* such as a highway system may be contrasted with an airline system, which is a *dynamic system*. In the former, structure exists without activity whereas in the latter, structural components are combined with the activities of aircraft being loaded and unloaded, aircraft in flight, and controls which govern the entire operation. Reference: Section 1.2.3 (page 7).

8) A cannon is an example of a *closed system*. When a cannon is fired, a one–to–one correspondence exists between the initial and final states. However, the defense contractor's design and manufacturing organization that produced the cannon and associated projectile is an *open system*, with a dynamic interaction of system components. These system components must be reconfigured and adapted to cope with changing requirements. Reference: Section 1.2.4 (page 8).

9) A watershed is a *natural system* made up of objects or components such as land, vegetation, and the watercourse; attributes such as the soil type, timber species, and the river width; and relationships such as the distribution of the attributes over the terrain. A chemical processing plant is a *human–made system* with components described in Answer 3 above, attributes such as tank volume and pipe diameter, and relationships such as the flow rates and the yield of final product per energy unit utilized. A person with a pacemaker is a *human-modified system* with components of body parts and pacemaker parts, attributes such as body mass, diseases, attitudes, battery, controller, and electrodes, and relationships such as implantation location, rhythm, and signal strength. Reference: Section 1.1.1 (pages 3-4) and Section 1.2.1 (page 6).

10) The *purposes* of a chemical processing plant in a market economy are to produce one or more chemical products and possibly byproducts that can be sold at a profit while fulfilling obligations to stakeholders and the public. *Measures of worth* include production cost per unit volume, product quality, flexibility of product mix, benefits to stakeholders, and compatibility with society. Reference: Section 1.1 (pages 3-5).

11) During startup the *state* of a chemical processing plant is that pipes and vessels are filled to a certain location and empty after that location; pumps for vessels being filled are running and valves are open while other pumps are not running and valves are closed. A *behavior* is that when a vessel is filled, the control system turns off the pump (in a batch system) or reduces its speed (in a continuous system) and activates the next step in the process. The *process* is to start up, achieve the designated operational speed for each subsystem, continuously monitor the production results and make needed adjustments, and eventually shut down and clean out. Reference: Section 1.1.1 (pages 3-4).

12) A pump and the tank it fills have a *relationship*. The pump provides the material that the tank needs, while the tank provides a location where the pump can store the material it needs to deliver. The *attributes* of the pump must be engineered so that it can reliably move the material(s) the tank needs at an adequate rate for any given speed of overall system operation. The *attributes* of the tank must be engineered so that it can store the quantities of material the pump must deliver without corrosion or contamination. Thus the downstream components have the material they need to fulfill the plant's production *purpose* without problems of quality or pollution. Reference: Section 1.1.1 (pages 3-4).

13) In a computer system, the power supply and system board have a *first-order* relationship because the system board must receive the reduced voltage produced by the power supply in order to function, and the power supply would be useless if there were no system board to perform and coordinate the computer functions. The system board has a *second-order*

relationship with a math coprocessor, or a video processor, or with video memory. The system board could perform the functions of these additional components, but the added components relieve the system board's workload, thereby improving its performance. A second power supply or a mirror image hard disk drive provide *redundance*, ensuring that the system board can continue receiving electrical power and the data storage function, thereby helping to assure continuation of the computer system function. Reference: Section 1.1.1 (page 4).

14) Human introduction of plant or animal species into regions where they do not naturally occur can provide the benefits of those species in the new regions, but the new species may become excessively dominant in those regions due to lack of natural enemies, crowding out or harming beneficial native species. Reference: Section 1.2.1 (page 6).

15) The movement of individual molecules is a random dynamic system property whose aggregate behavior is influenced by temperature. The microwave signal that electrons emit when they change energy states is a steady state dynamic system property that forms the basis for atomic clocks. Reference: Section 1.2.3 (page 7) and Section 1.2.4 (page 8).

16) A forest reaches equilibrium. A tree is in equilibrium until it dies, and then it disintegrates. Reference: Section 1.2.1 (page 6) and Section 1.2.4 (page 8).

17) The government described is a single system because the branches thereof are functionally related. Refer to the opening paragraph of Section 1.1 (page 3).

18) Analyzing a company's information systems as a system-of-systems can reveal the need for common databases. Analysis of the individual systems would not reveal this need and its potential design benefit. Reference: Section 1.2.2 (page 7).

19) *Cybernetics* may be described and explained by considering the early mechanical version of a governor to control the revolutions per minute (RPM) of an engine. Centrifugal force, acting through a weight mechanism on the flywheel, is used to sense RPM. The outward movement of the weight against a spring acts through a link to decrease the throttle setting, thus reducing engine speed. Reference: Section 1.3.1 (page 8).

20) Student exercise. Refer to Section 1.3.2 (page 10) for Boulding's hierarchy. Describe the inspiration obtainable through viewing the outdoors by standing at a window or on an outside balcony.

21) Student exercise. Refer to Section 1.3.2 (page 10).

22) Health care is a societal need. Requirements of a health care system include diagnostic services, curative services, and services to help individuals maintain and improve their health. The objectives of a health care system include facilitating good health at a reasonable cost, motivating participants to be efficient and effective, financing the cost in an equitable manner for all stakeholders, and continually improving the system, including its technology. Reference: Section 1.1.1 (pages 3-4).

23) Both systemology and synthesis produce systems. Systemology produces a system of processes by which systems are brought into being and carried through the life cycle. Synthesis produces any kind of system. Synthesis is a part of systemology and also a product of systemology. Reference: Section 1.3.3 (pages 10-11).

24) The phrase "technical system" is used to represent all types of human–made artifacts, including engineered products and processes. Classifying a technical system is generally difficult, because a technical system derives its inputs from several disciplines or fields which may be very different from one another. Refer to Section 1.4.2 (page 12) augmented by Section 1.4.3 (page 13).

25) Factors driving technological change include attempts to respond to unmet current needs and attempts to perform ongoing activities in a more efficient and effective manner, as well as social factors, political objectives, ecological concerns, and the desire for environmental sustainability. Reference: Section 1.4.3 (page 13).

26) Human society is *characterized by its culture*. Each human culture manifests itself through the medium of technology. It takes more than a single step for society to transition from the past, to present and future technology states. A common societal response is often to make the transition and then to adopt a static pattern of behavior. A better response would be to **continuously seek** new but well-thought-out possibilities for advancement. Improvement in technological literacy embracing *systems thinking* should increase the population of individuals capable of participating in this desirable endeavor. Reference: Section 1.4.1 (pages 11-12) and Section 1.5.2 (pages 14-15).

27) Attributes of the *Machine Age* are determinism, reductionism, physical, cause and effect, and closed system thinking. The *Systems Age* has attributes of open systems thinking, expansionism, human–machine interfacing, automation, optimization, and goal orientation. Reference: Section 1.5.1 and Section 1.5.2 (pages 13-15).

28) Analytic thinking seeks to explain the whole based on explanations of its parts. Synthetic thinking explains something in terms of its role in a larger context. Reference: Section 1.5.2 (pages 14-15).

29) The special engineering requirements of the Systems Age are those which pertain to integration, synthesis, simulation, economic analysis, and environmental concerns, along with the necessity to bring the classical engineering disciplines to bear on the system under development through collaboration. Reference: Section 1.5.3 (pages 15-16).

30) Both systems engineering and the traditional engineering disciplines deal with technology and technical (human-made) entities. The focus of traditional engineering is on technical design of the entities in human-made systems, whereas systems engineering concentrates on what the entities are intended to do (functional design) before determining what the entities are. Traditional engineering focuses on technical performance measures, whereas systems engineering considers all requirements of the client, system owner, and/or the user group, as well as the effects on related systems.

Traditional engineering focuses on designing products for their operational uses, whereas systems engineering considers all the life cycles of the systems that include its products. Traditional engineering tends to proceed from the bottom-up, whereas systems engineering favors a top-down approach. Traditional engineering favors analytic thinking while systems engineering favors synthetic thinking. Traditional engineering applies the skills of particular engineering disciplines to problems, whereas systems engineering defines problems before determining what disciplines are needed. Systems engineering provides methodologies that facilitate effective teamwork among not only the traditional engineering disciplines, but also among other technical as well as social disciplines. Reference: Section 1.5 and Section 1.6 (pages 13-19).

Due to the shift in the social attitudes of people towards moral responsibility, the ethics of corporate and governmental decisions are becoming more of a professional concern. In general, people are not satisfied with the impact of human–made systems upon themselves and upon the natural world. Ecological, political, cultural, and even psychological factors have become important requirements in engineering undertakings. In this day and age, technological and economic feasibility can no longer be considered the sole determinants of the success of engineering applications. Special challenges now exist for most engineering activities in the classical disciplines and in systems engineering alike. Reference: Section 1.5.4 (pages 16-17).

31) Student exercise requiring consideration of the chosen major curriculum at the student's educational institution in light of the trends summarized in Section 1.5.4 (pages 16-17).

32) The problem of predicting the availability and amount of oil and natural gas from a certain geological region, which might be available to refineries and power plants in another region in future time periods, requires the disciplines of geology, petroleum engineering, regional planning, civil engineering, ecological science, transportation engineering, and economics. The validity of the prediction depends largely upon the proper utilization and interpretation of findings by the relevant disciplines and their domains of inquiry. Reference: Section 1.3.3 (pages 10-11).

33) Systems engineering is an interdiscipline (sometimes called a multidiscipline or transdiscipline) drawn mainly from the engineering disciplines, but also from mathematics, operations research, systemology, project management, and increasingly, other fields. Reference: Section 1.3.3 (pages 10-11).

34) Refer to Section 1.6 (pages 17-19) for several definitions and then offer one that you prefer. The description **preferred by the authors** is given in Section 1.7 on page 20 as **a technologically-based interdisciplinary process for bring systems into being**.

35) Student exercise requiring use of the ISSS web site, **www.isss.org**. Reference: Section 1.7 (page 19).

36) Student exercise requiring use of the INCOSE web site, **www.incose.org**. Reference: Section 1.7 (page 20).

37) Student exercise. Utilize your responses to Questions 35 and 36 as a basis for providing an answer about the requested comparison. Reference: Section 1.7 (pages 19-20).

38) Student exercise requiring use of the OAA web site, **www.omegalpha.org**. Refer to the last paragraph of Section 1.7 (page 20).

CHAPTER 2

BRINGING SYSTEMS INTO BEING

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1) A *human–made* or *engineered* system comes into being by **purpose-driven human action**. It is distinguished from the natural world by characteristics imparted by its human originator, innovator, or designer. The human–made system is made up of elements (materials) extracted from the natural world and it is then embedded therein. Human–made systems may or may not meet human needs in a satisfactory manner. Reference: Sections 1.2.1 (page 6) and 2.1.1 (pages 24-25).

2) Interfaces between the human–made and the natural world arise from human–made products, systems, and structures for the use of people. An example interface is a system of pipes, pumps, and tanks bringing water from a natural system, such as a lake, or a human–made system like a reservoir, to a city. The human–made water distribution system creates an interface when it is brought into being. Interface-creating entities such as this draw upon natural resources and impact the environment during use and at the end of their useful life. Reference: Section 2.1.1 (pages 24-25).

3) A watershed in its natural state is a natural system that receives rainfall, absorbs some rainwater, and accumulates and discharges runoff. This system becomes human-modified if a dam is constructed at a point on the watercourse. The watershed is now a human-modified system that differs from the original system. Some differences are the new capacity for water storage, a change in the rate of runoff, and some change in the pattern of water absorption into the soil. A change will also occur in the distribution and density of vegetation in the watershed. Reference: Section 2.1.1 (pages 24-25) and item 9 (page 48).

4) Every engineered system provides a *product*, either tangible or intangible. The product (or prime equipment) is not the system, but is a component thereof. It is the result of successful system existence and may or may not be cost–effective in meeting a human need. The function of the system is to bring the product into being and to support it over time. The function of the product is to meet the need in a beneficial and cost–effective manner. Often the “product” is a service, such as the output expected from a service system. Reference: Section 2.1 (pages 24-28).

5) Student exercise. Reference: Section 2.1.2 (pages 25-26).

6) Student exercise. Reference: Section 2.1.2 (page 26).

7) Student exercise. Refer to Section 2.1.2 (see single-entity product systems on page 25).

8) Student exercise. Reference: Section 2.1.3 (page 27).

9) The overarching factor in *engineering for product competitiveness* is the requirement to meet customer expectations cost–effectively. Competitiveness is the assurance of corporate

health and advancement in the global marketplace. This desideratum cannot be achieved by advertising, acquisitions, mergers, and outsourcing alone. Product competitiveness requires focus on **design characteristics.** Product (and system) design is now being recognized by forward-looking enterprises as an underutilized strategic weapon. Reference: Sections 2.1.3 and 2.1.4 (pages 27-28).

10) System *life–cycle thinking* necessitates engineering for the life cycle. This is in contrast to engineering as historically practiced, in which downstream considerations were often deferred or neglected. Life–cycle thinking can help preclude future problems if emphasis is placed on: (a) Improving methods for defining system and product requirements; (b) Addressing the total system with all its elements from a life–cycle perspective; (c) Considering the overall system hierarchy and the interactions between various levels in that hierarchy.

    Some of the problems that life–cycle thinking can help alleviate are: (a) The dwindling of available resources by looking ahead and considering timely substitution; (b) The erosion of the industrial base through international competition by emphasizing design–based strategies; (c) The loss of market share by providing the right product at the right price to avoid the need to downsize or merge to synchronize operations; (d) The demand for more complex products, which increases the cost of operations for the producer. Reference: Section 2.2 (pages 29-33).

11) The first life cycle involves technological activity beginning with need identification and revolves around *product design* and development. Consideration is then given to the production or construction of the product or structure. This is depicted in the second life cycle which involves bringing a *manufacturing* or *construction* capability into being. The third life cycle concerns the maintenance and *logistic support* needed to service the product during use and to support the manufacturing capability. Finally, the fourth life cycle addresses the *phase–out and disposal* of system and product elements and materials. Reference: Section 2.2.1 (page 26).

    The major functions of the system engineering process during conceptual design are the establishment of performance parameters, operational requirements, support policies, and the development of the system specification. As one proceeds through design and development, the functions are primarily system dependent, and may include functional analyses and allocations to identify the major operational and maintenance support functions that the system is to perform. Criteria for system design are established by evaluating different (alternative) design approaches through the accomplishment of system/cost effectiveness analyses and trade–off studies, the conduct of formal design reviews, and preparing system development, process, and material specifications.
    The production and/or construction phase may entail technical endeavors such as the design of facilities for product fabrication, assembly, and test functions; design of manufacturing processes; selection of materials; and the determination of inventory needs.
    The major functions during system use and life–cycle support can involve providing engineering assistance in the initial deployment, installation, and checkout of the system in preparation for operational use; providing field service or customer service; and providing

support for phase–out and disposal of the system and its product for the subsequent reclamation and recycling of reclaimable components. Reference: Section 2.2 (pages 29-33).

12) Designing for the life cycle means **thinking about the end before the beginning**. It questions every design decision on the basis of anticipated downstream impacts. Design for the life cycle is enabled by application of systems engineering defined as an interdisciplinary approach to derive, evolve, and verify a life–cycle balanced system solution which satisfies customer expectations and meets stakeholder expectations. It promotes a top–down, integrated life–cycle approach to bringing a system into being, embracing all of the phases exhibited in Figure 2.2 (page 30). Reference: Section 2.2 (pages 29-33).

13) Student exercise. Refer to Figures 2.1, 2.2, and 2.3 (pages 29-32).

14) Student exercise. Refer to Figure 2.5 (pages 36 and 37) and note the characteristics of each model. Preference is subjective, so give some reasons for your choice.

15) *Design considerations*, exemplified in Figure 2.6 (page 38) exhibit the panorama of almost all design-dependent parameters that may be important in a given design situation. Some of these must be stated in Technical Performance measure (TPM) terms. This is a necessary first step because of the obligation to satisfy requirements. Next, the TPMs must be stated in such a way that their estimated or predicted values can be compared to the desired or required values (design criteria). Refer to Section 2.4 (pages 35-41), including Figure 2.7 (page 39).

16) After the need has been identified, it should be translated into system *operational requirements*. In determining system requirements, the engineering design team needs to know what the system is to *accomplish*, when the system will be *needed*, how the system is to be *utilized*, what *effectiveness* requirements the system should meet, how the system is to be *supported* during use, and what the requirements are *for phase–out and disposal*. TPMs identify the degree to which the proposed design is likely to meet customer expectations.

    Many parameters may be of importance in a specific design application and most of these are *design–dependent*. These are appropriately called *design–dependent parameters* (DDPs). Requirements are the driving force for identifying those design considerations that must be measured and expressed as TPMs. TPMs are specific estimated and/or predicted values for DDPs and they may or may not match required values. When requirements and TPMs are not in agreement, the system design endeavor must be continued by altering those factors and/or design characteristics upon which design values inherently depend; i.e., DDPs. Alternatively, the customer may be made aware of the discrepancy and be given the opportunity to modify initially stated requirements. Reference: Section 2.4.1 (page 40).

17) Student exercise. Reference: Sections 2.4.1 and 2.4.2 (pages 38-41).

18) Student exercise based on Figure 2.7 (page 39).

19) An essential element of the system engineering process is system design evaluation. To design is to synthesize (i.e., to put known elements together into a new combination). Evaluation is an assessment of how good the design alternative might be from the standpoint of the customer if chosen for implementation. System design evaluation is preceded by systems analysis which, in turn, is preceded by synthesis. Reference: Section 2.5 and Figure 2.9 (pages 41-46).

20) Student exercise based on Figure 2.8 (page 42).

21) Insofar as possible, each block in the *ten–block morphology* is classified with respect to synthesis, analysis, and evaluation as follows: synthesis (Blocks 2, 3, 4, and 5); analysis (Blocks 5, 6, and 7); evaluation (Blocks 7, 8, and 9). Synthesis, analysis, and evaluation are invoked on behalf of Block 1 (the customer) utilizing the knowledge and information contained in Block 0 (research and technology) and Block 7 (databases of system studies, existing subsystems, and components). Refer to Figure 2.10 (page 43) and the discussion of each block therein.

22) Formal *engineering domain manifestations* of systems engineering that are offered as academic degrees are biological systems engineering, computer systems engineering, industrial systems engineering, manufacturing systems engineering, and others. Informal domains exist with employment opportunities in aerospace systems engineering, armament systems engineering, network systems engineering, information systems engineering, health systems engineering, service systems engineering, and many others.

Systems engineering utilizes appropriately applied technological inputs from various engineering disciplines together with management principles in a synergistic manner to create new systems. Traditional engineering domains tend to focus on the bottom–up approach in designing new systems, whereas systems engineering uses the top–down approach. Unlike the traditional disciplines, it adopts a life–cycle approach in the design of new systems.

23) Some organizational *impediments* to the implementation of systems engineering include: (a) the dominance of disciplines over interdisciplines, (b) a tendency to organize SE in the same manner as the traditional engineering disciplines, (c) an excessive focus on analysis at the expense of synthesis and process, (d) difficulty in integrating the appropriate discipline contributions with the relevant system elements, (e) the lack of sufficient communication, especially where system contributors are geographically dispersed, (f) deficiencies in balancing technologies and tools with planning and management of the activities required to accomplish objectives, (g) an ineffective general organizational environment to enable the systems engineering function to truly impact design and system development.

Other impediments related to the above include (a) the lack of a good understanding of customer needs and definition of the *system requirements*, (b) ignorance of the fact that the majority of the projected life-cycle cost for a given system is committed because of engineering design and management decisions made during the early stages of conceptual and preliminary design, (c) the lack of a disciplined top–down “systems approach” in meeting desired objectives, (d) system requirements defined from a short term perspective and, (e) lack of good planning early, and the lack of subsequent definition and allocation of requirements in a complete and disciplined manner. Reference: Sections 2.6.2 and 2.6.3 (pages 48-51).

24) Some of benefits that accrue from the application of the concepts and principles of systems engineering are: (a) *Tailoring* involving the modification of engineering activities applied in each phase of the product or system life cycle to adapt them to the particular product or system being brought into being. Its importance lies in that the proper amount of engineering effort must be applied to each phase of the system being developed, and it must be tailored accordingly; (b) *Reduction in the life–cycle cost* of the system. Often it is perceived that the implementation of systems engineering will increase the cost of the system acquisition. This is misconception since there might be more steps to perform during the early (conceptual and preliminary) system design phases, but this could reduce the requirements in the integration, test and evaluation efforts later in the detail design and development phase; (c) More visibility and *a reduction of risks* associated with the design decision making process, with a consequent increase in the potential for greater customer satisfaction; (d) promotion of *a top–down integrated* life–cycle approach for bringing a system into being.

    The benefit of systems engineering is needed when the engineering specialists in one of more of the conventional engineering areas may not be sufficiently experienced or capable to ensure that all elements of the system are orchestrated in a proper and timely manner. See Section 2.6.3 (page 50-51).

25) Student exercise based on information about the INCOSE Journal from **www.incose.org**.

26) Student exercise. Go to the Fellows Section of the INCOSE web site **www.incose.org**.

CHAPTER 3

CONCEPTUAL SYSTEM DESIGN

1) The first step is to thoroughly *define the problem*, or the current deficiency, which then leads to the identification of a *need* for a system that will ultimately provide a solution. *What functions must be performed that are not now being accomplished?* This includes a complete understanding of the nature of the problem, its magnitude, and the causes for such, as well as the risks involved in the event that the problem is not solved. Within the problem description, include the appropriate quantitative measures as required to define the magnitude of the problem. Quite often, there is a tendency to go ahead and specify the requirements for a new system capability (based on a "perceived" need) without having first defined the problem! The questions are — *is there a* ***real*** *need? Is the current deficiency* ***significant****? What will happen if the current deficiency is not corrected?* By concentrating on defining the current problem first, this should lead to a better definition of the ***true*** need.

   The process might include the establishment of a small team of individuals with representation from the customer's organization (and procuring agency if different from the customer), the ultimate system "user," producer or prime contractor, and perhaps a major supplier. The customer must be able to define the problem in detail, and the producer must thoroughly understand the problem and be able to translate the customer's requirement into a *statement of need.* This will include a description of the functions that must be performed, the geographical location and required time of performance, and an estimate of the anticipated resources required. Proposed team members should include a systems engineer, a senior–level design engineer, technical marketing, and related support personnel who have had prior experience in developing system requirements. The development of a good "statement of need" can be accomplished (in an iterative manner) by a small team of individuals, meeting on several different occasions. This process constitutes a *needs analysis.* Reference: Section 3.1 (page 57).

2) Given a good understanding of the problem to be addressed and a comprehensive description of the customer's need (to include a description of the functions that must be performed — the *what, when,* and *where*), a *feasibility analysis* is accomplished in order to develop an **overall technical approach** to solving the problem at hand. *What "technologies" are available and can be applied that could lead to problem solution? Will they be available when required? Are they reasonable candidates for consideration when addressing the issues of projected technology life, reliability, maintainability, supportability, producibility, sustainability, disposability, life–cycle cost, etc.*? Given several alternatives, trade–offs are conducted, and a preferred approach is recommended. If there is no apparent resolution, then further research may be appropriate. It is **not** the intent at this stage to recommend specific hardware, software, facilities, etc., as we are dealing with *functional* requirements. The purpose is to identify a technical approach in response to a functional requirement. Considerations include identifying applicable technologies, their

possible sources of supply and availability, anticipated costs, and associated priorities. Reference: Section 3.3 (page 60).

3) The QFD method constitutes a *process*, involving the establishment of a team of individuals representing the customer and producer organizations, implemented with the objective of: (a) further refining system requirements (based on the established system operational requirements and the maintenance and support concept — see Sections 3.4 and 3.5 respectively); (b) identifying and prioritizing technical performance measures (TPMs – the metrics that reflect these true customer requirements); (c) identifying potential technical design–related solutions and relating these to each of the prioritized TPMs (design–dependent parameters); (d) assessing these potential solutions in terms of what is available in the market place; and (e) evaluating whether the results will ultimately meet the expectations of the customer. The objective is to establish quantitative design–to requirements similar to what is illustrated in Figure 3.17 (Section 3.6, page 83), and to identify specific technical approaches that need to be built into (inherent within) the ultimate system design configuration. These attributes (or characteristics), as they are incorporated in the design, must be "responsive" to the initial customer requirements, the degree to which is reflected by the prioritized TPMs (i.e., the "importance" factors).

   Referring to Section 3.6 (page 82), an excellent "tool" for facilitating these objectives is through use of the *house of quality (HOQ)* structure illustrated in Figure 3.18 (page 84). A "teaming" approach is first used to identify and rank (in order of priority) the specific needs in terms of levels of importance; i.e., the **whats**. The results are conveyed in the left side of the house. Then, the appropriate technical design characteristics (i.e., design dependent parameters) are identified at the top of the house. The correlation of these with the input requirements is identified through the matrix in the center of the house. Each internal design characteristics (or attribute) must be in response to some specific requirement; i.e., the **hows**. This process is iterative, and through the application of a team approach, the detailed design requirements for a system can be defined. Referring to Figure 3.19 (page 85), the design requirements at the system level (i.e., the top of block 1) constitute the input requirements for the subsystem (i.e., the left side of block 2), and so on, providing a top–down and bottom–up **traceability of requirements**. References: Section 3.6 (page 82) in the text; and Appendix G (page 755), Section G.7, items 1 and 7.

4) The definition of *system operational requirements* forms the basis for all subsequent design and development, test and evaluation, production/construction, and system maintenance and support activities. It includes a complete description of all of the functions required to successfully accomplish the mission(s) that the system must perform. Information included should address *operation scenarios or mission profiles, operational distribution and the system life cycle, performance and related factors, utilization requirements, effectiveness requirements,* and *environmental factors.* Reference: Section 3.4 (pages 61-75).

5) In a system-of-systems (SOS) configuration, there may be two or more different systems operating in the same general environment, each responding to a different set of requirements. On some occasions, the requirements may be complementary and a sharing of components (elements) may be possible. On other occasions, there may be conflicting

requirements and interferences causing degradation in the operation of one or more of the other systems in the configuration. In the design and development of a new system, one of the challenges is to ensure that the new system, when introduced for customer utilization, will operate in a satisfactory manner and will not result in the degradation of other systems operating in the same general environment. The *design for interoperability* pertains to the design of new system such that it will operate satisfactory when introduced into the inventory and will not have a negative impact on other systems operating in the same environment. An example of a SOS configuration is illustrated in Figure 3.13 (page 75). The design objective for any one of these systems (e.g., transportation system, communication system, etc.) is to ensure compatibility throughout the overall network. Reference: page 62 (interoperability requirements) and page 74 (SOS configuration). Also, refer to Figure 3.24 on page 91 (functional interfaces in a SOS configuration).

6) One needs to know the specific system functions (or a good representation of such) that must be performed to accomplish its mission, and how the system might be utilized in terms of number of "on–off" cycles, the various modes of operation and likely sequences, the length of time in each mode, and so on. It is essential that one understand the "dynamics" associated with the operation of the system. While the system may be operated differently by different operators, it is necessary to define a few of the anticipated scenarios (i.e., those anticipated as being more frequent than others and/or those that appear to impose more stresses on the system — see Figure 3.4 on page 66 and Figure 3.6 on page 68). These, in turn, will serve as a "baseline" for the development of performance requirements, the identification of effectiveness requirements (e.g., availability and reliability requirements related directly to a particular scenario or series of scenarios), and the definition of environmental requirements. If one is to design a system to accomplish a specific function, he/she needs to know the intent relative to how the system will be utilized. Reference: Section 3.4 (page 61).

7) The *maintenance concept* is a "before–the–fact" series of illustrations and statements describing how the system is to be designed such that it can be effectively and efficiently supported throughout its planned life cycle. The *concept*, which ultimately leads to the development of a detailed *maintenance plan*, includes a description of the anticipated levels of maintenance, repair policies (major functions to be performed at each level), organizational responsibilities, design criteria for the various elements of support (test equipment, spares and associated inventories, transportation, facilities, etc.), effectiveness requirements as they pertain to the maintenance and support infrastructure, and environmental requirements pertaining to the accomplishment of maintenance functions. The *concept* constitutes an <u>input</u> to design, whereas the *plan* is an <u>output</u>.

   The maintenance concept is based on the definition of system *operational* requirements; i.e., the identification of "operational" functions to be performed, description of mission scenarios and utilization profiles, identification of geographical location(s) and where the missions are likely to be performed, and specification of the planned system life cycle and the period of time over which these missions are to be accomplished. This leads to the definition of the maintenance concept and the requirements for system life–cycle support. Reference: Section 3.5 (pages 76–81).

8) Given a description of the mission (operational scenarios, utilization profiles, anticipated hours of operation per period of time) and the applicable measures of effectiveness (e.g., reliability and maintainability factors), one can determine the nature and the extent to which maintenance can be anticipated. Maintenance frequencies, downtimes, personal labor hours, and the basic resource requirements for system support can be initially determined. Given the geographical location(s) and where the operational scenarios will take place, one can determine where the required maintenance is likely to occur (i.e., the points from where the demands for support are likely to evolve). This will aid in identifying some of the anticipated packaging and transportation requirements which, in turn, will lead to the determination of the environments which are likely to be experienced as items are shipped, stored, etc. Given the projected system life cycle, one can determine the length of time that the appropriate level of support will be required. Thus, the determination of system operational requirements will not only lead to the definition of the maintenance concept, but such requirements will significantly influence the design of the system and its maintenance and support infrastructure. The maintenance concept serves as the basis for the development of reliability requirements (Chapter 12, page 362), maintainability requirements (Chapter 13, page 410), and logistics and supportability requirements (Chapter 15, page 497), in particular. Reference: Section 3.5 (page 76).

9) The maintenance concept contains valuable information that can significantly influence system design. For instance, *are we planning on the availability of two levels, three levels, or four levels of maintenance?* In identifying the levels of maintenance, there may be different repair policies, personnel quantities and skills, facilities, support equipment, etc., at each level. The specific requirements will be based on the functions to be performed at each level. Further, the repair policy (based on an early level–of–repair analysis which is accomplished initially in support of the maintenance concept development process) will indicate the degree of reparability and the levels at which certain items should be repaired (versus discarded). These decisions will be based on the anticipated frequency of maintenance (i.e., reliability), cost, and related factors. This information, in turn, should influence the design relative to system packaging schemes (the quantity, size, interchangeability, and functionality of system elements), the level of diagnostics and built–in versus external test (which should be compatible with the packaging scheme and the depth of maintenance to be performed at each level), the degree of accessibility that should be incorporated, the amount and type of labeling, and so on. Further, these design–related characteristics may vary with the identification of maintenance responsibilities. An item may be designed one way if it is of a “proprietary” nature, or if there is a safety or security issue, and the maintenance of such must be accomplished in the producer’s factory; or, it may be designed differently if it is to be maintained at the intermediate level. In essence, decisions pertaining to the levels of maintenance, responsibilities, effectiveness factors, environment, etc., can significantly influence design of not only the prime mission–related elements of the system but the design of the maintenance and support infrastructure as well. Reference: Section 3.5 (page 76).

10) Student exercise. It is recommended that the student response include figures such as 3.3, 3.4, 3.5, 3.14, and 3.16 to convey the appropriate information for the system selected. Reference: Sections 3.4 (page 61) and 3.5 (page 76).

11) Student exercise. It is recommended that the student develop a figure similar to 3.12 (page 73). Critical metrics may include such factors as shown on page 74, but tailored to the local configuration. A figure similar to Figure 3.22 (page 88) may be developed to help better define some of the lower-level functions required. Reference: Illustration 5 (page 72).

12) Student exercise. It is recommended that the student develop a figure similar to 3.13 (page 75) and describe the operational requirements, the maintenance concept, and significant technical performance measures (TPMs) for each of the major systems in the overall configuration. The student should identify some of the more critical interface requirements (interoperability requirements), and potential problems areas (if any). Reference: Figure 3.13 (page 75) and Figure 3.24 (page 91).

13) Initially, in defining the maintenance concept during conceptual design, the levels of maintenance should be specified; i.e., two levels versus three levels. In accomplishing such, one needs to consider the type of system and its complexity, the makeup of the system in terms of its packaging, the reliability of the system elements and expected requirements pertaining to anticipated frequency of maintenance, and estimated cost from a life–cycle perspective. If the system and its elements are relatively simple (in design), are of a standard variety, and very reliable (i.e., the anticipated frequency of maintenance is low), then it may not be feasible to establish a maintenance capability at the intermediate level, thus resulting in a two–level concept (i.e., organizational and depot/producer). If, on the other hand, the system complexity is high, the reliability is not too good, and certain elements of the system are *critical* (such that when they fail the mission of the system will be impaired significantly), then it may be feasible to establish a maintenance capability at the intermediate level in order to be more responsive in terms of turn–around time (TAT), thus resulting in a three–level concept (i.e., organizational, intermediate, and depot/ producer). In essence, these factors, as they pertain to the basic system design approach, must be addressed.

    Additionally, there are some external factors that must be considered and may *dictate* a certain policy. One may not be able to repair an item at the intermediate level because the design is too complex and neither the potential personnel skills or facilities are available at this level; or not be allowed to repair an item at the intermediate level because it is "proprietary" in nature and must be repaired at the producer's manufacturing plant; or it must be repaired at a specific remote facility or in a specific country for political reasons. These external issues may force a three–level concept and, in some instances, even a four–level concept.

    In summary, the desired levels of maintenance should be specified initially as part of the maintenance concept development process and as an *input* to design. Later, in evaluating a given design configuration (an *output* from design), the results could dictate the addition and/or deletion of certain requirements. For instance, one may start out by specifying a two–level concept, and then (from the results of a supportability analysis) find that three levels are necessary. Reference: Section 3.5 (page 76). Figure 3.16 (page 80) provides an illustration of an assumed repair policy where three levels are required.

14) In developing the maintenance concept and the support infrastructure (refer to Figure 3.14, page 77), there are many interrelationships that exist when conducting the necessary trade–offs between the spares inventory requirements at each level of maintenance and the transportation requirements between levels, between test and support equipment and spares inventory requirements at each level, between personnel and facilities at each level, and so on. One must address the entire infrastructure in Figures 3.14 and 3.16 as a major subsystem, and address all of its components on an integrated basis. Reference: Section 3.5 (page 76).

15) Technical performance measures (TPMs) constitute those quantitative measures (or "metrics") to which the system must be designed in order to fulfill its mission requirements in a successful manner. TPMs must be both specified and prioritized as part of the initial system requirements definition process. The specification of such is critical in order to define the appropriate *criteria* (in the form of desired built–in characteristics or attributes) as an input to the design, and the prioritization of TPMs is necessary in order to establish the relative level(s) of importance of the various requirements in the event that trade–offs and compromises in design are necessary. For instance, one might ask — *is range more important than accuracy in a radar system? Is capacity in a manufacturing capability more important than quality? Is system availability more important than life–cycle cost? For a communication system, is the rate of message handling more important than message clarity?* And so on. The designer needs some guidance as to where to place the emphasis in design. TPMs are initially specified in conceptual design. Later, the system and its elements are measured and evaluated relative to being in compliance with these requirements. Reference: Section 3.6, page 82. Also, check Sections 4.7 (page 120), 5.8 (page 142), and Chapter 6 (page 150) for the "tracking" of TPMs from a validation perspective.

16) Referring to Figure 3.17 (page 83), it is recommended that the QFD approach, or some equivalent method, be utilized in developing such information as shown in the figure. QFD is a *process* that involves a "team" approach (including representation from the customer/user, key designers, and major suppliers), and that leads to the identification of specific design requirements. Through good two–way communications, customer requirements are refined, TPMs are identified and prioritized, and specific attributes (characteristics) that must be inherent and built into the design are specified. This may constitute an iterative process involving several meetings in the establishment of the proper priorities. The intent is to relate and incorporate specific design characteristics in response to a good set of customer requirements, with the degree of incorporation being in line with the prioritized TPMs and the "level–of–importance" of each. Also, refer to the response to Question 3 above. Reference: Section 3.6 (page 82).

17) The QFD process can initially be applied in the conceptual design phase to aid in defining the design requirements at the system level (and possible at the sub–system level). Quantitative design–to factors, such as those in Figure 3.17 (page 83), are specified, leading to the identification of design technologies (and associated characteristics/ attributes) that need to be inherent within the ultimate configuration in order to comply with the quantitative TPMs. These top–level requirements can then be allocated down to

the subsystem, unit, assembly, and so on, as shown in Figure 3.19 (page 85). This top–down allocation can be facilitated following the approach illustrated in Figure 4.6 (page 109). Design checklists may be prepared to enhance this overall process. Reference: Section 3.6 (QFD, page 82), and Sections 3.7 (page 86) and 4.3 (page 104) (Functional Analysis and Allocation).

18) *Functional analysis* is the process of translating top system–level requirements into detailed design criteria and the subsequent identification of specific resource requirements at the subsystem level and below. One commences with an abstraction of the customer need(s) and works down to identifying the specific requirements for hardware, software, people, facilities, data, information, elements of support, and so on. The first step is to identify the functions (i.e., operational mission or series of missions) that the system must perform in response to some requirement, along with the supporting functions that are needed for this to happen. Construct a functional flow block diagram (FFBD) at the system level (refer to Figure 3.20, page 87). Include design functions, test functions, production functions, operational functions, maintenance and support functions, and retirement and material recycling/disposal functions as applicable. All system life–cycle activities should be included. Each functional block may be broken down into sub–functions and below, as shown in Figures 3.20 (page 87), 3.21 (page 88), and 3.23 (page 89). From the results of the TPM identification and prioritization process (see Figure 3.17, page 83), one can identify the metrics associated with each function and, through allocation, each sub–function, etc. Each functional block of the FFBD should be evaluated in terms of input–output requirements, constraints, and the resources required in order to accomplish the function (see Figure 4.2, page 105). The functions may then be combined, partitioned, grouped, and packaged into various elements of the system. Refer to Figure 3.25 (page 92) for identification of the elements of a system and Figure 4.5 (page 108) for an illustration of the process.

The functional analysis is first accomplished at a top–level as the customer need is defined during the early stages of conceptual design. This involves identifying and describing the functions that the system must accomplish in fulfilling its mission requirements. Development of the functional analysis effort continues throughout conceptual design and preliminary system design, to the depth required to provide the necessary visibility for the subsequent design of system elements and components. A good functional baseline is established in order to provide a foundation for all follow–on design activities (refer to the “functional baseline” in Figure 2.4, page 34). From this point on, the functional analysis serves as the basis for the development of all detailed design requirements; i.e., electrical design, mechanical design, structural design, reliability models and block diagrams, FMECA, FTA, RCM, maintainability models, MTA, LORA, OTA, OSDs, supportability analysis (SA), and other similar efforts. In other words, many of the activities in Chapters 4–6, 12, 13, 14, 15, 16, and 17 stem from this functional baseline (specific applications of the functional analysis are presented in Section 4.3, page 104). A functional analysis can be accomplished on any type of system, constituting a process leading from the definition of a customer requirement to definition of the specific elements of a system and their interrelationships. References: Section 3.7 (page 86), Section 4.3 (page 104), and Appendix *A* (page 699).

Functional analysis can be accomplished on any system by following the same approach as described in Section 3.7, Section 4.3, and Appendix A. In a system-of-systems (SOS) configuration, one would accomplish a functional analysis for each of the systems in the configuration; identify the functional interfaces; determine whether there is some degree of "commonality" for a given functional requirement (where there are distinct interface relationships) and whether a "common" function can be introduced to support two or more system requirements; identify a "common" function where appropriate; and re-evaluate the functional analysis results for the applicable systems where a "common" function has been introduced to ensure that the overall functional requirements for both systems have not been compromised in any way. Reference: Section 3.7 (page 86) and Figure 3.24 (page 91).

19) ~~A *common* function is one where the functional requirements for two or more systems in a system-of-systems (SOS) configuration may be "shared" in terms of input-output requirements. Refer to the response to Question 18, the description on page 90 and Figure 3.24 (page 91), and the illustration in Figure 4.7 (page 110).~~

~~20) Referring to Figures 3.20, 3.21, and 3.22 (pages 87-88), each functional block reflects some "activity" in terms of the **whats**; i.e., what must be accomplished? Further, one can allocate or apportion (from system-level requirements) and assign the appropriate metrics associated with each block. The next question relates to the **hows**; i.e., how can the function be accomplished? There may be any number of solutions involving different mixes of equipment, software, people, facilities, data, or various combinations thereof. Trade-off studies are conducted, and a preferred solution is selected. The process is illustrated in Figure 4.2 (page 105), with the results being the identification of various system elements (see Figure 3.23, page 89). The block-numbering configuration in Figures 3.20 – 3.22 is for the purposes of *traceability*, both downward and upward. Top-level functions can be broken down into sub-functions, job-operations, duties, human tasks, and resources (equipment, software, people, facilities, and data) can be traced upward to a functional requirement. References: Section 3.7 (page 86), Section 4.3 (page 104), and Appendix *A* (page 699).~~

~~21) *Allocation* constitutes a top-down apportionment of system-level requirements to the sub-system level, configuration item level, and lower-level elements of the system. The purpose is to establish "design to" requirements to the depth necessary in order to influence the design. Such requirements, specified in both qualitative and quantitative terms, are provided as an input to design. The characteristics (attributes) of design must then support these input requirements. Thus, the impact can be significant. Reference: Section 3.7 (page 86). Additionally, this topic is discussed further in Section 4.3 (page 104), and an example of allocation is shown in Figure 4.6 (page 109).~~

~~The allocation process for a SOS configuration becomes a little more complex. If a newly designed system is being added to a network where there are a number of existing systems already in being and operational (and particularly where there are "common" units in place), the allocation requirements may be somewhat influenced by the systems already in the network. This, in turn, may result in a negative impact on the requirements for the new system unless the requirements for the existing systems are upgraded. On the other hand, if~~

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~~there are two or more new closely related systems being added, then the allocation process for each of the systems will be accomplished such as described above, and trade offs may be necessary in synthesizing the requirements for each of the systems before arriving at a final design input requirement. This process is described in more detail in Section 4.3.2 (page 105) and illustrated in Figure 4.7 (page 110).~~

~~22) Referring to Figure 2.9 (page 43) in Section 2.5 (page 41), system *synthesis*, *analysis*, and *evaluation* are closely related, interactive, and reflect a process. Synthesis refers to the combining and structuring of components in such a way as to represent a feasible system configuration. Analysis involves the application and utilization of various analytical techniques/tools in the accomplishment of trade offs, in the comparison of alternatives, and in the selection of a preferred design approach. Evaluation involves an assessment of the configuration that is currently being considered for operational use. This process reflects an on going iterative activity, starting with the initial design configuration proposed early in conceptual design and extending through the final configuration ready to enter the production/construction phase. Initially, design concepts are vague and are presented in the form of informal engineering sketches. This leads to detailed design, the availability of a good design data package, and the development of pre production prototype models. This process is inherent within the systems engineering process and incorporates many of the techniques/tools/methods discussed throughout Parts III and IV of this text. Reference: Section 2.5 (page 41) and Section 3.8 (page 93). Evaluation is discussed further in Chapter 6 (page 150).~~

~~23) The purpose of a *formal design review* is to periodically review and evaluate (in a formal sense) the system design configuration (or elements of such) that is in existence and being considered at the time of the review. Referring to Figure 2.4 (page 34), formal reviews may include a *conceptual design review*, one or more *system design reviews*, one or more *equipment/software reviews*, and so on. Potential benefits in conducting such reviews are presented in Section 3.10 (page 95). Problems may occur when the review meetings are not properly planned or conducted, when the wrong people are at the meeting, when the items being reviewed are not properly covered by the appropriate documentation, when the meetings are not properly funded ahead of time, and when there is no follow up action to correct any noted design deficiencies. Design review meetings can be very beneficial and productive if properly planned and implemented. Reference: Section 3.10 (page 95). Additional coverage is provided in Sections 4.8 (page 123) and 5.8 (page 142).~~

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~~24) The objective in conducting a *conceptual design review* is to formally and logically cover and review the proposed design from a total "system" perspective. This particular review, accomplished at the end of the Conceptual Design Phase (refer to Figure 2.4, page 34), covers the results of the feasibility analysis, system operational requirements, system maintenance and support concept, system level TPM requirements, functional analysis and description of system architecture, system specification, and the system engineering management plan (SEMP). This is the first in a series of formal design reviews, and constitutes a final review and approval of all of the major design and early planning related activity accomplished during the Conceptual Design Phase. A few specific objectives are noted in Section 3.10 (pages 95 and 97). Reference: Section 3.10 (page 95).~~

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~~CHAPTER 4~~

~~PRELIMINARY SYSTEM DESIGN~~

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~~1) Student exercise. Refer to Sections 3.7 (page 86), 4.3 (page 104), and Appendix *A* (page 699) for assistance and guidance.~~

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~~2) See the response for Problem 20 in Chapter 3. Referring to Figure 4.2 (page 105), each of the blocks in the functional flow block diagrams (FFBDs) reflects the *whats*; i.e., what must be accomplished? There are *input* factors, *output* expectations, and external *controls and constraints* that have an impact on the function under consideration. Given these, there may be a variety of ways of accomplishing the function; i.e., the *hows*. Various combinations of equipment, software, people, facilities, etc., may be utilized in response to the functional requirement. For example, a function may be accomplished manually or through the use of automation. Trade off studies are conducted and a preferred approach is selected. The format presented in Figure 4.3 (page 106) might be appropriate for use in documenting the resources required for each function. These various functional requirements may then be combined to reflect a single comprehensive set of resource requirements. Reference: Section 4.3 (page 104).~~

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~~3) Given a top level description of the system in functional terms, the next step is to combine, or group, similar functions into logical subdivisions, identifying major sub systems and lower level elements of the overall system; i.e., the development of a functional packaging scheme as shown in Figure 3.25 (page 92). An example of the process, as it was accomplished for System XYZ, is presented in an abbreviated form in Figure 4.5 (page 108). While the illustration presents the details in a rather broad manner, the process was to first describe the overall functions, then the sub functions, and then to group similar or "like" functions into a packaging scheme; i.e., Unit *A*, Unit *B*, and Unit *C*. The objective is to package the functions in such a way that there is minimum interaction between any two or more units. In the maintenance area, for example, if corrective maintenance is required, one should be able to remove and replace Unit *A* without having any effect on Units *B* and *C*. One should not have to remove all three units when any one of them has failed, and there should not be any adjustment or alignment requirements after a remove and replace action. In other words, any complexities in design should be internal within a given package, and any external interaction effects should be minimized (or eliminated if possible). Full functional and physical *interchangeability* is required. The student is encouraged to provide a specific example familiar to him/her. Reference: Sections 3.7 (page 86) and 4.3 (page 104).~~

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~~4) Referring to Figure 4.6 (page 109), the TPM and related requirements at the system level were established through the development of system operational requirements, the maintenance concept, and the identification of TPMs (refer to Figure 3.17, page 83). The functional analysis and partitioning (packaging scheme) were accomplished leading to the identification of units and assemblies in Figure 4.6 (page 109). Through the allocation process, described in Section 4.3 (page 104), the specific quantitative metrics (i.e., TPMs)~~

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~~were established for Units *A*, *B*, and *C*, and Assemblies *1*, *2*, and *3*. If the requirements for the design of Unit *A*, for example, dictate the use of a commercial and standard off-the-shelf (COTS) item or some "known" entity, then (hopefully) there may be some actual field data with a known MTBM, MLH/OH, etc., that may be applied to Unit *A*. On the other hand, if there is a "new" design requirement, it may be appropriate to assign a complexity factor and assign an individual MTBM (or equivalent) value to each of the remaining elements of the system. The TPM "design to" factors assigned for Assemblies *1*, *2*, and *3*, when combined, must equate to the MTBM requirement for Unit *B*; and the MTBM values for Units *A*, *B*, and *C* must support the MTBM at the system level. In other words, there must be a top-down and bottom-up traceability of requirements. Quite often, in accomplishing the allocation process, trade-off studies are accomplished, leading to a "juggling" of requirements between units and assemblies. The objective is to provide a logical and meaningful set of "design to" requirements for the various elements of the system as required. At this point in the text, it is important to understand the "principles and concepts" of *allocation*; i.e., the apportionment of system-level requirements down to its various elements. The details pertaining to the allocation of reliability requirements, maintainability requirements, etc., are presented further in the different chapters in Part IV. Reference: Section 4.3 (page 104).~~

~~5) Referring to Figure 3.13 (page 75), there may be a number of different systems within an overall system-of-systems (SOS) configuration; e.g., transportation system, communication system, and so on. The allocation process for each of these systems is accomplished following the same basic procedure and approach described in Section 4.3.2 (page 105), with anticipated results similar to that illustrated in Figure 4.6 (page 109). Given such, then one needs to determine the interacting effects among the various systems operating in the same general environment and also to identify any negative impacts of one system on others. The identification of undesirable impacts may lead to the requirement for a re-allocation of any one or more of the systems in question. This may constitutes an iterative process ending when the desired interoperability requirements are present. Reference: Section 4.3.2 (page 105).~~

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~~6) Student exercise. The output should be similar to what is presented in Figure 4.6 (page 109).~~

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~~7) Referring to Figure 4.7 (page 110), a *common unit* has been identified through the functional analysis and the packaging of a "common" function operating as part of each of two or more systems. Refer to the response for Question 19 in Chapter 3. Given that, the recommended procedure is as described in Section 4.3.2 under Items 1 and 2 (starting on page 110 and illustrated in Figure 4.7). One may commence with a traditional top-down allocation process for each of the systems in question and then incorporate the necessary modifications as required to cover the interaction affects which may occur. The important issue is to ensure that the basic requirements for each of the systems within the given SOS configuration are not compromised in any way. Having described the function and its overall requirements, the next step is to proceed with the development of the applicable resource requirements for the common function using the approach illustrated in Figure 4.2 (page 105). Reference: Section 4.3.2 (page 105).~~

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~~8) *Interoperability* pertains to the ability of different systems, located in the same general user environment, to operate (function) in a satisfactory manner in the accomplishment of their respective missions. In the development of new systems, the *design for interoperability* is a major goal. An objective is to minimize interference between the new system and those other systems already in the operational inventory. This includes not only minimizing the negative impact of the new system on other systems, but to ensure that those other systems already in operational use have minimum negative impact on the new system. Reference: page 62 and Section 4.4, page 112.~~

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~~9) *Environmental sustainability* pertains to the operation and support of systems, throughout their respective life cycles, without causing any degradation to the environment or to the earth's natural resources. In the development of a new system, the *design for sustainability* is a major goal. An objective is to design a system so as to eliminate wastes, greenhouse gases, toxic substances, air and water pollution, and any other factors that would cause degradation to the environment. Reference: Section 4.4, page 112. Sustainability is also covered extensively in Chapter 16, page 541.~~

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~~10) *Security* pertains to those inherent characteristics of design that will prevent (or at least deter) one or more individuals from intentionally inducing faults that will destroy the system and its ability to accomplish its mission, cause harm to personnel, and/or have an impact that will endanger society and the associated environment. A design objective is to provide an external alarm that will detect the presence of unauthorized personnel and to prevent them from gaining access to the system, incorporate a condition-based monitoring capability that will enable one to check the status of the system and its elements, and include a built-in detection and diagnostic capability leading to the cause of any recurring problem and to subsequent self-repair, or rapid repair, of the system. Reference: Section 4.4, page 113.~~

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~~11) Referring to Section 2.4 (page 38), *design criteria* constitute a set of "design to" requirements which can be expressed both in quantitative and qualitative terms. These represent the bounds within which the designer must "operate" when evolving through the process of synthesis, analysis, and evaluation. Sometimes these "bounds" represent an upper limit (e.g., the system shall be designed for a unit life-cycle cost not to exceed "x" value), while there are other occasions when a lower limit is specified (e.g., the system shall be designed for a MTBM greater than "y" value). On other occasions, criteria may be specified in broad qualitative terms such as indicated in Figure 2.8 (page 42).~~

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~~Design criteria may be specified in a hierarchical manner, and criteria may be allocated from the top down as shown in Figures 4.6 (page 109) and 4.8 (page 115). Such criteria are developed through the identification and prioritization of TPMs (Figure 3.17, page 83), the identification of the required design characteristics developed through the "relationship matrix" of the HOQ (see Figure 3.18, page 84), and the identification of DDPs. Design guidelines (standards manuals) may be developed to assist the designer in his/her day-to-day activities, and checklists may be used to facilitate the design review and evaluation task. Reference: Sections 2.4 (page 35) and 4.4 (page 112). Also refer to Appendix A.1 on page 709 for specific checklist items.~~

~~12) Referring to Figure 4.1 (page 103), a *specification tree* is important to: (a) ensure that ALL system design requirements are covered; (b) ensure that there is a "traceability" of design requirements from the top down; and (c) indicate a hierarchical relationship and which specification has "preference" in the event of conflict. Reference: Section 4.2 (page 102).~~

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~~13) Referring to Figure 4.2 (page 105), the "metrics" (or TPMs) for each block in the functional flow block diagram (FFBD) are determined through the *requirements allocation process*. Metrics are established for the overall system. Those metrics, in turn, are related to the blocks making up the functional description of the system. Subsequently, each metric is broken down into lower level metrics for each sub function. Trade off studies are conducted to determine a preferred approach (in terms of resource requirements) in accomplishing a given function, and the metrics may then require some adjustment subsequently. This basically constitutes an iterative top down approach. Reference: Section 4.3 (page 104).~~

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~~14) Refer to Figure 4.4 (page 107). As part of the functional analysis and allocation process, trade off studies were accomplished, which led to determining the requirements (and proper mix) for hardware, software, and people. This, in turn, led to the projected life cycles for each (i.e., hardware, software, human) as shown in Figure 4.4 (page 107). As one proceeds through the system design and development process (and the process of developing hardware, software, human system integration requirements), there are many interfaces which may occur. Hardware development must ensure compatibility with software, software development must consider the hardware interface, and both must consider the human interfaces, and so on. There needs to be an ongoing (and continuous) day to day liaison activity across these different life cycles, and it is important that periodic formal design reviews be scheduled at critical times as the design evolves for each. Waiting until the formal system integration and test activity (refer to block 2.3) to determine whether the hardware, software, and human interfaces are all compatible with each other (and other elements of the system) is too late, and any subsequent required system modifications could be very costly. Reference: Sections 4.3 (page 104) and 4.4 (page 112).~~

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~~15) Referring to Figure 4.10 (page 118), CAD refers to the application of computerized methods in the accomplishment of various design related activities (design layouts and component part lists, development of three dimensional graphics models, processing and storage of design data). CAM refers to the application of computerized methods in the accomplishment of manufacturing and assembly activities (purchasing, materials handling, numerical control, quality control, manufacturing and assembly data). CAS refers to the application of computerized methods used in the accomplishment of logistics and maintenance related support activities (development and processing of supportability analysis data, development and storage of spares/repair parts provisioning data, development and automation of technical publications). Many inter relationships exist between CAD, CAM, and CAS. Micro CAD constitutes a "concept" which refers to the integration of the various computerized methods into a system life cycle entity. There needs to be a continuous computer based "thread" throughout system design and development, production and/or construction, and system utilization, which can include~~

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~~synthesis, analysis, evaluation, assessment, reporting and feedback activities. Reference: Section 4.6 (page 117).~~

~~16) In selecting an analytical model for application, care must be exercised to ensure that the considerations identified in Section 4.6.2 (page 119) are addressed. From the development of system operational requirements, the maintenance and support concept, and the identification and prioritization of TPMs, one can identify the appropriate design characteristics that must be incorporated in the ultimate configuration. The model selected must be "sensitive" to these characteristics, and incorporate some of the features identified in the text. Additionally, the requirement may dictate to utilization of several different models, applied on an integrated basis. Reference: Section 4.6.2 (page 119), and Figure 4.12 (page 122) for multiple model applications.~~

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~~17) One way to "validate" the model for its application is to select a known (already existing) design configuration and to utilize the model in assessing the characteristics of this known entity. Through an assessment and the implementation of a sensitivity analysis, one can gain some degree of confidence as to the model's capability relative to its application in a new system design effort. Reference: Section 4.6.2 (page 119).~~

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~~18) This question was missed in the initial text editing process. Please proceed to Question 19.~~

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~~19) Some of the benefits that can be derived through the use of computer-based models are listed under "Analytical Models and Modeling" in Section 4.6.2 (page 119). Some concerns include selecting a model that (a) is not sensitive the system configuration and its characteristics; (2) does not address all of the desired activities and system metrics; and (3) does not include the correct parameter relationships. Selecting a model strictly based on the promotional sales material alone (and what it is supposed to do) can be highly risky. Reference: Section 4.6 (page 117).~~

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~~20) Referring to Figure 4.8 (page 115), the two right hand columns pertain to (a) general design requirements, and (b) specific design-related tasks that must be accomplished. Within the latter category is the accomplishment of various analyses (e.g., functional analysis, reliability and maintainability analysis, supportability analysis, life-cycle cost analysis, and so on), with the appropriate mix of models and analytical techniques to facilitate such. As one proceeds from the top-down, there needs to be a traceable series of tools that can be effectively applied, utilized, and integrated in such a way that the results will provide a smooth and evolving path as one proceeds from conceptual design, to preliminary system design, detailed design and development, and so on. The individual models utilized must not be selected as independently entities, but must tie into the overall systems engineering process in some way. Reference: Section 4.6 (page 117).~~

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~~21) Referring to Figure 4.12 (page 122), the objectives in designing such a tool set are: (a) to select a group of tools that will provide the analyst with enough visibility such that one can view requirements at the overall system-level and yet can break these requirements down and view such at a more detailed level (i.e. the "systems analysis process"); and (b) to select a group of tools that can be properly integrated to support many different~~

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~~applications and levels of analysis as one proceeds through the design process from conceptual design and down to detail design and development. Reference: Section 4.7 (page 120).~~

~~22) Referring to Figure 4.13 (page 124), there are four basic types (categories) of formal design review discussed throughout this text; i.e., *conceptual design review, system design review, equipment/software design review,* and *critical design review.* There may be a series of such reviews within the second and third categories. The basic *input–output* requirements for each are presented in Section 4.8 (page 123).~~

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~~23) Formal design reviews are scheduled at specific points throughout the design process when: (a) the depth of design definition evolves from one level to the next (e.g., when conceptual design is complete and before entering into the preliminary system design phase); (b) major design related decisions are required and the results may constitute potentially high risks; (c) the design of major subsystems is complete and a review is required before proceeding further; (d) designated suppliers complete their contracted tasks and approval is necessary; and (e) when there is a need for review and communications across the various organizations involved in system design. Reference: Sections 3.10 (page 95), 4.8 (page 123), and 5.8 (page 142). Also, refer to Figure 4.13 (page 124).~~

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~~24) As the design definition process evolves and the various elements of the system are defined through the functional analysis and allocation process (see Figure 3.25, page 92), trade-off studies are conducted pertaining to the source(s) of supply for a particular item of hardware, an element of software, a facility, a data package, a service to be provided, and so on. The question is — *should the item(s) in question be designed and developed, or manufactured, internally within the producer's (prime contractor's) facility, or should it be developed and procured from an outside source (supplier)?* There may be a number of different possibilities to include: (a) the design, development, and production of an item accomplished by an external supplier; (b) the design and development of an item internally and the subsequent production of the item externally by a supplier; and (c) the procurement of a commercial off-the-shelf (COTS) item from an outside supplier. Influencing the "make or buy" decision here depends on the producer's interest and capability to accomplish the job, the resources required and the costs associated with the different alternatives, the time to accomplish each alternative with regard to program schedules, and so. Given a decision, the specific requirements may be passed on through one or a combination of specifications, depending on the specific item in question. Reference: Section 4.2 (page 102). The determination of "outsourcing" requirements is discussed further in Section 19.2 (page 676).~~

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~~25) The design of any system requires a *team* approach. There may be many different engineering and supporting technical and non-technical disciplines required to participate in the design process, and these various requirements must be made available when needed and often at different points in time throughout the system design and development process. In some instances, the design objectives for one discipline may conflict with the design objectives of another and there needs to be a trade-off study and resulting compromise to arrive at a final resolution. In any event, the design requirements for a~~

~~system must be well defined and integrated from the beginning, and the various design disciplines involved in the process must be well coordinated, as conveyed in Figure 4.9 (page 116). During the early stages of conceptual design, only a very few knowledgeable systems-oriented designers, with prior experience, would be required as regular members of the *design team*. As the design process evolves and becomes more complex (during the preliminary and detail design and development phases), additional design expertise will be required and the design team will include representation of a wide mix of different engineering disciplines. The design team at this point may be fairly extensive and, once again, there is a need for a well-coordinated and highly integrated effort. (Refer again to Figure 4.9, page 116). Finally, the ongoing leadership of the *design team* should be the responsibility of systems engineering. Reference: Section 4.5 (page 114).~~

~~26) Referring to Figure 4.13 (page 124), a series of *system design reviews* are usually conducted throughout the Preliminary System Design Phase. The purpose of these reviews, and the material covered, is described in Section 4.8 (page 123). Basically, system conceptual design has been completed and a system specification (type *A*) has been prepared by the end of the Conceptual Design Phase. Functional analyses and allocations are accomplished and major subsystems are then identified, leading to the preparation of development, product, and process specifications (types *B*, *C*, and *D*) as applicable. Evolving from the Preliminary System Design Phase is a good definition of the system, its subsystems, and its major elements. This definition is supported by completed specifications and a good and comprehensive design data package, which constitutes the prime output for the phase. The work to be accomplished is described throughout Chapter 4 (pages 100-127).~~

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~~CHAPTER 5~~

~~DETAIL DESIGN AND DEVELOPMENT~~

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~~1) *Conceptual Design* primarily deals with the early definition of system requirements and the ultimate design of the overall *system* per se. The results are usually included in the System Specification (Type *A* — see Figure 3.27, page 96). *Preliminary System Design* usually includes the design of subsystems, configuration items, and major elements of the system, and the results are usually defined through the Development, Product, and/or Process Specifications (Types *B*, *C*, and *D*) as applicable. *Detail Design and Development* usually includes the design down to the component level, and requirements at the component level are usually defined in Material Specification (s) (Type *E*). System test and evaluation is also included here. Review of Figures 2.3 (page 32), 2.4 (page 34), and 4.13 (page 124) will provide some idea as to the major activities in each phase. It should be noted that, while the specific nomenclature associated with each of these phases may vary somewhat, the type of activities within the various phases will basically follow the same overall pattern.~~

~~These stages of design are applicable in the acquisition of *all* systems, with the level and depth of activity varying from one instance to the next. Regardless of the type of system and the extent to which new development is required, there is still a need for conceptual design, preliminary system design, and so on. It is the top‑down/bottom‑up "thought process" that is important. Reference: Section 2.2 (page 29).~~

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~~2) As a start, refer to the answer for Question 25 in Chapter 4. To successfully accomplish design definitely requires a *team* approach. There must be full support from the top down, and the proper organizational environment must be established to allow the "team" to perform in a satisfactory manner. Design team participants must be technically competent in their respective areas of expertise, be respected by their peers, be able to make on‑the‑spot decisions as necessary, possess initiative and be able to work together, and be able to communicate and have some understanding of the other participating disciplines. Often, as the design process evolves, the team "make up" may change somewhat as the specific design requirements change. As the role of systems engineering requires an understanding of the overall design process and the requirements for participating design disciplines (and their integration), it is appropriate that systems engineering assume a leadership role in this area throughout the entire design process. Reference: Section 4.5 (page 114) and Section 5.2 (page 130).~~

~~3) Throughout the design process, described in Chapters 3‑5, there is a definite need for a highly competent and strong, well respected, technical leader who: (a) understands the overall design requirements; (b) understands the design process; (c) recognizes the need for various types and levels of technical expertise in design; and (d) who is a good manager (leader) and can effectively integrate the appropriate personnel requirements in accomplishing the design objectives that have been specified. The role of systems engineering is to assume a leadership position in guiding and implementing these~~

~~requirements from the beginning and extending throughout. Systems engineering must be involved and highly visible throughout the entire design and evaluation process. Specific systems engineering program tasks are discussed in detail in Section 18.2.2 (page 646), and leadership objectives are discussed further in Section 19.3 (page 680).~~

~~4) Refer to Figure 5.1 (page 130). By "concurrent" approach, one can refer to the advantages and disadvantages of *concurrent engineering*. Concurrent engineering is "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." (This definition was developed in response to a Department of Defense initiative).~~

~~Relative to the benefits, one such advantage pertains to the significant reduction in system acquisition time (i.e., the length of time from the initial identification of a customer need to the delivery of the system for operational use) that can be realized by accomplishing many different activities *concurrently*. Another relates to the necessary communications that take place throughout design, individual designers working as a "team," and the follow on integration that occurs through the concurrency approach. Conversely, problems will occur if there is a lack of good initial planning and follow on communications across the board. Given such, there may be a lot of organizations and individuals accomplishing tasks in parallel without knowledge of what is going on across the board which, in turn, could result is much waste and high cost. Also, with the objective of "minimizing" acquisition time, there may be a tendency to skip some of the steps that may be essential in design and in fulfilling systems engineering requirements. Reference: Section 5.1 (page 129).~~

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~~5) Refer to Figures 4.4 (page 107) and 4.8 (page 115). Ensure that the overall system requirements are well defined from the beginning; ensure that the functional analysis is complete and that all hardware, software, and human requirements are identified through the functional analysis (i.e., the *same* functional analysis); co locate design and support personnel who are responsible for the design activities (in each of the three life cycles) in the same area in order to promote good day to day communications; and ensure that the appropriate type and number of formal design reviews (and necessary follow up action) are conducted to verify that the proper level of integration has been accomplished. Hardware, software, and human factors engineers need to participate in all design reviews, both informal and formal. The hardware design must **not** be allowed to proceed without proper integration with the applicable software, the software development must tie in with the hardware design, and both must address the human element on a continuing basis. There must be a day to day integration process from the beginning, leading to the system integration and test requirement (Block 2.3 in Figures 4.4 and 4.8). Reference: Sections 5.2 (page 130) and 5.3 (page 134).~~

~~6) As a first priority, select a common and standard component with *known* characteristics (performance factors, physical makeup, and physics of failure characteristics) and supported with "operational" field data demonstrating past experience. Second, select common and standard components that are already incorporated in operating systems, but~~

~~perhaps not well supported with "operational" field data. Third, select existing off the-shelf components that can be modified for application in the system being designed. Fourth, design and develop new components for the application intended. Reference: Section 5.3 (page 134).~~

~~7) Design standards usually cover standard components or parts, and/or standard design procedures, practices, or processes. These constitute "known" components utilized in many different applications and proven procedures and practices which have been successfully applied across the board. They are important so as to: (a) aid the designer in selecting a design approach that will likely result in a successful outcome; (b) ensure that common practices are followed to the maximum extent possible where applicable; and (c) facilitate the communications process throughout the design project. The selection of standard components (standardization) is particularly important in the design for reliability, maintainability, human factors, producibility, supportability, disposability, and sustainability. Reference: Section 5.3 (page 134).~~

~~8) Engineering documentation and the establishment of a design database are necessary in order to completely describe the system configuration, its components and components relationships, and supporting justification for the design as configured at a given point in time. There must be a common and standardized description of the system (i.e., baseline), and every project engineer must work to the same baseline. Good up to date design documentation is essential for communications across the project (within developers and producers, between suppliers, etc.), and for "tracking" the design changes from one baseline to the next. Reference: Section 5.5 (page 137).~~

~~9) Refer to Figure 5.5 (page 134). Initially, there must be a good definition of the "functional" requirements, leading to the need for an item of equipment/software; i.e., the input/output and metrics associated with each block in the FFBD. One needs to have a good and precise definition of all quantitative and qualitative "design to" requirements for the function to be accomplished. Second, one needs to have a good and complete "specification" for each of the equipment/software items being considered for application. Many problems, from past experience, have evolved as a result of not first defining a good set of requirements and, second, not having a good specification covering the items being considered for application, or various combinations of each. Reference: Section 5.3 (page 134).~~

~~10) Refer to the response to Question 15 in Chapter 4. The application of CAD, CAM, and CAS tools (or related design aids) can significantly enhance the design process. In the utilization of CAD, one can graphically simulate the design of a total system, or any part thereof, through the presentation of three-dimensional models, graphic displays, different views of various specific design features, and so on. The same is true utilizing CAM and CAS as applied to the design of a manufacturing capability and the design of a logistics and maintenance support infrastructure, respectively. The benefits are best described in Section 4.6.1 (page 117) and amplified in Section 5.4 (page 136). In selecting the proper tools, care must be taken to ensure that the tools are compatible and adaptable for the system being designed, are sensitive to the various system characteristics desired, and are compatible with each other in terms of interactions and interfaces. If these conditions are not met, then~~

~~the design process will produce poor and inaccurate design data, resulting in many additional problems. Reference: Sections 4.6 (page 117) and 5.4 (page 136).~~

~~11) Refer to the answers in response to Questions 15 in Chapter 4 and Question 10 in this chapter. The benefits from using CAD, CAM, CAS, and related methods, are highlighted in Chapter 4 on Page 118. The proper application of CAD, CAM, CAS, and various combinations thereof, can result in the development of three-dimensional "computerized" models of a selected design configuration that "simulate" (replicate) the proposed system configuration. Examples include an airplane or ship configuration, a manufacturing plant layout, a control panel with knobs and display arrangements, and so on. Through the use of simulation methods, combined with the application of computer-based tools, one can accomplish the "validation" of many different facets of design, although not "validation" of the overall system. Reference: Section 4.6.1 (page 117) and Section 5.4 (page 136).~~

~~12) "Physical" models and mock-ups are built and utilized to aid in the design evaluation process, and they help the designer to be able to visualize the current design configuration of the item being evaluated. They provide a better "replica" of the item being evaluated than one can see through a computerized database. Mock-ups are developed primarily in the Preliminary System Design Phase when the design is relatively fluid and one needs an aid of some type in order to facilitate design evaluation. Major applications and benefits are noted by the eight points listed in Section 5.4. Reference: Section 5.4 (page 136).~~

~~13) Referring to Section 5.4 (page 136), a "mock-up" may be developed early in system design and development with the objective of providing a physical model "replicating" an element or component of a system for the purposes of design evaluation. Mock-ups are not real "working" models and can be constructed of cardboard, wood, bits and pieces of metal, or various combinations thereof. Referring to Section 5.6 (page 139), "Engineering Models" are "working" models, usually built in an engineering laboratory, that can be utilized to demonstrate selected functions, or performance features, that the system (or an element thereof) must ultimately accomplish later on when the system is operated by the "user." The construction of this model may not include the utilization of approved and qualified components/parts, or may not exactly replicate the physical characteristics of the item being evaluated. The purpose is to ensure "functional" performance. Referring to Section 5.7 (page 142), a "prototype" is a "working" model, constructed with the same approved and qualified components/parts and in the same configuration as a regular "production" model. It actually represents the product evolving from the regular production/construction process. A "prototype" is often available in the latter stages of the Detail Design and Development Phase, but one that has not actually been fully tested and qualified for operational use. It is utilized for the purposes of evaluating a system (or an element thereof) for both functional and physical compliance with the application specifications. Reference: Sections 5.4 (page 136), 5.6 (page 139), and 5.7 (page 142).~~

~~14) Student exercise. The output may be in the form of a checklist similar to the one illustrated in Figure 5.8 (page 141), supported by a list of detailed questions covering at least two of the subject items on the checklist. Refer to Appendix B (page 709) for an example of questions that may be included.~~

~~15) As a start, refer to the answer for Problem 23 in Chapter 4. The benefits derived through the implementation of a formal design review process are indicated in Section 3.10 (note the five listed benefits starting on page 95). Additional coverage is provided in Sections 4.8 and 5.8. Reference: Sections 3.10 (page 95), 4.8 (page 123), and 5.8 (page 142).~~

~~16) Refer to Figure 5.9 (page 143). Accomplish a life-cycle cost analysis (LCCA); identify the high cost contributors; determine the “cause and effect” relationships and identify the actual “causes” for the high cost; prioritize these in terms of highest contributors and on down; review and evaluate possible alternative design approaches to accomplishing the function(s) that are the “cost drivers;” and recommend a proposed solution in terms of a design change; incorporate the change; and verify that the incorporated modification has indeed resulted in a reduction in LCC. This can be an iterative process, identifying the next highest contributor and going through the process again. The procedure and steps in accomplishing a life-cycle cost analysis (LCCA) are described further in Chapter 17 (page 566). Reference: Section 5.8 (page 142).~~

~~17) Refer to Figure 5.10 (page 144). For large projects, in particular, there may be many different TPMs that have been identified as system design requirements. Further, the relative degree of importance of each of these TPMs may be perceived differently by the various system designers (i.e., design engineer “A” may believe that availability is more important than life-cycle cost, design engineer “B” may have a different view as to what is important, and so on). A good way to keep “track” of each of the specified TPMs is to select an area of design (i.e., a design discipline) that is likely to be significantly impacted by a given TPM, and assign some individual from that discipline to “track” the design and status in terms of compliance with the selected TPM requirement. For example, it would be natural to assign the “tracking” of MTBF to the reliability engineering organization, MTBM to an individual in the maintainability organization, LCC to an individual in the logistics organization, and so on. Then, it would be necessary to review the status pertaining to these overall requirements, on an integrated basis, in a formal design review. Each TPM requirement and status must be evaluated in terms of each other, and in the context of the system as a whole. Reference: Section 5.8.1 (page 142).~~

~~18) As an input, there are a number of factors that are necessary in preparing for and later in conducting a design review meeting so that success is realized as an outcome; i.e., the identification and description of items to be reviewed, a good agenda distributed ahead of time, and the proper level of funding established, etc. Refer to the nine points listed in Section 5.8.3 (page 145). There are some conditions that need to exist and be promulgated during the design review meeting; i.e., the meeting must be well organized and firmly controlled with the right people participating. As an output, a desired objective is to have a good and well defined baseline, with all of the essential design changes already incorporated. Hopefully, the design review process has promoted good communications across the board, everyone who has been involved is knowledgeable of the current design configuration and the reasons for the existence of that configuration, and that the overall process has instilled a “positive” feeling throughout the project. Reference: Sections 3.10 (page 95), 4.8 (page 123), and 5.8 (page 142).~~

~~19) Refer to Figure 5.11 (page 147). In evaluating the feasibility of an Engineering Change Proposal (ECP) one should determine the impact of such on other elements of the system, on the specified TPMs, on life cycle cost, on the various considerations that have been addressed throughout the earlier stages of design (e.g., reliability, maintainability, human factors, producibility, supportability, disposability, and sustainability), and on the cost of change implementation. Approved changes will then lead to the development of the required modification kit, installation instructions, and the ultimate incorporation of the change. There needs to be a highly disciplined *configuration management* (*CM*) process in being from the beginning and throughout the entire system life cycle. Reference: Section 5.9 (page 146).~~

~~20) Develop the appropriate design documentation covering the change; construct a modification kit for installation in the system; install the modification kit in the applicable equipment, software, facilities, data, or whatever; and implement a test and evaluation effort to "validate" that the incorporated change does indeed accomplished what was initially intended. Reference: Section 5.9 (page 146) and Figure 5.11 (page 147).~~

~~21) *Configuration management* (*CM*) pertains to the management and control of a design "baseline" to include a complete description of a given system configuration (the elements and components of a system and how they are they connected), and the subsequent "management of change." Referring to Figure 2.4 (page 34), there are specific "baselines" where the system (and its configuration) is defined and documented. As changes are incorporated, the relevant baseline needs to be updated. CM refers to the control of baselines and any changes that may affect a given baseline. Reference: Section 5.9 (page 146).~~

~~22) Good *baseline management* is very important in the implementation of systems engineering. It is essential that all affected personnel work with the "same" baseline and "one" system configuration at any given point in time. All designers and support personnel must "track" the same configuration. Otherwise, there is likely to be much confusion across the project(s), the communications will be ineffective, and much waste (and high cost) could occur. Your authors are familiar with a situation where there was no CM being implemented on a given project, equipment changes were being incorporated somewhat at random on the production line, there were many different configurations of the same equipment being delivered to the customer, and there were seven different sets of maintenance and support requirements (spares, support equipment, maintenance personnel, data). The result – a **big mess**! Reference: Section 5.9 (page 146).~~

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~~CHAPTER 6~~

~~SYSTEM TEST, EVALUATION, AND VALIDATION~~

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~~1) Specific test and evaluation requirements are first identified during the conceptual design phase when system operational requirements, the maintenance and support concept, and the prioritized TPMs are defined. As system requirements are initially established, one must begin to determine just how the system can be evaluated to ensure that requirements have been met. The established TPM priorities will indicate the levels of importance which, in turn, will have some influence on the depth and methods used for evaluation. Newly designed elements of a system (or high risk items) may require more testing than known commercial or standard components. Reference: Section 6.1 (page 151).~~

~~2) Refer to Figure 6.2 (page 153). The "process," reflected in the figure, is established to acquire the necessary confidence, as one proceeds through the system design and development process, that the system will indeed meet all of the specified requirements when it is ultimately delivered to the customer for utilization in the field. Verification of a given design approach, or validation that a particular system component will meet a given requirement, can often be accomplished early in the life cycle. If problems are detected at this point, then design changes can be implemented at minimal cost. On the other hand, such changes later in the life cycle may be much more costly to implement. As confidence is acquired, then additional testing is accomplished and perhaps to a great depth. The goal is to enter into the final system test and evaluation task (refer to Figure 2.4, page 34 and block 2.3 in Figure 4.4, page 107) with the confidence that all requirements will be met. Any "surprises" at this stage can be quite costly. The objective here is to develop an overall test and evaluation process, such as illustrated in Figure 6.2 (page 153), and to include this in a formal plan (i.e., the TEMP) during the final stages of the conceptual design phase. Reference: Section 6.1 (page 151).~~

~~3) The various categories of test, as defined by your authors, are described in Section 6.2 (page 153); i.e., Analytical Evaluation, Type 1, Type 2, Type 3, and Type 4 Testing. Figure 6.2 (page 153) basically shows these stages, what is accomplished in each stage, and how these fit into the systems engineering process. Reference: Section 6.2 (page 153).~~

~~4) Refer to Figure 2.4 (page 34). The test and evaluation activity identified by block 0.6 is essentially accomplished under "Analytical Evaluation" in Figure 6.2 (page 153); identified in block 1.5 is accomplished as "Type 1 Test" in Figure 6.2; identified in block 2.3 is accomplished as "Type 2 Test" in Figure 6.2; identified in block 3.4 is accomplished as "Type 3 Test" in Figure 6.2; and identified in block 4.4 is accomplished as "Type 4 Test" in Figure 6.2. The accomplishment of the various tests is described in Section 6.5 (page 162). Reference: Sections 6.2 (page 153), 6.4 (page 160), and 6.5 (page 163).~~

~~5) For a new system operating within the context of a SOS configuration, the same overall testing approach, as shown in Figure 6.2 (page 153), applies. Initial Analytical Evaluation (simulation) and Type 1 testing are accomplished as with any new system requirement~~

~~(Sections 6.2.1 and 6.2.2, page 154. In Type 2 testing, the objective is to simulate (to the extent possible) the future operational environment and to evaluate compatibility with the major interfaces. Through the accomplishment of earlier analyses, the design team often can identify potential areas (i.e., elements of the system) where compatibility problems may arise and, through Type 2 testing, some selected compatibility tests can be accomplished on an item-by-item basis (refer to Item 11 on page 156). While these tests certainly don't reflect a true operational condition, they may result in the identification of some problems which can be corrected relatively early. The first true test of the system in a SOS environment can be accomplished through Type 3 testing. The system can be tested to a greater extent through Type 4 testing when it is fully operational (Section 6.2.4 on page 156 and Section 6.2.5 on page 157). Again, the overall process of system evaluation and validation remains the same, but the breadth and depth of the actual testing will be more extensive for a system in a SOS network. The objective is identify the major interfaces, develop a formal test plan for the evaluation of such, prepare for the formal test and evaluation, analyze the test data and evaluate the results, and so on. Reference: Section 6.2 (page 153).~~

~~6) Planning for system test and evaluation begins in the *conceptual design phase* when the requirements for the system are first defined and are being specified (i.e., operational requirements, maintenance and support concept, and the prioritized TPMs). As the requirements are being identified, particularly those of a quantitative nature, one must decide how these requirements will ultimately be verified and validated through test and evaluation. This, in turn, results in some early planning and the development of the *Test and Evaluation Master Plan* (*TEMP*). The information that should be included in the TEMP is outlined in Section 6.3 (i.e., the seven items noted on page 158). Refer to the TEMP in Figure 2.4 (page 34), and the test and evaluation requirements in Figure 6.2 (page 153). Reference: Section 6.3 (page 157).~~

~~7) Student exercise. The seven items noted in Section 6.3 (page 158) should be included (or addressed) in the plan.~~

~~8) The proper level of logistic support is essential for the successful evaluation of a system and its elements. Further, the nature and configuration of the maintenance and support infrastructure utilized must represent that which will be available later on when the system is in operational use by the customer, particularly with a system operating within a SOS configuration.~~

~~If the appropriate procedures are not available for the operation and maintenance of the system while in test, then there is no assurance that the system will be operated and maintained properly and as initially planned. This may lead to many problems as a result of personnel-induced failures (i.e., errors of omission, errors of commission, etc.). If the operating and maintenance personnel are not properly trained, this will again lead to personnel-induced errors. If the proper test and support equipment is not available, there is no assurance that the system will be adequately tested (and operating properly) in the event of failure and after corrective maintenance has been accomplished. Further, the procedures and allocated test times may be different. For example, if the design specifies built in and external~~

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~~"automated" testing and the only test equipment available must be operated "manually," then the procedures, downtime factors, personnel quantities and skills, facilities, etc., are likely to be affected. Reference: Section 6.4 (page 160).~~

~~9) A good data subsystem is required for two reasons: (a) to enable a true assessment (evaluation) of the system and its elements while being utilized by the operator and/or maintainer in the field; and (b) to provide a good historical record of the system that can be fed back and serve as an aid in the design and development of new systems. Our engineering capability in the future certainly depends on our ability to capture experiences from the past, and to subsequently be able to apply the results in terms of what to do and what not to do in new design situations. Without such a data collection and feedback capability (reflecting past experience), designers will tend to make some of the same mistakes over and over again when going from one project to the next. Reference: Section 6.5 (page 162).~~

~~10) The prime objective is to develop and implement a data collection, analysis, reporting, and feedback capability that will provide the right information, in the right format, to the right location(s), at the right time, and at the right cost. More specifically, one needs to determine the particular characteristics of the system that must be recorded and measured. This, of course, stems from the definition of system operational requirements, the maintenance and support concept, and the prioritized TPMs. For example, if *Operational Availability* (*Ao*) must be measured, the data subsystem must provide the right information (e.g., MTBM and total downtime). Unfortunately, there are many data collection subsystems in existence that involve a great deal of data, but very little information. This, of course, results in little (if any) feedback to the design community and can be costly. Reference: Section 6.5 (page 162).~~

~~11) Refer to Figure 2.8 (page 42). *Cost effectiveness* (which is reflected by "system value" in the figure) refers to the measure of a system in terms of its applicable technical factors (e.g., system effectiveness, operational availability, producibility, dependability, supportability, sustainability, and those applicable "technical" factors that relate to overall system "performance") and total life-cycle cost. Thus, the data collected must enable the assessment of system performance (or the critical TPMs) and total cost. *System effectiveness* is a function of system performance, availability, dependability, supportability, sustainability, and related technical factors. Thus, the data collected must enable an assessment of overall system performance, but not necessarily cost. *Operational availability (Ao)* is a function of system "uptime" and "downtime," or MTBM and MDT, or the percentage of time that the system is "operational" when required. Thus, the data collected must enable the assessment of the system in terms of its mission, its time of operation, and any downtime that is expended in the accomplishment of maintenance. *Life-cycle cost (LCC)* includes all future costs associated with research and development, design, test and evaluation, production and/or construction, system utilization, maintenance and support, and system retirement, material recycling and disposal. Thus, the data collected must include ALL costs, cost projections and profiles, the appropriate reliability and maintainability data, logistics data, and so on. *Reliability* (*R, MTBF*) is a function of system operating time (or operating cycles), system failures and failure rates, the actual~~

~~causes of failures, and so on. The data collected must cover system operations, system failures, and the requirements associated with the repair actions taken in response to failures. Reference: Section 6.5 (page 162) and Figure 6.4 (page 164).~~

~~12) Evaluating the adequacy of the system's supply chain can effectively commence as part of Type 2 testing (Section 6.2.3, Item 10, page 155). Specific candidates for evaluation may include individual segments associated with packaging and handling of different system elements, transportation and distribution mode compatibility, warehousing and storage adequacy, specific procurement approaches, and so on. Through the follow-on Type 3 and Type 4 testing, the supply chain can be evaluated to a greater extent and as an integrated entity (Section 6.2.4, page 156, and Section 6.2.5, page 157). Such measures as availability, readiness, implementation time, reliability, maintainability, cost, and related logistics factors may be appropriate depending on the overall system requirement(s). These factors are covered further in Chapter 15 (page 497). Reference: Section 6.2 (page 153).~~

~~13) *Sustainability* pertains to the system's overall impact on the environment, with the objective of not causing any degradation to the environment while the system is being operated and maintained in the field by the user. As the system (and elements thereof) progresses through Type 2 testing (i.e., the 11 tests identified in Section 6.2.3, page 155), an integral part of the evaluation process must be directed not only to the "internal" aspects of testing (e.g., the results of performance testing) but the "external" effects as well. More specifically, *what impact did the test have on the environment and what natural earth's resources were consumed in the process?* Referring to Section 4.4 (page 112), *were there any wastes, gases, toxic substances, effects of air and water pollution, etc., caused as the various tests were conducted?* As the evaluation progresses through the subsequent accomplishment of Type 3 and Type 4 testing, the concern for sustainability continues to be very important, as the system as an entity is evaluated and there may be some sustainability impacts that didn't appear earlier but have become quite visible later. Again, the issues of concern (and measures) are as noted in Section 4.4. Sustainability is covered in more depth in Chapter 16 (page 541). Reference: Section 6.2 (page 153).~~

~~14) If a "non-compliance" situation should evolve as a result of evaluation, the causes for such need to be identified and a recommendation for corrective action must be initiated; i.e., an Engineering Change Proposal (ECP). Trade-off studies may be conducted in evaluating possible alternative approaches for correcting the problem, and a preferred approach is selected and submitted for approval. An approved ECP leads to a system modification, followed by a test and verification that the problem has indeed been corrected. Reference: Section 6.5.2 (page 163).~~

~~15) Refer to Section 5.9 (page 146). The proposed design change should be incorporated through the design and development, installation, and test of a modification kit. Within the content of the modification kit one should readily find the necessary hardware, software, technical data sheets, and related components. Additionally, needed technical instructions for kit installation and its verification testing should be present by the provision of paper documents, or electronically via a laptop or hand-held device as appropriate to the situation. Reference: Section 6.5.2 (page 163).~~

~~16) Refer to the responses in Problems 19, 21 and 22 in Chapter 5. Good *configuration management* (*CM*) is important in all phases of the life cycle. In particular, in conducting “test and evaluation” activities, one must know the “configuration” that is being evaluated, whether this configuration reflects that which was initially specified, and whether the configuration tested does indeed meet all of the requirements of the customer. This includes a configuration with all of the approved changes and modifications already incorporated. A proper “validation” cannot be accomplished by testing a “configuration” that is non-relevant and does not reflect the ultimate requirements. Reference: Section 6.4 (page 160).~~

~~17) The successful accomplishment of all engineering and management functions is highly dependent on a good two way communications process. There needs to be a complete record and accountability of what was accomplished initially, as well as knowledge of the consequences resulting from those actions taken (i.e., the proper *feedback*). In the accomplishment of design, there needs to be some feedback from the customer on just how well that design is satisfying the specified requirements. In conducting system testing, the process must include the reporting (feedback) of test results. In essence, we all need some “feedback” pertaining to what we do, how we act, and so on, if we are to learn and benefit from the process as we go along. Referring to Figures 2.3 (page 32), 2.4 (page 34), 2.7 (page 39), 3.2 (page 60), 4.4 (page 107), 5.1 (page 130), and others, one can identify the important “feedback loops.” Reference: Sections 5.8 (page 141), 6.5 (page 162), and 6.6 (page 166).~~

~~18) Refer to Figure 6.2 (page 153). *System evaluation* during conceptual design and early in the preliminary system design phase is generally accomplished (through “Analytical” and “Type I Testing”) by the producer (or prime contractor) with engineering in the lead, and may involve a major supplier when determining the feasibility of incorporating a new product/process in the design. At the component level, the producer (engineering with laboratory test support) and the applicable component supplier are often involved in the conduct of “component life testing,” with the producer being in the lead. Evaluation is usually accomplished at the producer’s facility.~~

~~In the detail design and development phase, the producer (engineering, manufacturing, and test support) usually takes the lead in accomplishing “Type 2 Testing,” with the support of a major supplier if required, and the customer may be included in an observational capacity for certain tests and demonstrations. The test site may include the producer’s facility, a special test facility, a customer-designated test site, and/or various combinations of these.~~

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~~It is during the production and/or construction phase that “Type 3 Testing” is generally accomplished. Here the customer (or a customer-designated special test capability) should be in the lead, but with producer support as required.~~

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~~During the system utilization and life-cycle support phase, “Type 4 Testing” will generally be accomplished by the customer at one (or more) customer operational sites. Producer support may be requested on special occasions and/or in the event of problems. While this represents a more normal allocation of test and evaluation functions, there may be any~~

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~~number of variations depending on the nature and type of system, the degree of new design versus the application of primarily COTS products, the extent of the risks involved, and so on. In any event, the interrelationships between the customer, producer, and supplier(s) are numerous throughout the entire spectrum of activity shown in Figure 6.2 (page 153). Reference: Section 6.2 (page 153).~~

~~19) Good test reporting is essential if one is to properly "assess" the system in terms of whether or not it is in compliance with the initially specified requirements. In addition to reporting the test results (in detail), it is important that one also reports the test conditions (e.g., test environment, type of tests conducted, availability of test supporting resources, etc.) which were in place when the formal testing was conducted. One must be able to ensure that all testing was accomplished in accordance with the pre approved test procedures, in the proper testing environment, and with the proper supporting resources available as required. Reference: Section 6.5 (page 162).~~

~~20) Inherent within the systems engineering process are (a) the initial establishment of system level requirements; (b) the iterative process of synthesis, analysis, and evaluation throughout the overall system design and development process; and (c) the ultimate "validation" and assurance that all requirements have been met through system test and evaluation. The systems engineering function must assume a leadership role in the initial establishment of system level requirements in conceptual design, in the development of the *Test and Evaluation Master Plan* (*TEMP*), in the day to day design and development process through implementation of the activities shown in Figure 6.2 (page 153 specifically Analytical, Type 1 Testing, and Type 2 Testing), and in the final system test and evaluation effort to ensure that the initially specified requirements have been met. The systems engineering function must ensure that the proper level of initial planning is accomplished in a timely manner, and that the appropriate disciplines and supporting resources are applied and integrated in accordance with the established plans. Reference: Sections 6.1, 6.3, 6.4, and 6.5 (pages 151, 157, 160, and 162 respectively).~~

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~~CHAPTER 7~~

~~ALTERNATIVES AND MODELS IN DECISION MAKING~~

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~~1) The process of generating alternatives may begin with a hazy idea about the problem to be addressed but with good understanding about system requirements. A complete and all inclusive alternative, the "ideal alternative," rarely emerges in its final state. The alternative which is chosen is usually not ideal, but the one which is *judged best by the customer*. Reference: Section 7.1 (page 171) and Figure 2.10 (page 43).~~

~~2) Decision making is best classified as a *combination of art and science*. Decision making is an "art" since the first step, generation of alternatives, requires creativity and the ability to break away from obvious and well established patterns of thought. Only after feasible alternatives are generated can the process of decision making become somewhat more "scientific". This is enabled when decisions are based on models and modeling as in "operations research" and/or "management science".~~

~~3) Once *limiting factors* have been identified, they are examined to locate *strategic factors*, those factors which can be altered to make progress toward a solution possible. These strategic factors may consist of a procedure, a technical process, or a physical, organizational, or managerial innovation or change. Reference: Section 7.1.1 (page 171).~~

~~4) The word *model* implies representation when used as a noun, implies ideal when used as an adjective, and implies explanation when used as a verb. All models are abstractions of reality. Reference: Section 7.2.1 (page 172).~~

~~5) *Physical models* are visual geometric equivalents; schematic models reduce a state or event to a chart or diagram; mathematical models use the language of mathematics to describe and explain. Reference: Section 7.2.1 (page 172-174).~~

~~6) *Mathematical models* directed to decision situations incorporate probabilistic elements to explain the random behavior arising mainly from economic and social factors, whereas those in the physical world deal with a high degree of certainty. Second, models for decision situations incorporate two classes of variables; those under direct control of the decision maker and/or designer and those not directly under control.~~

~~7) In *direct experimentation*, the object, state, event, and/or the environment are manipulated and the results are observed. *Indirect experimentation* is effected through the formulation and manipulation of decision models that are representations of reality. Reference: Section 7.2.2 (page 174-175).~~

~~8) The general form of the **evaluation function for money flow modeling** may be stated as:~~

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~~PE, AE, or $FE = f(F_t, i, n)$~~

~~where $t = 0, 1, 2, \ldots, n$ and where~~

~~F_t = positive or negative money flow at the end of year t~~

~~i = annual rate of interest~~

~~n = number of years~~

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~~Reference: Equation 7.1 (page 176) and Figure 7.1 (page 177).~~

~~9) An example of a decision situation is the establishment of an optimal procurement quantity for a single-item inventory. Here the evaluation measure is cost, and the objective is to choose a procurement quantity in the face of demand, procurement cost, and inventory holding cost, so that the total system cost is minimized. The decision variable under direct control of the decision maker is the procurement quantity.~~

~~10) The economic optimization function given by Equation 7.2 is a mathematical model formally linking an evaluation measure, *E*, with controllable decision variables, *X*, and system parameters, *Y*, which cannot be directly controlled by the decision maker. Equation 7.3 is an extension of the economic optimization function, intended to enable **inclusion of operational and design decisions involving alternatives**. This extension involves the identification and isolation of design or decision-dependent system parameters, Y_d, from design or decision-independent system parameters, Y_i. Reference: Section 7.3.2 (page 177), Table 7.1 (page 179), and Figure 7.2 (page 180).~~

~~11) Any model that accurately represents reality would be *reality itself*. A model is defined as an abstract version of reality, making it incorrect (impossible) to consider reality to be a model. With the complexity of systems increasing, models as representations are becoming more complex. If during the process of formulation, only those elements of the system that are anticipated to significantly affect the final outcomes are considered, much of the unnecessary detail and complexity can be eliminated. Being abstractions of the system itself, models involve many assumptions. These assumptions support the desirable objective of simplifying model construction, but decrease the reality of the model.~~

~~12) A properly formulated model may become useless due to a change in the predicted or estimated values of input system parameters and/or by errors in determining the actual values of those parameters.~~

~~13) The *increasing cost* of more frequent review should be balanced against the *reduction in cost* from good decisions resulting from a frequently reviewed dynamic environment.~~

~~14) Caution must be exercised in the use of a model because it is possible to come to believe that the model result is infallible.~~

~~15) Models take the decision maker *part way* to the point of decision. They permit experimentation (during operations) without disturbing the existing system under study. They also permit insight into operations that do not yet exist if properly utilized during the system design phase of the life cycle. Reference: Figure 7.2 (page 180).~~

~~16) Student exercise. Suggestion: use the ideas in Section 7.4.1 (page 181).~~

~~17) Specific situation not given. Consider applying the ideas suggested in Section 7.4.2 (page 182).~~

~~18) Extension not given. The tabular additive method presented in Section 7.4.4 (page 186) is suggested.~~

~~19) (a) Alternative B is dominated by Alternative A and may be eliminated from further consideration.~~

~~(b) Alternative A may be retained for further consideration under Rule 1 (meets at least one criterion). Under Rule 2, Alternative C is the only one that may be retained for further consideration. It meets all criteria.~~

~~(c) Rule 1: Criterion 2 is most important, so Alternative A is the indicated best. However, it fails to meet the minimum standard for Criterion 1.~~

~~Rule 2: Examination of one criterion at a time and eliminating alternatives that do not meet the minimum standards results in the selection of Alternative C as shown below:~~

~~Criterion~~	~~Eliminate~~	~~Remaining~~
~~1~~	~~A, B~~	~~C~~
~~2~~	~~None~~	~~C~~
~~3~~	~~None~~	~~C~~
~~4~~	~~None~~	~~C~~

~~20) Develop a relative ranking for each criterion (e.g., $/10 for both profit potential and risk and use a 5 point scale for market share with 5=H, 4=MH, 3=M, etc.) giving the following:~~

	~~SW I~~	~~SW II~~	~~SW III~~	~~SW IV~~
~~Profit potential~~	~~10.0~~	~~14.0~~	~~15.0~~	~~13.0~~
~~Profit risk~~	~~4.0~~	~~3.5~~	~~5.0~~	~~4.5~~
~~Market share~~	~~5.0~~	~~3.0~~	~~1.0~~	~~3.0~~

~~Tabulate the product of weight times ranking; add the products across all criteria to obtain:~~

	~~SW I~~	~~SW II~~	~~SW III~~	~~SW IV~~
~~Profit potential~~	~~6.50~~	~~9.10~~	~~9.75~~	~~8.45~~
~~Profit risk~~	~~0.80~~	~~0.70~~	~~1.00~~	~~0.90~~
~~Market share~~	~~0.75~~	~~0.45~~	~~0.15~~	~~0.45~~
	~~8.05~~	~~10.25~~	~~10.90~~	~~9.80~~

~~Under the given weights and the ranking values chosen, it would be best for the firm to offer SW III. SW II is found to be a close second choice.~~

~~21) The stacked bar chart is:~~

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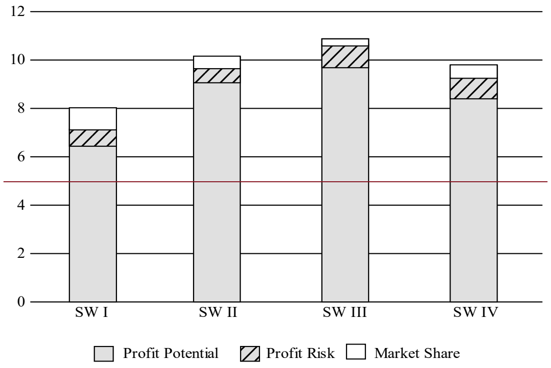

~~22) Refer to the example in Section 7.4.4 (page 185) and Table 7.5 (page 186).~~

~~The additive weights are recalculated to be:~~

~~Better 9 9/20 = 0.45~~
~~Cheaper 7 7/20 = 0.35~~
~~Faster 4 4/20 = 0.20~~
~~1.00~~

~~And, the aggregate weighted ranking is now:~~

	~~(R)~~	~~W×R~~	~~(R)~~	~~W×R~~
~~Better (0.45)~~	~~6~~	~~2.70~~	~~7~~	~~3.15~~
~~Cheaper (0.35)~~	~~10~~	~~3.50~~	~~6~~	~~2.10~~
~~Faster (0.20)~~	~~5~~	~~1.00~~	~~3~~	~~0.60~~
	~~Alt. A~~	~~7.20~~	~~Alt. B~~	~~5.85~~

~~The importance ranking change does not change the alternative selected.~~

~~23) Student exercise based on Section 7.5 (page 187).~~

~~24) Assume Alternatives A, B, and C to be purchase alternatives. Use RM to designate the remanufacture alternative and name Other Criteria X, Y, and Z that would be applicable.~~

~~25) Student exercise. Reference: Section 7.6.1 (page 189).~~

~~26) Student exercise. Reference: Section 7.6.2 (page 190).~~

~~27) Student exercise based on non-quantifiable alternatives per Section 7.6.2 (page 191).~~
~~28) The lack of certainty about future outcomes makes decision making one of the most challenging tasks faced by an individual or an organization. Decision making requires the~~

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~~assignment of probabilities to future outcomes. These probabilities may be based on experimental evidence, expert opinion, subjective judgment, or a combination of these.~~

~~29) Examining the various alternatives for dominance serves to eliminate those alternatives that are definitely inferior to the others being considered. This helps the decision maker to focus only on those alternatives that hold promise for the objective being pursued.~~

~~30) In the decision of buying a new car, an aspiration level can be the minimum performance desired or the maximum highway gas mileage obtained.~~

~~31) The most probable future criterion works well when the most probable future has a significantly high probability of occurrence so as to partially dominate. Refer to page 193.~~

~~32) While the most probable future criterion may work well in some cases, its application is quite similar to decision making when assuming certainty. Knowing that the evaluation matrix under assumed certainty is not a matrix at all, the result could be erroneous.~~

~~33) When faced with making a decision under certainty, one can assume the probability of the occurrence of each future state of nature to be 1/*n* (where *n* is the number of possible future states). This converts the situation to making a decision under risk with a specific probabilistic future. Reference: Section 7.6.4 (page 194).~~

~~34) In making a decision under uncertainty using the Hurwicz rule, the decision maker has the flexibility to decide on a level of pessimism or optimism. This involves an index of relative optimism and pessimism, α, such that 0 < or = α < or = 1. α = 0 represents the case when the decision maker is pessimistic about nature and this is actually the maximin rule. Whereas, α = 1 represents the case when the decision maker is optimistic about nature. This is actually the minimax rule.~~

~~35) Expected cost = \$80,000 (0.20) + \$95,000 (0.30) + \$105,000 (0.25) + \$115,000 (0.20) + \$130,000 (0.05) = \$100,150~~

~~Most probable cost = \$95,000 by inspection of the probabilities.~~

~~Maximum cost with 95% assurance = \$115,000. This is derived by summing probabilities up to, but excluding, the 0.05 and observing that the maximum cost will be \$115,000.~~

~~36) Under most probable future criterion, choose A_2.~~

~~Expected value for alternative A_1 = \$100,000 (0.3) + \$100,000 (0.2) +~~

~~\$380,000 (0.5) = \$240,000~~

~~EV_{A2} = \$267,000; EV_{A3} = \$286,000; EV_{A4} = \$189,000; EV_{A5} = \$228,000~~

~~Max EV_{A1}, EV_{A2}, EV_{A3}, EV_{A4}, EV_{A5} = \$286,000; choose A_3~~

	~~$P(\theta \geq 9)$~~	~~most probable (F_3)~~

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~~37)~~

~~A_1~~	~~0.30~~	~~-4~~
~~A_2~~	~~0.50~~	~~5~~
~~A_3~~	~~0.50~~	~~10~~
~~A_4~~	~~0.65~~	~~20~~
~~A_5~~	~~0.65~~	~~12~~
	~~max = 0.65~~ ~~choose A_4 or A_5~~	~~max = 20~~ ~~choose A_4~~

~~38) Laplace: A_1 (50 + 80 + 80)/3 = 70~~
~~A_2 (60 + 70 + 20)/3 = 50~~
~~A_3 (90 + 30 + 60)/3 = 60~~
~~Choose A_1~~
~~Maximin: A_1 50~~
~~A_2 20~~
~~A_3 30~~
~~Choose A_1~~
~~Maximax: A_1 80~~
~~A_2 70~~
~~A_3 90~~
~~Choose A_3~~
~~Hurwicz: A_1 0.75 (80) + 0.25 (50) = 72.5~~
~~A_2 0.75 (70) + 0.25 (20) = 57.5~~
~~A_3 0.75 (90) + 0.25 (30) = 75.0~~
~~Choose A_3~~

39)

	~~Maximin~~	~~Maximax~~	~~Laplace~~	~~(α = 0.2) Hurwicz~~
~~O_1~~	~~20~~	~~35~~	~~27.5~~	~~23~~
~~O_2~~	~~20~~	~~40~~	~~32.5~~	~~24~~
~~O_3~~	~~10~~	~~60~~	~~31.25~~	~~20~~
~~Decision~~	~~O_1 or O_2~~	~~O_3~~	~~O_2~~	~~O_2~~

~~40) (a) The maximum probability of being in any area is 0.30. All systems will maximize this probability of achieving a navigation error of 0.10 nm or less.~~

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~~(b) The probabilities of achieving this minimum navigation error of 0.10 nm are: N_1 – 0.30, N_2 – 0.50, N_3 – 0.50, N_4 – 0.65, and N_5 – 0.65. It is noted that N_4 and N_5 will equally maximize the probability of achieving a navigation error of 0.10 nm or less.~~

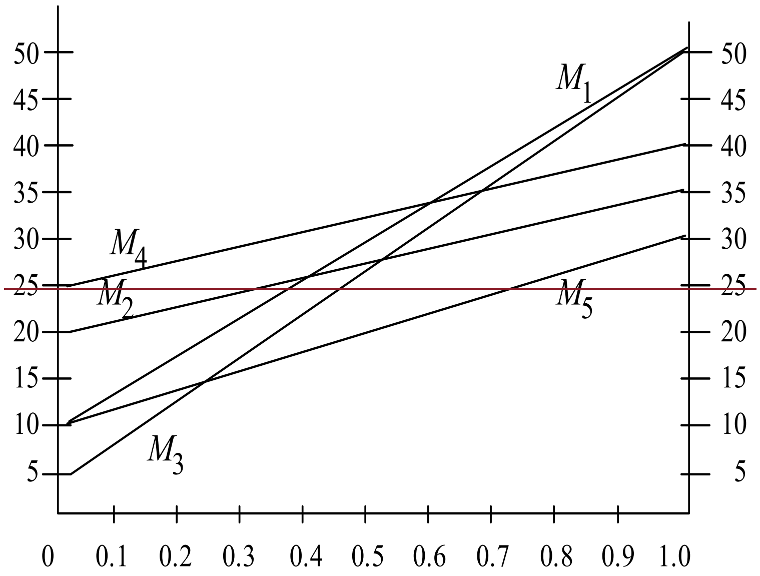
~~(c) Only systems N_3, N_4, and N_5 would satisfy the most probable future criterion.~~

~~The authors gratefully acknowledge that this problem and its solution were contributed by Professor Scott Jackson of the University of Southern California.~~

~~41)~~

	~~Maximin~~	~~Maximax~~	~~(α = 0.4) Hurwicz~~
~~M_1~~	~~10~~	~~50~~	~~26~~
~~M_2~~	~~20~~	~~35~~	~~26~~
~~M_3~~	~~5~~	~~50~~	~~23~~
~~M_4~~	~~25~~	~~40~~	~~31~~
~~M_5~~	~~10~~	~~30~~	~~18~~
~~Strategy~~	~~M_4~~	~~M_1 or M_3~~	~~M_4~~

~~42) Using the payoff matrix of Problem 41, not 40 as stated, gives:~~



43)

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~~Policy~~	~~Most Probable~~	~~Laplace~~	~~Maximax~~	~~Hurwicz~~
~~M_1~~ ~~M_2~~ ~~M_3~~	~~30~~ ~~26~~ ~~15~~	~~20.00~~ ~~24.67~~ ~~28.33~~	~~30~~ ~~26~~ ~~40~~	~~14.0~~ ~~22.8~~ ~~20.0~~
~~Policy~~	~~M_1~~	~~M_3~~	~~M_3~~	~~M_2~~

~~44) Facets of a decision situation which cannot be explained by a model being utilized should be reserved for intuition and judgment applied by the decision maker.~~

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~~CHAPTER 8~~

~~MODELS FOR ECONOMIC EVALUATION~~

~~P/F,6,8~~
~~1) *P* = $10,000 (0.6274) = $6,274~~

~~2) (a) *F* = $8,000 (2.004) = $16,032~~

~~F/P,8,5~~
~~(b) *F* = $52,500 (1.469) = $77,123~~

~~P/A,8,5~~
~~3) *P* = $6,000 (3.9927) = $23,956~~

~~4) *g′* = (1 + 0.08)/(1 + 0.08) – 1 = 0~~

~~P/A,0,20 is indeterminate as shown from [(1 + 0)^20 – 1] /(0) (1 + 0)^20 = (0)/(0). Thus, when g = i, *g′* = 0. P should be found from the expression at the top of page 210 as:~~

$$P=\frac{F_1}{1+g}\left[\frac{1}{(1+g')^1}+\frac{1}{(1+g')^2}+\cdots+\frac{1}{(1+g')^{20}}\right]$$

$$P=\frac{\$1,000}{1+0.08}\left[\frac{1}{1+0}+\frac{1}{1+0}+\cdots+\frac{1}{1+0}\right]=\frac{\$1,000}{1.08}[20]=\underline{\$18,519}$$

~~5) *g′* = [(1 + 0.06)/(1 – 0.25)] – 1 = 0.413~~

~~P/A 0.413,4~~
~~*P* = $1,000,000 [(1.813008)/(1 – 0.25)] = $2,417,344~~

~~6) F/P,*i*,6 F/P, *i*,6~~
~~$4,000 ( ) = $10,000 giving (2.500)~~

~~Solve for *i* by taking 2.5 to the 1/6 power resulting in *i* = 16.5%~~

~~7) F/P,10,*n*~~
~~$4,000 ( ) = $7,000~~

~~F/P,10,*n*~~
~~(1.750) is satisfied when *n* = 6 years by solution to Equation 8.1 on page 206.~~

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~~F/P,*i*,8~~

~~8) 2 = 1( ) for doubling with~~

~~F/P,*i*,8~~

~~(2) is satisfied when *i* = 9% by solution to Equation 8.1 (page 206).~~

~~The doubling period of 8 years results from the “Rule of 72” (9 times 8 = 72). The “Rule of 72” is quite accurate for interest rates between 9% and 10%, but becomes gradually less accurate outside of that range. Reference: Figure 8.4 (page 213).~~

~~9) A/P,14,12~~

~~(a) *A* = ($52,000 – $6,000)(0.17667) + $6,000 (0.14) = $8,967 from Equation 8.16 (page 220). Note that the $6,000 to be received from scrapping the asset at the end of the 12th year is equivalent to a $6,000 receipt at the beginning of the first year less the 14% interest on that receipt each year for the 12 years.~~

~~A/P,14,5~~

~~(b) *A* = ($52,000 – $18,000)(0.29129) + $18,000 (0.14) = $12,424~~

~~10) A/P,8,3~~

~~(a) *A* = ($33,000 – $5,000)(0.3880) + $5,000 (0.08) = $11,264~~

~~A/P,12,3~~

~~(b) *A* = ($33,000 – $5,000)(0.4164) + $5,000 (0.12) = $12,259~~

~~The cost per pound = $12,259/[(200)(12)] = $5.11~~

~~11) Present Equivalent Comparison:~~

~~P/F,14,1 P/F,14,2 P/F,14,3~~

~~Receipts = $6,000 (0.8772) + $5,000 (0.7695) + $5,000 (0.6750)~~

~~P/F,14,4~~

~~+ $12,000 (0.5921) = $19,590~~

~~P/F,14,2 P/F,14,4~~

~~Disbursements = $20,000 + $4,000 (0.7695) + $1,000 (0.5921) = $23,670~~

~~Receipts – Disbursements = $19,590 – $23,670 = –$4,080~~

~~Annual Equivalent Comparison:~~

~~A/P,14,4~~

~~–$4,080 (0.3432) = –$1,400~~

~~This venture is not desirable at 14%, but would be at a lesser rate that could be determined.~~

~~P/A,*i*,*n* P/F,*i*,*n*~~
~~12) (a) $4,000 ( ) + $3,000 ( )~~

~~P/A,7,10 P/F,7,10~~
~~For *i* =7%: $4,000 (7.0236) + $3,000 (0.5083) = $29,619~~

~~P/A,6,10 P/F,6,10~~
~~For *i* =6%: $4,000 (7.3601) + $3,000 (0.5584) = $31,116~~

~~Interpolating for *i* gives: 6 + (30,000 − 29,619) / (31,116 − 29,619) = 6.7%~~

~~(b) The life would have to be infinite, since a return of 15% is not possible to obtain.~~

~~13) 40-passenger bus at 15% interest:~~
~~P/A,15,10 P/F,15,10~~
~~Receipts − Disbursements = $16,000 (5.0188) + $8,000 (0.2472) − $75,000 = $7,278~~

~~50-passenger bus at 15% interest:~~
~~P/A,15,10 P/F,15,10~~
~~Receipts − Disbursements = $20,000 (5.0188) + $8,000 (0.2472) − $95,000 = $7,353~~

~~There is very little difference in the alternatives at 15%.~~

~~40-passenger bus at 7.5% interest:~~
~~P/A,7.5,10 P/F,7.5,10~~
~~Receipts − Disbursements = $16,000 (6.8375) + $8,000 (0.4852) − $75,000 = $38,282~~

~~50-passenger bus at 7.5% interest:~~
~~P/A,7.5,10 P/F,7.5,10~~
~~Receipts − Disbursements = $20,000 (6.8375) + $8,000 (0.4852) − $95,000 = $45,632~~

~~The larger bus should be recommended at 7.5% interest.~~

~~14) (a) Without sprinkler system:~~

~~P/A,*i*,20~~
~~*P* = $0.85 (71,000) ( )~~

~~With sprinkler system:~~

~~P/A,*i*,20 P/A,*i*,20~~
~~*P* = $180,000 + $3,600 ( ) + $0.40 (71,000) ( )~~

~~P/A,*i*,20~~
~~(6.3492) = $180,000/$28,350, from which *i* = 14.78 percent by interpolation.~~

~~(b) Without sprinkler system:~~
~~P/A,12,*n*~~
~~*P* = ($0.85) (71,000) ( )~~

~~With sprinkler system:~~
~~P/A,12,*n* P/A,12,*n*~~
~~*P* = $180,000 + $3,600 ( ) + $0.40 (71,000) ( )~~

~~P/A,12,*n*~~
~~(6.3492) = 180,000/28,350, from which *n* = 12.68 years by interpolation.~~

~~15) The present equivalent payoff matrix for the three futures of the two alternatives is:~~

	~~Optimistic~~	~~Expected~~	~~Pessimistic~~
~~Design 1~~	~~$12.31~~	~~$14.61~~	~~$16.84~~
~~Design 2~~	~~$11.08~~	~~$16.81~~	~~$18.48~~

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~~The expected cost for each alternative is calculated as:~~

~~Design 1: $12.31(0.3) + $14.61(0.5) + $16.84(0.2) = $14.37 million~~
~~Design 2: $11.08(0.3) + $16.81(0.5) + $18.48(0.2) = $15.43 million~~
~~Therefore, Design 1 should be chosen.~~

~~16) Laplace Criterion:~~

~~Design 1: ($2.31 + 14.61 + 16.84) / 3 = $14.59 million~~
~~Design 2: ($11.08 + 16.81 + 18.48) / 3 = $15.46 million~~
~~Select Design 1~~

~~Maximin Rule:~~

~~Design 1: $16.48 million~~
~~Design 2: $18.48 million~~
~~Select Design 1~~

~~Maximax Rule:~~

~~Design 1: $12.31 million~~
~~Design 2: $11.08 million~~
~~Select Design 2~~

~~Hurwicz Criterion with α = 0.6:~~

~~Design 1: 0.6($12.31) + 0.4($16.84) = $14.13 million~~
~~Design 2: 0.6($11.03) + 0.4($18.48) = $14.04 million~~
~~Select Design 2~~

~~17) A/P,9,10 A/F,9,10~~
~~\$36,500 (0.1558) + \$3.20*x* − \$5,000 (0.0658)~~

~~A/P,9,10 A/F,9,10~~
~~= \$47,000 (0.1558) + \$2.00*x* − \$6,000 (0.0658)~~

~~Solving for *x* gives 1,308 hours~~

~~18) \$4.20 (1,000) − \$1.50 (1,000) − \$1,200 = \$1,500~~

~~19) \$960*N* = \$460*N* + \$80,000~~

~~\$500*N* = \$80,000 and *N* = 160 units~~

~~20) \$0.018*N* + \$35 = \$0. 45*N*~~

~~*N* = 130 miles~~

~~21) $TC_A = TC_B$ for break-even~~

~~\$14.40 *N* + \$20,000 = \$16.40 *N* + \$5,000, from which *N* = 7,500~~

~~Machine A should be purchased for all sales values ≥ 7,500.~~

~~22) A/P,10,*n* A/P,10,*n*~~
~~\$20,000 ( ) + \$1.15 (20,000) = \$36,000 ( ) + \$0.90 (20,000)~~
~~A/P,10,*n*~~
~~\$16,000 ( ) = \$5,000, from which *n* is 4.06 years~~

~~23) Annual cost by hand wiring = \$10,000 + \$9.80*N*~~
~~A/P,8,8~~
~~Annual cost by printing = (\$180,000 − 12,000) (0.1740) +~~
~~\$12,000 (0.08) + \$4,000 + \$3.20*N*~~

~~\$06.60*N* = \$24,192, from which *N* is 3,665 units to break even.~~

~~24) P/F,9,4 P/F,9,1 P/F,9,2~~
~~PE_A = \$120,000 − \$15,000 (0.7084) + (20,000×\$8) (0.9174) + (30,000×\$8)(0.8417)~~
~~P/F,9,3 P/F,9,4~~
~~+ (40,000×\$8)(0.7722) + (50,000×\$8)(0.7084) = \$988,630~~
~~P/F,9,4 P/F,9,1~~
~~PE_B = \$280,000 − \$32,000 (0.7084) + (20,000×\$0.26) (0.9174)~~
~~P/F,9,2 P/F,9,3 P/F,9,4~~
~~+ (30,000×\$0.26)(0.8417) + (40,000×\$0.26)(0.7722)+(50,000×\$0.26)(0.7084) = \$285,906~~
~~Since $PE_B < PE_A$: Select proposal B.~~

~~25) (a) $TC = NV + F$~~

~~(b) $TC_h = V + F/N$~~

~~(c) $M = t\,(TC_h) = t\,(V + F/N)$~~

~~26) (a) Sample calculations for N = 4,000:~~

~~M = 0.2 ($50 + $60,000/4,000) = $13~~

~~(b) $TC_u = t\,(W + V + F/N)$~~

~~27) (0.75×800,000)($0.10 – $0.06) – $28,000 = $4,000 (annual loss)~~

~~0.04N$ = $28,000 giving N = 700,000 units~~

~~Break-even occurs at 87.5%~~

~~28) Annual cost of capital recovery and return~~

~~A/P,8,5~~
~~= ($90,000 – $10,000) (0.2505) + ($10,000)(0.08) = $20,840~~

~~Cost per unit for producing N units per year~~

~~= $28.00 + $65.00 + {($5,000 + $20,840)/$N$}~~

~~N~~	~~200~~	~~600~~	~~1,800~~
~~Cost/Unit~~	~~$222.20~~	~~$136.07~~	~~$107.36~~

~~29) Annual income at 100% capacity =~~ $\frac{\$416,000}{0.65}$ ~~= $640,000 or $0.984615 per unit~~

~~(a) Annual profit = $416,000 – $192,000 – $0.38(650,000) 0.65 = $63,450~~

~~(b) $x\,(0.984615) = \$192,000 + 0.38x$~~

~~For break-even x =~~ $\frac{\$192,000}{0.604615}$ ~~= 317,557 units~~

~~(c)~~

	~~Production~~	~~Revenue~~	~~Variable Cost~~	~~Profit~~
~~70%~~	~~$275,100~~	~~$ 83,100~~		
~~80%~~	~~314,400~~	~~122,400~~		
~~90%~~	~~353,700~~	~~161,700~~		

~~30) (a) Total cost at Plant A:~~

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~~$2,600,000 + $32(60,000)(0.35) = $3,272,000 at the current production level~~
~~$2,600,000 + $32(60,000) = $4,520,000 at full capacity~~

~~Total cost at Plant B:~~

~~$2,800,000 + $39(80,000)(0.40) = $4,048,000 at the current production level~~
~~$2,800,000 + $39(80,000) = $5,920,000 at full capacity~~

~~(b) Total cost at both plants:~~

~~$2,600,000 + $32(21,000) + $2,800,000 + $39(32,000) = $7,320,000~~

~~Average unit cost per gallon of both plants:~~

~~$7,320,000 / (21,000 + 32,000) = $138.11~~

~~(c) Total cost if all production is transferred to plant A:~~

~~$260,000 + $280,000 + $3.20(21,000 + 32,000) = $7,096,000~~

~~Unit cost per gallon =~~ $\frac{\$7,096,000}{53,000}$ ~~= $133.89~~

~~(d) Total cost if all production is transferred to plant B:~~

~~$260,000 + $280,000 + $3.90(21,000 + 32,000) = $746,700~~

~~Unit cost per gallon =~~ $\frac{\$7,467,000}{53,000}$ ~~= $140.89~~

~~CHAPTER 9~~

~~OPTIMIZATION IN DESIGN AND OPERATIONS~~

~~1) Let h = height; w = width; p = perimeter~~

~~$p = 2h + 2w$~~

~~$A = hw = ph/2 - h^2$~~

~~$\frac{dA}{dh} = p/2 - 2h = 0$~~

~~$h = p/4$ and $w = p/4$~~

~~Both the height and the width must be ¼ of the perimeter for the area of the rectangle (square) to be a maximum.~~

~~2) Value of x for minimum unit cost~~

~~$UC' = 4x - 10 = 0$ $x = 2.5$ or 2,500 units~~

~~Minimum cost at this volume~~

~~$UC = 2(2.500)^2 + 50 - 10(2.500) = \underline{\$37.50}$~~

~~This value is truly a minimum since $UC'' = 4$.~~

~~3) Advertising expenditure which maximizes profit is found from~~

~~$P' = 3x^2 - 200x + 3{,}125 = 0$~~

~~$x = \frac{200 \pm \sqrt{200^2 - 4(3)(3{,}125)}}{2(3)} = \frac{200 \pm 50}{6}$ from which $x = 25$ or 41.66~~

~~Profit expected at this expenditure ($25,000)~~

~~$P = (\$25{,}000)^3 - 100(\$25{,}000)^2 + 3{,}125(\$25{,}000) = \underline{\$31{,}250}$~~

~~This profit is truly a maximum since~~

~~$P'' = 6x - 200$~~

~~For $x = 25$, $P'' = -50$~~

~~4) Profit = revenue − cost~~

~~If $x < 1{,}000$, Profit = $P = -20x - \$15{,}000$~~

~~If $1{,}000 \le x < 2{,}500$, Profit = $P = 80x - \$115{,}000$~~

~~If $2{,}500 \le x$, Profit = $P = -5x + \$97{,}500$~~

~~The profit is maximum at $dP/dx = 0$.~~

~~If $x < 1000$, $dP/dx = -20$~~

~~If $1{,}000 \le x < 2{,}500$, $dP/dx = 80$~~

~~If $2{,}500 \le x$, $dP/dx = -5$~~

~~The break-even point is given by $X = 115{,}000/80 = 1437.5$ units = 1,438 units~~

~~The level of production which maximizes profit is 2,500 units, since dP/dx changes sign from negative to positive in the production range between 1,000 units and 2,500 units. The maximum profit = (2,500)80 − $115,000 = $85,000~~

~~5) (a) For ratio = 2, take x = 1 lb and y = 1/2 lb, then~~

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$$\frac{z^2}{(1.47\times 1-z)(1.91\times 1/2-z)}=3.91$$

$$2.91z^2-9.48z+5.49=0$$

$$z=\frac{9.48\pm\sqrt{(9.48)^2-4\times 2.91\times 5.49}}{2\times 2.91}$$

~~= 2.5 or 0.75. Since 2.5 lb is greater than x + y, the correct solution is 0.75.~~

~~See column *z* in the table below.~~

~~(b)~~

~~*x*~~	~~*y*~~	~~*z*~~	~~Cost *x*~~	~~Cost *y*~~	~~Total Cost~~	~~Cost per lb of *z*~~
~~1~~	~~1/2~~	~~0.75~~	~~$0.80~~	~~$0.46~~	~~$1.26~~	~~$1.68~~
~~1~~	~~1~~	~~1.09~~	~~0.80~~	~~0.92~~	~~1.72~~	~~1.72~~
~~1~~	~~3/2~~	~~1.21~~	~~0.80~~	~~1.44~~	~~2.24~~	~~1.85~~

~~6) Total BTU required for insulation *t*" thick~~
~~= 2,200 [1/[(1/0.13) + (*t*/0.27)]] (3,000)(72° − 45°)/0.5~~
~~= 35.64 ×~~ 10^7 ~~(1/[(1/0.13) + (*t*/0.27)]) BTU per year~~
~~Total annual cost of BTUs required for insulation *t*" thick~~
~~= 35.64 ×~~ 10^7 ~~(1/[(1/0.13) + (*t*/0.27)])($8.80/1,000)(1,000/1,020,000)~~
~~= $3,074.824 (1/[(1/0.13) + (*t*/0.27)])~~

~~Thickness~~	~~Initial Investment~~	~~Capital Recovery~~	~~Cost of Heating~~	~~Total Cost~~
~~0~~	~~$ 0~~	~~$ 0~~	~~$399.73~~	~~$399.73~~
~~2~~	~~396~~	~~77.36~~	~~203.63~~	~~126.27~~
~~4~~	~~660~~	~~43.87~~	~~136.62~~	~~180.49~~
~~6~~	~~968~~	~~185.31~~	~~102.79~~	~~288.10~~

~~7) Total Cost = Superstructure Cost + Pier Cost, *TC* = *SC* + *PC*~~

$$= [(32S + 1{,}850)\,(600)\,(3.20)] + \left[\left(\frac{600}{S} - 1\right)(250{,}000)\right]$$

~~To find the optimum span between piers, differentiate the total cost function with respect to *S*, set to zero, and solve for *S* giving:~~

$$\frac{dTC}{dS}=(32)(600)(3.20)-\frac{(600)(250{,}000)}{S^2}=0$$

$$S=\sqrt{\frac{250{,}000}{32(3.2)}}=49.41.$$

~~The theoretical optimum number of piers~~ $N=\frac{L}{S}-1=\frac{600}{49.41}-1=11.14$

~~For 11 piers:~~

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~~$$S = \frac{L}{N+1} = \frac{600'}{12} = 50'$$~~

~~$$TC_{11} = [(32X50 + 1850)(600)(3.20)] + \left[\left(\frac{600}{50} - 1\right)(250,000)\right] = \$9,374,000$$~~

~~For 12 piers:~~

~~$$S = \frac{L}{N+1} = \frac{600'}{13} = 46.153846'$$~~

~~$$TC_{12} = [(32X46.153846 + 1850)(600)(3.20)] + \left[\left(\frac{600}{46.153846} - 1\right)(250,000)\right] = \$9,387,692$$~~

~~The best discrete adjustment gives *11 piers* for a minimum total cost. The span will be 50 feet, slightly more than the theoretical span with minimum cost.~~

~~8) Tabular solution for Design 1:~~

~~Span in Feet~~	~~Number of Piers~~	~~Pier Cost ($)~~	~~Superstructure Cost ($)~~	~~Total Cost ($)~~
~~240.00~~	~~6~~	~~1,320,000~~	~~4,012,800~~	~~5,332,800~~
~~200.00~~	~~7~~	~~1,540,000~~	~~3,432,000~~	~~4,972,000~~
~~171.42~~	~~8~~	~~1,760,000~~	~~3,017,143~~	~~4,777,143~~
~~150.00~~	~~9~~	~~1,980,000~~	~~2,706,000~~	~~4,686,000~~
~~133.33~~	~~10*~~	~~2,200,000~~	~~2,464,000~~	~~4,664,000~~
~~120.00~~	~~11~~	~~2,420,000~~	~~2,270,400~~	~~4,690,400~~
~~109.09~~	~~12~~	~~2,640,000~~	~~2,112,000~~	~~4,752,000~~

~~The optimum design is 10 piers (including 2 abutments) with TC_1 = $4,664,000.~~

~~Tabular solution for Design 2:~~

~~Span (Feet)~~	~~Number of Piers~~	~~Pier Cost ($)~~	~~Superstructure Cost ($)~~	~~Total Cost ($)~~
~~240.00~~	~~6~~	~~1,320,000~~	~~3,828,000~~	~~5,148,000~~
~~200.00~~	~~7~~	~~1,540,000~~	~~3,330,000~~	~~4,840,000~~
~~171.42~~	~~8~~	~~1,760,000~~	~~2,922,857~~	~~4,682,857~~
~~150.00~~	~~9*~~	~~1,980,000~~	~~2,640,000~~	~~4,620,000~~
~~133.33~~	~~10*~~	~~2,200,000~~	~~2,420,000~~	~~4,620,000~~
~~120.00~~	~~11~~	~~2,420,000~~	~~2,244,000~~	~~4,664,000~~
~~109.09~~	~~12~~	~~2,640,000~~	~~2,100,000~~	~~4,740,000~~

~~The optimum design is either 9 or 10 piers (including 2 abutments) with TC_2 = $4,620,000, therefore select Design 2~~

~~9) Cost advantage = $TC_1 - TC_2$ = $44,000~~

~~Cost penalty = $44,000~~

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~~10) (a) Without taking the time value of money into consideration,~~

~~EOY~~	~~Decrease in Market Value~~	~~O+M Cost~~	~~Total Cost for Year~~	~~Cumulative Total Cost~~	~~Equivalent Annual Cost at EOY~~
~~1~~	~~$825.00~~	~~$1,550~~	~~$2,375.00~~	~~$2,375.00~~	~~$2,375.00~~
~~2~~	~~70.25~~	~~1,650~~	~~2,351.25~~	~~4,726.25~~	~~2,363.13~~
~~3~~	~~596.06~~	~~1,750~~	~~2,346.06~~	~~7,072.31~~	~~2,357.44~~
~~4~~	~~506.65~~	~~1,850~~	~~2,356.65~~	~~9,428.96~~	~~2,357.24~~
~~5~~	~~430.65~~	~~1,950~~	~~2,380.65~~	~~11,809.61~~	~~2,361.92~~
~~6~~	~~366.00~~	~~2,050~~	~~2,416.00~~	~~14,225.61~~	~~2,370.94~~

~~From the above table, the lowest equivalent annual cost is obtained when the asset is retired at the end of Year 4. Therefore, the Economic Life of the asset is 4 years.~~

~~(b) Capital recovery cost calculations with an interest rate = 16%:~~

~~EOY~~	~~Market value at EOY ($)~~	~~Decrease in Market Value ($)~~	~~Interest on Investment~~	~~Capital Recovery Cost for Year ($)~~
~~1~~	~~4,675~~	~~825~~	~~880~~	~~1,705~~
~~2~~	~~3,973~~	~~701~~	~~748~~	~~1,449~~
~~3~~	~~3,378~~	~~596~~	~~636~~	~~1,232~~
—	—	—	—	—
—	—	—	—	—
~~14~~	~~564~~	~~100~~	~~106~~	~~206~~

~~Sample calculations for Economic Life of the asset:~~

~~EOY~~	~~Capital Recovery Cost ($)~~	~~O+M Cost ($)~~	~~Total Cost ($)~~	~~PE Cost ($)~~	~~Sum of PE Cost ($)~~	~~(A/P 16%, N)~~	~~Equivalent Annual Cost ($)~~
~~1~~	~~1,705~~	~~1,550~~	~~3,255~~	~~2,806~~	~~2,806~~	~~1.1600~~	~~3,255~~
~~2~~	~~1,449~~	~~1,650~~	~~3,150~~	~~2,341~~	~~5,147~~	~~0.6230~~	~~3,206~~
~~3~~	~~1,232~~	~~1,750~~	~~2,982~~	~~1,911~~	~~7,058~~	~~0.4453~~	~~2,142~~
—	—	—	—	—	—	—	—
—	—	—	—	—	—	—	—
~~13~~	~~244~~	~~2,750~~	~~2,994~~	~~435~~	~~15,884~~	~~0.1872~~	~~2,973~~
~~14~~	~~206~~	~~2,850~~	~~3,056~~	~~383~~	~~16,267~~	~~0.1829~~	~~2,975~~

~~From the calculations above, the lowest Equivalent Annual Cost occurs when the asset is retired at the end of year 12. This is the Economic Life.~~

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~~11) (a) Without taking the time value of money into consideration, the calculation is:~~

~~EOY~~	~~Decrease in Market Value ($)~~	~~O+M Cost ($)~~	~~Total Cost for the Year ($)~~	~~Cum. Total Cost ($)~~	~~Equivalent Annual Cost ($)~~
~~1~~	~~5,440~~	~~900~~	~~2,260~~	~~2,260~~	~~2,260~~
~~2~~	~~4,332~~	~~950~~	~~2,058~~	~~4,318~~	~~2,159~~
~~3~~	~~3,466~~	~~1,000~~	~~1,866~~	~~6,184~~	~~2,061~~
~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~
~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~
~~15~~	~~238.15~~	~~1,600~~	~~1,659~~	~~25,311~~	~~1,687~~
~~16~~	~~190.52~~	~~1,650~~	~~1,697~~	~~27,009~~	~~1,688~~

~~From the above table, the lowest equivalent annual cost is obtained when the asset is retired at the end of the year 15. Therefore, the Economic Life of the asset (without considering interest) = 15 years.~~

~~(b) Capital recovery cost calculations (interest rate = 16%):~~

~~EOY~~	~~Market Value at EOY ($)~~	~~Decrease in Market Value ($)~~	~~Interest on Investment ($)~~	~~Capital Recovery Cost for Year ($)~~
~~1~~	~~5,440~~	~~1,360~~	~~1,088~~	~~2,488~~
~~2~~	~~4,332~~	~~1,108~~	~~870~~	~~1,978~~
~~3~~	~~3,457~~	~~866~~	~~693~~	~~1,559~~
	~~—~~	~~—~~	~~—~~	~~—~~
~~—~~	~~—~~	~~—~~	~~—~~	~~—~~
~~23~~	~~40~~	~~10~~	~~8~~	~~18~~
~~24~~	~~32~~	~~8~~	~~6~~	~~14~~
~~25~~	~~25~~	~~6~~	~~5~~	~~11~~

~~Calculations for Economic Life of asset:~~

~~EOY~~	~~Capital Recover Cost ($)~~	~~O+M Cost ($)~~	~~Total Cost ($)~~	~~PE Cost ($)~~	~~Cum. PW ($)~~	~~(A/P, 16, N)~~	~~Equiv. Annual Cost ($)~~
~~1~~	~~2,448~~	~~900~~	~~3,348~~	~~2,785~~	~~2,785~~	~~1.1600~~	~~3,232~~
~~2~~	~~1,978~~	~~950~~	~~2,928~~	~~2,176~~	~~4,962~~	~~0.6230~~	~~3,091~~
~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~
~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~
~~21~~	~~27~~	~~1,900~~	~~1,928~~	~~75~~	~~13,648~~	~~0.1674~~	~~2,284~~
~~22~~	~~22~~	~~1,950~~	~~1,972~~	~~75~~	~~13,724~~	~~0.1654~~	~~2,270~~
~~23~~	~~18~~	~~2,000~~	~~2,017~~	~~66~~	~~13,790~~	~~0.1647~~	~~2,271~~
~~24~~	~~14~~	~~2,050~~	~~2,064~~	~~59~~	~~13,849~~	~~0.1640~~	~~2,271~~
~~25~~	~~11~~	~~2,100~~	~~2,111~~	~~52~~	~~13,900~~	~~0.1634~~	~~2,272~~

~~From the table above, the lowest equivalent annual cost is obtained when the asset is retired at the end of year 22. Therefore, the Economic Life of asset = 22 years.~~

~~12) Capital recovery cost calculations (interest rate = 10%):~~

~~EOY~~	~~Market Value~~	~~Decrease~~	~~Interest on~~	~~Capital Re-~~

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	~~at EOY ($)~~	~~In Market Value ($)~~	~~Investment ($)~~	~~covery Cost for Year ($)~~
~~1~~	~~70,000~~	~~10,000~~	~~8,000~~	~~18,000~~
~~2~~	~~60,000~~	~~10,000~~	~~7,000~~	~~17,000~~
~~3~~	~~50,000~~	~~10,000~~	~~6,000~~	~~16,000~~
~~4~~	~~40,000~~	~~10,000~~	~~5,000~~	~~15,000~~
~~5~~	~~30,000~~	~~10,000~~	~~4,000~~	~~14,000~~
~~6~~	~~20,000~~	~~10,000~~	~~3,000~~	~~13,000~~
~~7~~	~~10,000~~	~~10,000~~	~~2,000~~	~~12,000~~
~~8~~	—	~~10,000~~	~~1,000~~	~~11,000~~

~~Calculations for Economic life of asset:~~

~~EOY~~	~~Capital Recovery Cost ($)~~	~~O+M Cost ($)~~	~~Total Cost ($)~~	~~PW of Cost ($)~~	~~Cum. PW ($)~~	~~(A/P 16%, N)~~	~~Equiv. Annual Cost ($)~~
~~1~~	~~18,000~~	~~18,000~~	~~36,000~~	~~32,727~~	~~32,727~~	~~1.1000~~	~~36,000~~
~~2~~	~~17,000~~	~~18,900~~	~~35,900~~	~~29,671~~	~~62,399~~	~~0.5762~~	~~35,954~~
~~3~~	~~16,000~~	~~19,845~~	~~35,845~~	~~26,930~~	~~89,329~~	~~0.4021~~	~~35,919~~
~~4~~	~~15,000~~	~~20,837~~	~~35,837~~	~~24,477~~	~~113,806~~	~~0.3155~~	~~35,906~~
~~5~~	~~14,000~~	~~21,879~~	~~35,879~~	~~22,277~~	~~136,083~~	~~0.2638~~	~~35,899~~
~~6~~	~~13,000~~	~~22,973~~	~~35,973~~	~~20,307~~	~~156,390~~	~~0.2296~~	~~35,907~~
~~7~~	~~12,000~~	~~24,121~~	~~36,122~~	~~18,538~~	~~174,928~~	~~0.2054~~	~~35,930~~
~~8~~	~~11,000~~	~~25,327~~	~~36,328~~	~~16,947~~	~~191,875~~	~~0.1875~~	~~36,977~~

~~From the table above, the lowest equivalent annual cost is obtained when the asset is retired at the end of year 5. Therefore, the Economic Life of the asset = 5 years.~~

~~13) Capital recovery cost calculations (MARR = 25%):~~

~~EOY~~	~~Market Value at EOY ($)~~	~~Decrease in Market Value ($)~~	~~Interest on Investment ($)~~	~~Capital Recovery Cost for Year ($)~~
~~1~~	~~600~~	~~350~~	~~238~~	~~588~~
~~2~~	~~400~~	~~200~~	~~150~~	~~350~~
~~3~~	~~200~~	~~200~~	~~100~~	~~300~~
~~4~~	—	~~200~~	~~50~~	~~250~~

~~Calculations for Economic Life of asset:~~

~~EOY~~	~~Capital Recovery Cost ($)~~	~~O+M Cost ($)~~	~~Total Cost ($)~~	~~(P/F, 10%, N)~~	~~PW of Cost ($)~~	~~Cum. PW ($)~~	~~(A/P, 10, N)~~	~~Equiv. Annual Cost ($)~~
~~1~~	~~588~~	~~100~~	~~688~~	~~0.8000~~	~~550~~	~~550~~	~~1.2500~~	~~688~~
~~2~~	~~350~~	~~250~~	~~600~~	~~0.6400~~	~~384~~	~~934~~	~~0.6945~~	~~649~~
~~3~~	~~300~~	~~325~~	~~625~~	~~0.5120~~	~~320~~	~~1,254~~	~~0.5123~~	~~642~~
~~4~~	~~250~~	~~400~~	~~650~~	~~0.4096~~	~~266~~	~~1,520~~	~~0.4235~~	~~644~~

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~~From the table above, the lowest equivalent annual cost is obtained when the asset is retired at the end of year 3. Therefore, the Economic Life of the asset = 3 years. Draw a graph of the number of years on the X- axis versus the annual equivalent value on the Y- axis.~~

~~14) $N = QD$ and $I^* = Q + L - DT$~~

~~$I = \frac{[Q+L-DT]^2}{2D}$; $S = \frac{(DT-L)^2}{2D}$~~

~~$IC = C_iD$; $PC = \frac{C_pD}{Q}$~~

~~$HC = \frac{C_hD}{Q}\left\{\frac{[Q+L-DT]^2}{2D}\right\}$~~

~~$SC = \frac{C_sD}{Q}\left[\frac{(DT-L)^2}{2D}\right]$~~

~~$TC = C_iD + \frac{C_pD}{Q} + \frac{C_hQ}{2} - C_h(DT-L) + \frac{C_h(DT-L)^2}{2Q} + \frac{C_s(DT-L)^2}{2Q}$~~

~~$\frac{dTC}{dQ} = -\frac{C_pD}{Q^2} + \frac{C_h}{2} - \frac{C_h(DT-L)^2}{2Q^2} - \frac{C_s(DT-L)^2}{2Q^2} = 0$~~

~~$\frac{dTC}{d(DT-L)} = C_h + \frac{C_h(DT-L)}{Q} + \frac{C_s(DT-L)}{Q} = 0$; From which,~~

~~$Q^* = \sqrt{\frac{2C_pD}{C_h} + \frac{2C_pD}{C_s}}$ $L^* = DT - \sqrt{\frac{2C_pD}{C_s(1+C_s/C_h}}$ $TC^* = C_iD + \sqrt{\frac{2C_pC_hC_sD}{C_h+C_s}}$~~

~~15) $IC = C_iD$~~

~~$PC = \frac{C_pD}{Q}$~~

~~$HC = \frac{C_hQ}{2}$~~

~~$TC = C_iD + \frac{C_pD}{Q} + \frac{C_hQ}{2}$~~

~~$\frac{dTC}{dQ} = \frac{C_pD}{2} + \frac{C_h}{2} = 0$~~

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~~$Q^* = \sqrt{\frac{2C_pD}{C_h}}$ $L^* = DT$~~

~~$TC^* = C_iD + \frac{C_pD}{\sqrt{2C_pD/C_h}} + \frac{C_h\sqrt{2C_pD/C_h}}{2}$~~

~~$= C_iD + \sqrt{2C_pC_hD}$~~

~~16) (a) $Q^* = \sqrt{2\times\$400\times82)/\$0.45(1-82/500)} = \underline{418}$~~

~~(b) $L^* = 82 \times 8 = \underline{656}$~~

~~(c) $TC^* = \$105(82) + \sqrt{[2\times\$400(1-82/500)(0.45\times82)]}$~~
~~$= \$8{,}610 + \$157 = \underline{\$8{,}967}$~~

~~17) (a) $Q^* = \sqrt{(2\times\$90\times82)/0.45} = 181$ units~~

~~$TC^* = (\$108 \times 82) + \sqrt{2\times\$90\times82\times\$0.45} = \$8{,}937.50$~~

~~(b) The advantage for subcontracting is \$8,967.00 – \$8,937.50 = \$29.50 per day.~~

~~18) (a) Purchase:~~

~~$TC^* = (\$11 \times 12) + \sqrt{(2\times\$20\times\$0.02\times12} = \underline{\$135.10}$~~

~~Manufacture:~~

~~$TC^* = (\$9.60 \times 12) + \sqrt{[(2\times\$90(1-12/25)\$0.02\times12]} = \underline{\$119.94}$~~

~~Economic advantage of manufacturing = \$15.16.~~

~~(b) $Q^* = \sqrt{(2\times\$90\times12)/[\$0.02(1-12/25)]} = \underline{\$456\text{ units}}$~~

~~(c) $L^* = 12 \times 13 = \underline{156\text{ units}}$~~

~~19) (a) $Q^* = \sqrt{1/\{1-(250/600)\}}\times\sqrt{(2\times\$400\times250)(0.15+1/3.25)} = \underline{1{,}546}$~~
~~(b) $L^* = (250 \times 12) = \sqrt{1-(250/600)}\times\sqrt{(2\times\$400\times250)/[3.25(1+3.25/0.15)]} = \underline{\$2{,}960}$~~
~~(c) $TC^* = (\$90 \times 250) + \sqrt{1-(250/600)}\times\sqrt{2\times\$400\times0.15\times3.25\times250)/(0.15+3.25)} = \underline{\$22{,}629}$~~

~~20) Student exercise. A model with an infinite C_h would apply in a situation where items cannot be stored due to deterioration or other reasons.~~

~~21) When, span ≥ 70 feet, inspection of the differential of the total cost function with respect to the span (see the solution for Problem 7) shows that the total cost increases as the span gets further from the optimal span. Therefore, the best discrete adjustment (with the lowest cost span that meets the constraints) gives 7 piers, excluding abutments, and a span of 75 feet.~~

~~$TC_1^* = ((32 \times 75) + 1{,}850)\,(600)\,(3.20) + \left[\left(\frac{600}{75} - 1\right)250{,}000\right] = \$9{,}910{,}000$~~

~~The total cost from Problem 7 is:~~

~~$TC_2^* = [(32 \times 50) + 1{,}850]\,(600)\,(3.20) + \left[\left(\frac{600}{50} - 1\right)250{,}000\right] = \$9{,}374{,}000$~~

~~Cost penalty = $TC_1^* - TC_2^*$ = \$536,000~~

~~22) Assume the number of piers (excluding abutments) = 5.~~

~~Therefore, span = 600/6 = 100~~

~~$TC = [(32 \times 100) + 1{,}850]\,(600)\,(3.20) + \left[\left(\frac{600}{100} - 1\right)300{,}000\right] = \$11{,}196{,}000$~~

~~Cost penalty = \$11,196,000 − \$9,374,000 = \$1,822,000~~

~~23) (a) $Q^* = \sqrt{\frac{2C_pD}{C_s(1-D/R)} + \frac{(C_h+C_s)(W/w)^2}{C_s(1-D/R)^2}}$~~

~~$Q^* = \left(\frac{1500}{2}\right) = 750$ units~~

~~$L^* = DT + \frac{W}{w} - Q^*\left(1 - \frac{D}{R}\right) = 600$ units~~

~~(b) Cost penalty due to the restriction is \$0.37~~

~~24) With a warehouse space restriction:~~

~~$Q^* = \sqrt{\frac{2 \times 48.20}{0.60(2/3)} + \frac{(0.04+0.60)100^2}{0.60(2/3)^2}} = 169.70$~~

~~$L^* = 20 \times 3 + \frac{300}{3} - 169.70 \times \frac{2}{3} = 160 - 113.14 = 46.86$~~

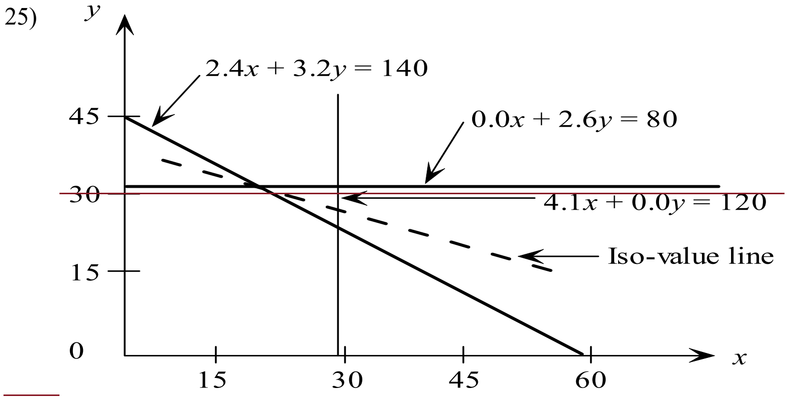
~~$TC_1^* = 98 + 33.94 + 33.94 = \$165.88$~~

~~Without a warehouse space restriction:~~

~~$TC_2^* = 7.90 \times 20 + \sqrt{2/3}\sqrt{\frac{2 \times 48 \times 0.04 \times 0.60 \times 20}{0.04 + 0.60}} = \$164.93$~~

~~Cost penalty = $TC_1^* - TC_2^* =$ \$0.95 per period~~

25)



~~The function is maximized when x = 17.30 and y = 30.76.~~

~~26) Graphical solution not given. Refer to Section 9.5.1 (page 275) for guidance.~~

~~27) Graphical solution not given. Refer to Section 9.5.1 (page 275) for guidance.~~

~~28) There are four available options to determine if the redesign alternative is worthwhile. These are as follows: (a) with the *optimization space* in mind, as in Figure 9.20 (page 278), solve the three new linear constraint equations simultaneously to determine the coordinates of extreme points 2, 3, 5, and 6 and pick the one that is a maximum distance from the origin; (b) redraw Figure 9.20, guided by the new linear constraint equations, placing the restrictions relative to each other to determine graphically the point that is a maximum distance from the origin; (c) Repopulate the initial matrix of Table 9.14 (page 280) with the new capacity values and profit coefficients and then proceed through the simplex optimization algorithm by hand producing a series of tables as in the text; (d) secure a PC-based simplex package and use it to receive inputs for the changed capacities and profit coefficients and produce the new production program. Compare the result obtained from the approach of your choice with the base case. Answer the question regarding the desirability of choosing the alternative over the baseline design.~~

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~~CHAPTER 10~~

~~QUEUEING THEORY AND ANALYSIS~~

~~1) Monte Carlo analysis must be used in the study of a queuing system when the arrival and service time distributions, the queuing discipline, or other system characteristics cannot be represented mathematically. But, there is an advantage in that *operational insight* will be gained from the analysis.~~

~~2) Solution not given. Proceed in accordance with Section 10.2 (pages 293-296).~~

~~3) If μ is not greater than λ, any service time lost due to an empty queue cannot be made up. This cumulative time loss will cause the queue to *grow without bound* over time.~~

~~4) Solution not given. Proceed in accordance with Section 10.2 (pages 293-296).~~

~~5) Solution not given. Proceed in accordance with Section 10.2 (pages 293-296).~~

~~6) $P_n = (1 - 0.625)(0.625)^n$~~
~~$P_0 = (1 - 0.625)(0.625)^0 = 0.375$~~
~~$P_1 = (1 - 0.625)(0.625)^1 = 0.234375$~~
~~$P_2 = (1 - 0.625)(0.625)^2 = 0.1464843$~~
~~$P_3 = (1 - 0.625)(0.625)^3 = 0.0915527$~~
~~$P_4 = (1 - 0.625)(0.625)^4 = 0.0572204$~~
~~$P(n > 4) = 1 - P(n \leq 4) = 1 - 0.9046324 = \underline{0.0953675}$~~

~~7) $P(n \geq 1) < 0.2$, therefore $P_0 \leq 0.80$~~
~~$0.80 = (1 - 0.5/\mu)(0.5/\mu)^0$~~
~~$\mu = \underline{2.5 \text{ units per period}}$~~

~~8) $n_m = 0.125/(0.25 - 0.125) = \underline{1 \text{ unit}}$~~
~~$w_m = 1/(0.25 - 0.125) = \underline{8 \text{ periods}}$~~

~~9) $8 = 0.4/(\mu - 0.4)$~~
~~Minimum service rate is $\mu = 0.450$ units per period.~~
~~The expected waiting time, n_m/λ, is 8/0.4 = <u>20 periods</u>~~
~~10) $TC_m = [\$5.00 \times 0.50)/(2.5 - 0.5)] + (\$2.5 \times 2.5) = \underline{\$7.5}$~~

~~$TC_m = [\$5.00 \times 0.50)/(5.00 - 0.5)] + (\$3.5 \times 5.00) = \underline{\$17.5}$~~

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~~11)~~

~~λ/μ~~	~~n_m~~	~~w_m~~				
		~~$\lambda = 0.2$~~	~~$\lambda = 0.4$~~	~~$\lambda = 0.6$~~	~~$\lambda = 0.8$~~	~~$\lambda = 1.0$~~
~~0.20~~	~~0.250~~	~~1.250~~	~~0.625~~	~~0.418~~	~~0.313~~	~~∞~~
~~0.40~~	~~0.667~~	~~3.335~~	~~1.667~~	~~1.114~~	~~0.834~~	~~∞~~
~~0.60~~	~~1.500~~	~~7.500~~	~~3.750~~	~~2.505~~	~~1.875~~	~~∞~~
~~0.80~~	~~4.000~~	~~20.000~~	~~10.000~~	~~6.680~~	~~5.000~~	~~∞~~
~~1.00~~	~~∞~~	~~∞~~	~~∞~~	~~∞~~	~~∞~~	~~∞~~

~~This table shows that the mean number in the system and the mean waiting time increases to infinity as λ/μ approaches unity. Plot not given.~~

~~12) $\mu = 0.75 +$~~ $\sqrt{[(0.9)(\$3.20)]/\$5.15}$ ~~= 1.455 units per period~~

~~$TC_m = [(\$3.20 \times 0.75)/(1.455 - 0.75)] + (\$5.15 \times 1.455) =$ $10.89~~

~~13) $5 = [(1.5/\mu)/2\mu] + 1/\mu$~~

~~$\mu = 0.850 \pm 0.757 = 1.607$ or 0.093~~

~~But $\mu < \lambda$, therefore μ must be 1.607 units per day~~

~~$n_m =$~~ $\{(1.5/1.607)^2/2 - [1(1.5/1.607)]\} + (1.5/1.607)$ ~~= 7.486 units~~

~~14) $TC_m =$~~ $\$320\{(3.5/4)^2/2[1-(3.5/4)] + (3.5/4)\} + \$440(4)$ ~~= $3,020 from Equation 10.33~~

~~15) $m_m =$~~ $\frac{(0.2)^2}{(0.4)(0.4-0.2)}$ ~~= 0.5 customers using Equation 10.11~~

~~$P_{0,0} =$~~ $1/\{(0.6/0.4)^2(1/2)1/(1-3/4) + (0.6/0.4)^0(1) + (0.6/0.4)^1(1)\}$ ~~= 1/7~~

~~m_m~~ $= P_{0,0} \cdot \frac{(0.6/0.4)^{2+1}}{(2-1)!(2-0.6/0.4)^2} = 1/7 \cdot (3/2)^3 \times 4 \cong$ ~~2 customers~~

~~16) (a) $P_{0,0} = 1/[\lambda/\mu)^c(1/c!)(1/(1-\rho)) + \sum_{0}^{c-1}(\lambda/\mu)^r(1/r!)]$~~

~~$\rho = \lambda/c\mu = 60/120 = 0.5$~~

~~$P_{0,0} =$~~ $1/[(60/30)^4(1/24)(1/0.5) + \{(2^0 \times 1) + (2^1 \times 1) + (2^2 \times 0.5) + (2^3 \times (1/6))\}]$

~~$= 1/7.67 = 0.1304$~~

~~(b)~~ $m_m = P_{0,0}[\{(\lambda/\mu)^{c+1}\}/\{(c-1)!(c-(\lambda/\mu))^2\}]$ ~~=~~ $(0.1304)[\{(2)^5\}/\{6 \times (4-2)^2\}]$

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~~= 0.174~~

~~(c) Average time spent by a vehicle in the plaza =~~ $n_m/c\mu$ ~~= (0.174 + 2)/120~~
~~= 1.087 minutes~~

~~Note in this problem that~~ λ/μ ~~=60/30 x 4 or 1/2, a low~~ ρ ~~leading to the question of why four booths are specified. See Problem 18.~~

~~17)~~

~~Booths~~	WC_m	FC_m	TC_m
~~3~~	~~$400.05~~	~~$720~~	~~$1120.05~~
~~4~~	~~78.30~~	~~960~~	~~1038.30~~
~~5~~	~~16.43~~	~~1200~~	~~1216.43~~

~~Accordingly, four booths should be operated to minimize cost.~~

~~From the above, it is now clear that 4 booths gives the optimum.~~

~~18) Probability of no waiting =~~ $P_{0,0} + P_{1,0} + P_{2,0} = P_{0,0}\{1 + (\lambda/\mu) + (1/2)(\lambda/\mu)^2 = $ ~~0.70 from Equation 10.25~~

~~19)~~ $M_m = \dfrac{(8/32)^2}{(1/8)(1/8 - 1/32)}$ ~~= 5.33 units using Equation 10.39~~

$$P_{0,0} = 1/[(8/32)^2(1/2)(1/1 - 4/32) + (8/32)^0(1) + (8/32)^1(1)]$$

$$= 1/[(1/4)^2(1/2)(1/0.875) + 1 + (1/4)] = 1/[1.285]$$

$M_m = \dfrac{1}{1.285} \cdot \dfrac{(8/32)^3}{(1)(2 - 8/32)^2} = 3.97 \times 10^{-3}$ ~~units using a single channel~~

~~20) With~~ $X = 20/(20 + 160) = 0.111$ ~~mainimum cost is when 4 warehouse people are employed.~~

~~M~~	~~F~~	~~H~~	~~L~~	~~H+L~~	~~Waiting Cost~~	~~Service Cost~~	~~Total Cost~~
~~7~~	~~0.9989~~	~~3.326~~	~~0.033~~	~~3.359~~	~~$61.13~~	~~$74.55~~	~~$135.68~~
~~6~~	~~0.9967~~	~~3.319~~	~~0.099~~	~~3.419~~	~~62.23~~	~~63.90~~	~~126.13~~
~~5~~	~~0.9873~~	~~3.288~~	~~0.381~~	~~3.669~~	~~66.78~~	~~53.25~~	~~120.03~~
~~4~~	~~0.9570~~	~~3.187~~	~~1.290~~	~~4.477~~	~~81.48~~	~~42.60~~	~~124.08~~
~~3~~	~~0.8521~~	~~2.837~~	~~4.437~~	~~7.374~~	~~134.21~~	~~31.95~~	~~166.16~~
~~2~~	~~0.6000~~	~~1.998~~	~~12.000~~	~~13.998~~	~~254.76~~	~~21.30~~	~~276.06~~

~~21) With~~ $X = 18/(18 + 144) = 0.111$

~~M~~	~~F~~	~~H~~	~~L~~	~~H+L~~	~~Waiting Cost~~	~~Service Cost~~	~~Total Cost~~

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~~3~~	~~0.9968~~	~~1.106~~	~~0.032~~	~~1.138~~	~~$64.48~~	~~$126~~	~~$190.48~~
~~2~~	~~0.9734~~	~~1.080~~	~~0.266~~	~~1.346~~	~~76.27~~	~~84~~	~~160.27~~
~~1~~	~~0.7912~~	~~0.878~~	~~2.088~~	~~2.966~~	~~168.07~~	~~42~~	~~210.07~~

~~Lease 2 ramps for minimum cost.~~

~~22)~~

~~T~~	~~X~~	~~F~~	~~H~~	~~L~~	~~H+L~~	~~Waiting Cost~~	~~Service Cost~~	~~Total Cost~~
~~1~~	~~0.047~~	~~0.998~~	~~0.469~~	~~0.02~~	~~0.489~~	~~$4.89~~	~~$15.00~~	~~$19.89~~
~~2~~	~~0.090~~	~~0.986~~	~~0.887~~	~~0.14~~	~~1.027~~	~~10.27~~	~~7.50~~	~~17.77~~
~~3~~	~~0.139~~	~~9.958~~	~~1.245~~	~~0.42~~	~~1.665~~	~~16.65~~	~~5.00~~	~~21.65~~
~~4~~	~~0.166~~	~~0.914~~	~~1.517~~	~~0.86~~	~~2.377~~	~~23.77~~	~~3.75~~	~~27.52~~

~~Optimum service time is 2 minutes.~~

~~23) With $N = 30$, $U = 68$~~

~~T~~	~~$X = T/(T+U)$~~	~~F~~	~~$J = NF(1 - X)$~~	~~$H + L$~~	~~Waiting Cost/ Min.~~	~~Service Cost/Min.~~	~~Total Cost~~
~~1~~	~~0.0145~~	~~0.990~~	~~29.269~~	~~0.73~~	~~$0.34~~	~~$16.00~~	~~$16.34~~
~~2~~	~~0.0286~~	~~0.930~~	~~27.109~~	~~2.90~~	~~1.35~~	~~12.00~~	~~13.35~~
~~3~~	~~0.0423~~	~~0.768~~	~~22.060~~	~~7.93~~	~~3.70~~	~~9.00~~	~~12.70~~
~~4~~	~~0.0556~~	~~0.599~~	~~16.971~~	~~13.03~~	~~6.09~~	~~7.00~~	~~13.09~~

~~The minimum cost service interval is three minutes.~~

~~24) For $M = 1$~~

~~X~~	~~F~~	~~J~~	~~$N - J$~~	~~$\frac{(N-J)}{N}\times 100$~~
~~0.02~~	~~0.989~~	~~19.40~~	~~0.60~~	~~3.00%~~
~~0.03~~	~~0.968~~	~~18.80~~	~~1.20~~	~~6.00%~~
~~0.04~~	~~0.929~~	~~17.82~~	~~2.18~~	~~10.90%~~
~~0.05~~	~~0.866~~	~~16.46~~	~~3.54~~	~~17.70%~~
~~0.06~~	~~0.785~~	~~14.75~~	~~5.25~~	~~26.25%~~
~~0.07~~	~~0.699~~	~~13.00~~	~~7.00~~	~~35.00%~~
~~0.08~~	~~0.621~~	~~11.44~~	~~8.56~~	~~42.80%~~
~~0.09~~	~~0.554~~	~~10.10~~	~~9.90~~	~~49.50%~~
~~0.10~~	~~0.500~~	~~9.00~~	~~11.00~~	~~55.00%~~

~~For $M = 2$~~

~~X~~	~~F~~	~~J~~	~~$N - J$~~	~~$\frac{(N-J)}{N}\times 100$~~

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~~0.02~~	~~0.999~~	~~19.55~~	~~0.45~~	~~2.25%~~
~~0.04~~	~~0.994~~	~~19.10~~	~~0.90~~	~~4.50%~~
~~0.06~~	~~0.978~~	~~18.40~~	~~1.60~~	~~8.00%~~
~~0.08~~	~~0.941~~	~~17.30~~	~~2.70~~	~~13.50%~~
~~0.10~~	~~0.878~~	~~15.80~~	~~4.20~~	~~21.00%~~
~~0.12~~	~~0.793~~	~~13.95~~	~~6.05~~	~~30.25%~~
~~0.14~~	~~0.703~~	~~12.10~~	~~7.90~~	~~39.50%~~
~~0.16~~	~~0.22~~	~~10.45~~	~~9.55~~	~~47.75%~~
~~0.18~~	~~0.555~~	~~9.10~~	~~10.90~~	~~54.50%~~
~~0.20~~	~~0.500~~	~~8.00~~	~~12.00~~	~~60.00%~~

~~25)~~ $X = \frac{T}{T+U} = \frac{T}{U+15}$

~~$J = NF(1 - X) = 10F(1 - X)$; where F is from Table C.1 for various values of M and X~~

~~Service cost/Hour/Facility = \$60/T~~ ~~Service cost/Hour = (\$60/T)M~~

~~Gross profit/Hour = \$10(J)~~ ~~Net profit = Gross profit − Service cost~~

~~Set up a table to evaluate the net profit for different discrete values of M and T as shown:~~

~~*M*~~	~~*T*~~	~~*X*~~	~~*F*~~	~~*J*~~	~~Cost Per Fac~~	~~Gross Profit~~	~~Total Service Cost~~	~~Net Profit~~
~~1~~	~~1~~	~~0.0625~~	~~0.944~~	~~8.85~~	~~60~~	~~88.50~~	~~60~~	~~28.50~~
~~2~~	~~1~~	~~0.0625~~	~~0.996~~	~~9.34~~	~~60~~	~~93.40~~	~~120~~	~~−26.60~~
~~1*~~	~~2*~~	~~0.1176~~	~~0.766~~	~~6.76~~	~~30~~	~~67.60~~	~~30~~	~~37.60*~~
~~2~~	~~2~~	~~0.1176~~	~~0.969~~	~~8.55~~	~~30~~	~~85.50~~	~~60~~	~~25.50~~
~~3~~	~~2~~	~~0.1176~~	~~0.996~~	~~8.78~~	~~30~~	~~87.80~~	~~90~~	~~−2.20~~
~~1~~	~~3~~	~~0.1667~~	~~0.589~~	~~4.91~~	~~20~~	~~49.10~~	~~20~~	~~29.10~~
~~2~~	~~3~~	~~0.1667~~	~~0.911~~	~~7.59~~	~~20~~	~~75.90~~	~~40~~	~~35.90~~
~~3~~	~~3~~	~~0.1667~~	~~0.983~~	~~8.19~~	~~20~~	~~81.90~~	~~60~~	~~21.90~~
~~1~~	~~4~~	~~0.215~~	~~0.474~~	~~3.74~~	~~15~~	~~37.40~~	~~15~~	~~22.40~~
~~2~~	~~4~~	~~0.2105~~	~~0.835~~	~~6.59~~	~~15~~	~~65.90~~	~~30~~	~~35.90~~
~~3~~	~~4~~	~~0.2105~~	~~0.961~~	~~7.59~~	~~15~~	~~75.90~~	~~45~~	~~30.90~~
~~1~~	~~5~~	~~0.2500~~	~~0.400~~	~~3.00~~	~~12~~	~~30.00~~	~~12~~	~~18.00~~
~~2~~	~~5~~	~~0.2500~~	~~0.753~~	~~5.65~~	~~12~~	~~56.50~~	~~24~~	~~32.50~~
~~3~~	~~5~~	~~0.2500~~	~~0.929~~	~~6.97~~	~~12~~	~~69.70~~	~~36~~	~~33.70~~
~~1~~	~~6~~	~~0.2850~~	~~0.351~~	~~2.51~~	~~10~~	~~25.10~~	~~10~~	~~15.10~~
~~2~~	~~6~~	~~0.2859~~	~~9,682~~	~~4.88~~	~~10~~	~~48.80~~	~~20~~	~~28.80~~
~~3~~	~~6~~	~~0.2850~~	~~0.890~~	~~6.36~~	~~10~~	~~63.60~~	~~30~~	~~33.60~~
~~2~~	~~7~~	~~0.3180~~	~~0.617~~	~~4.21~~	~~8.57~~	~~42.10~~	~~17.14~~	~~24.95~~
~~3~~	~~7~~	~~0.3180~~	~~0.845~~	~~5.76~~	~~8.57~~	~~57.60~~	~~25.71~~	~~31.90~~

~~26) Comparison of two plans for preventative maintenance, do nothing or employ one maintenance technician.~~

~~Plan~~	~~*X*~~	~~% Not Running (Fig.~~	~~Machines Not Running~~	~~Cost of Lost Profit~~	~~Cost of Mechanic~~	~~Total Cost~~

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	~~10.9)~~					
~~Present~~	~~0.12~~	~~40~~	~~4.8~~	~~$24.96~~	~~$20.40~~	~~$45.36~~
~~Proposed~~	~~0.08~~	~~20~~	~~2.4~~	~~12.48~~	~~37.00~~	~~49.48~~

~~The economic disadvantage for the proposed preventive maintenance plan that would involve one technician is $4.12 per hour.~~

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~~CHAPTER 11~~

~~CONTROL CONCEPTS AND METHODS~~

~~1) Speed, the characteristic to be controlled, is measured by a well known sensory device called a speedometer and monitored by the automobile driver. Measured speed is compared to planned speed by the driver who activates the throttle to make the speed change needed to achieve the desired velocity.~~

~~2) An input fuel or electrical energy is utilized in a furnace to produce an output temperature (Block 1) which is measured by the thermometer component of a thermostat (Block 2). When a predetermined temperature is reached, an electrical circuit is broken (Block 3) shutting off a valve or switch altering the input (Block 4), allowing the temperature to decline. Refer to Figure 11.1 (page 324).~~

~~3) A cooking oven, set to bake for a predetermined time interval, is an example of open loop control. Closed loop control takes place in a human equipment test system checking the operational status of a signal processor that must conform to a certain output specification within a predetermined tolerance over time. Reference: Section 11.1.2 (page 324).~~

~~4) An unstable pattern of variation exists when the *parameters* of the statistical distribution describing the operation have changed. Control limits enable a **hypothesis test regarding a change in the values of underlying parameters** by sampling, subject to a Type I error (sample outside limits) or a Type II error (sample inside limits).~~

~~5) Utilizing the factors in Table 11.2, page 329:~~

~~$UCL_x = \bar{X} + A_2\bar{R} = 0.025 + 0.308(0.002)$ = 0.02562~~

~~$LCL_x = \bar{X} - A_2\bar{R} = 0.025 - 0.308(0.002)$ = 0.02438~~

~~$UCL_R = D_4\bar{R} = 1.777(0.002)$ = 0.003554~~

~~$LCL_R = D_3\bar{R} = 0.223(0.002)$ = 0.000446~~

~~6) Utilizing the factors in Table 11.2, page 329~~

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~~(a) UCL_x = 44.125 + 0.577(6) = 47.587~~
~~LCL_X = 44.125 − 0.577(6) = 40.663.~~
~~(b) UCL_R = 2.115(6) = 12.690~~
~~LCL_R = 0~~

~~7) Sketch not given. Calculate $\sigma = \bar{R}/d_2$ = 6/2.326 = 2.58~~

~~$Z = (X - \bar{\bar{X}}/\sigma)$ = (42 44.125)/2.58 = 0.8236~~

~~Proportion defective = the area from ∞ to 0.8236σ = 20.52%~~

~~8) $\bar{p}$ = 15,998/112,708 = 0.1419~~

~~$3s_p = 3\sqrt{\bar{p}(1-\bar{p})/n} = (3\sqrt{0.1419 \times 0.8581})/\sqrt{n} = 1.169/\sqrt{n}$~~

~~Weekend~~	~~P~~	~~$3s_p$~~	~~$UCL_P = \bar{p} + 3s_p$~~
~~23~~	~~0.1342~~	~~0.0156~~	~~0.1575~~
~~24~~	~~0.1231~~	~~0.0153~~	~~0.1572~~
~~25~~	~~0.1270~~	~~0.0159~~	~~0.1578~~
~~26~~	~~0.1311~~	~~0.0168~~	~~0.1587~~
~~27~~	~~0.1324~~	~~0.0168~~	~~0.1587~~
~~28~~	~~0.1569~~	~~0.0174~~	~~0.1593~~
~~29~~	~~0.1395~~	~~0.0165~~	~~0.1584~~
~~30~~	~~0.1436~~	~~0.0169~~	~~0.1588~~

~~9) $\bar{c}$ = 138/20 = 6.9~~

~~$s_c = \sqrt{6.9}$ = 2.627~~

~~$UCL_c = \bar{c} + 3s_c$ = 6.9 + 7.881 = 14.781~~

~~Days 9 and 13 appear to indicate an out of control situation. But to declare so might produce a Type I error.~~

~~10) $\bar{c}$ = 378/30 = 12.6~~

~~$s_c = \sqrt{12.6}$ = 3.55~~

~~$UCL_c = \bar{c} + 3s_c$ = 12.6 + 10.65 = 23.25~~

~~$UCL_c = \bar{c} + 3s_c$ = 12.6 10.65 = 1.95~~

~~There is no evidence in these data of an assignable cause of variation.~~

~~11) Proceed as in Table 11.6 on page 338.~~

~~n~~	~~P_n/P_o~~	~~P_n~~	~~$\sum P_n$~~
~~0~~	~~1.00000~~	~~0.00472~~	~~0.00472~~
~~1~~	~~1.80000~~	~~0.00135~~	~~0.00607~~
~~2~~	~~7.28000~~	~~0.00345~~	~~0.00952~~

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~~3~~	~~17.47200~~	~~0.00826~~	~~0.01778~~
~~4~~	~~38.43841~~	~~0.01814~~	~~0.03592~~
~~5~~	~~76.87680~~	~~0.03625~~	~~0.07217~~
~~6~~	~~138.37825~~	~~0.06520~~	~~0.13737~~
~~7~~	~~221.40519~~	~~0.10433~~	~~0.24170~~
~~8~~	~~309.96725~~	~~0.14605~~	~~0.38775~~
~~9~~	~~371.96070~~	~~0.17525~~	~~0.56300~~
~~10~~	~~371.96070~~	~~0.17525~~	~~0.73825~~
~~11~~	~~297.46586~~	~~0.14015~~	~~0.87840~~
~~12~~	~~174.44514~~	~~0.08221~~	~~0.96061~~
~~13~~	~~69.77805~~	~~0.03291~~	~~0.99352~~
~~14~~	~~13.95561~~	~~0.00644~~	~~0.99996~~
	~~2113.18396~~		

~~It is required that P (Type I error) be less than or equal to 0.05~~

~~Therefore, $\sum P_n = 0.95$ and, from inspection of the table, $UCL = 12$~~

~~12) There are two Critical Paths in the network shown at the bottom of page 356. They are: 1 4 6 8 10 11 and 1 4 7 8 10 11. Both exhibit a value of 30.~~

~~13) (a) Network not given. Refer to the Activity / Completion Time table on page 357 and draw the requested network.~~

~~(b)~~

~~Event~~	~~T_E~~	~~T_L~~	~~S~~
~~A~~	~~0~~	~~0~~	~~0~~
~~B~~	~~5~~	~~5~~	~~0~~
~~C~~	~~6~~	~~7~~	~~1~~
~~D~~	~~3~~	~~13~~	~~10~~
~~E~~	~~15~~	~~15~~	~~0~~
~~F~~	~~16~~	~~17~~	~~2~~
~~G~~	~~17~~	~~17~~	~~0~~
~~H~~	~~23~~	~~23~~	~~0~~

~~(c) The Critical Path is $A \to B \to E \to G \to H$ and the shortest completion time is 23 weeks.~~

~~14) Even though the earliest time for D changes to 6 weeks from 3, the Critical Path remains unchanged.~~

~~15) (a) Network not shown. The Critical Path is $A \to B \to C \to E \to F$.~~

~~(b) The earliest program completion time under normal conditions is 27 weeks.~~

~~(c)~~

~~Crash Schedule~~	~~Reduction in Weeks~~	~~Critical Path~~

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~~25 week~~	~~2 weeks in *CE*~~	~~$A \rightarrow B \rightarrow C \rightarrow E \rightarrow F$~~
~~23 week~~	~~2 weeks in *AB*~~	~~$A \rightarrow B \rightarrow C \rightarrow E \rightarrow F$~~
~~20 week~~	~~3 weeks in *EF*~~	~~$A \rightarrow B \rightarrow C \rightarrow E \rightarrow F$~~
~~17 week~~	~~3 weeks in *BC*~~	~~$A \rightarrow B \rightarrow C \rightarrow E \rightarrow F$~~

~~The Critical Path remains unchanged as above and no more time reductions are possible without altering it from $A \rightarrow B \rightarrow C \rightarrow E \rightarrow F$.~~

~~Crash Schedule~~	~~Crash Cost~~	~~Overhead Saved~~	~~Net Saving~~
~~25 week~~	~~$400~~	~~$2,200~~	~~$1,800~~
~~23 week~~	~~2,400~~	~~4,400~~	~~2,000~~
~~20 week~~	~~6,700~~	~~7,700~~	~~1,000~~
~~17 week~~	~~15,700~~	~~11,000~~	~~–4,700~~

~~The 23 week schedule yields a minimum cost (a maximum net saving).~~

~~16) (a) Network not shown.~~

~~(b) The Critical Path is $A or B \rightarrow C \rightarrow D \rightarrow F \rightarrow G$. This gives the shortest completion time to be 21 weeks under normal schedule.~~

~~(c) Normal is the 21 week schedule with a penalty cost of $5,000.~~

~~A Nineteen-Day Schedule is obtainable by reducing 2 weeks on *DE* at a crash cost of $120. The penalty cost = $2,500. An Eighteen Day Schedule is obtainable by reducing 3 weeks on *DE* and 1 week on *EF* at a crash cost of $350. The penalty cost = $1,250.~~

~~No more reductions result in a shorter completion time for the project. This is the minimum cost schedule.~~

~~17) Refer to Section 11.5.2 on page 346 and Table 11.11 on page 348 to tabulate:~~

~~Event~~	~~Previous Event~~	~~*a*~~	~~*m*~~	~~*b*~~	~~t_θ~~	~~σ^2~~	~~*TE*~~	~~*TL*~~	~~*TL – TE*~~
~~11~~	~~10~~	~~10~~	~~12~~	~~16~~	~~12.3~~	~~1.00~~	~~47.0~~	~~47.0~~	~~0~~
	~~9~~	~~6~~	~~8~~	~~14~~	~~8.6~~	~~1.78~~			
	~~8~~	~~2~~	~~6~~	~~10~~	~~6.0~~	~~1.78~~			
	~~6~~	~~9~~	~~13~~	~~15~~	~~12.6~~	~~1.00~~			
~~10~~	~~9~~	~~5~~	~~8~~	~~10~~	~~7.8~~	~~0.69~~	~~34.7~~	~~34.7~~	~~0~~
	~~7~~	~~7~~	~~9~~	~~11~~	~~9.0~~	~~0.44~~			
~~9~~	~~7~~	~~10~~	~~14~~	~~20~~	~~14.2~~	~~2.77~~			
	~~6~~	~~2~~	~~8~~	~~10~~	~~7.3~~	~~1.78~~	~~26.9~~	~~26.9~~	~~0~~

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~~8~~	~~6~~ ~~5~~	~~10~~ ~~4~~	~~12~~ ~~7~~	~~16~~ ~~11~~	~~12.3~~ ~~7.1~~	~~1.00~~ ~~1.36~~	 ~~21.7~~	 ~~41.0~~	 ~~19.3~~
~~7~~	~~4~~	~~5~~	~~5~~	~~10~~	~~5.8~~	~~0.69~~	~~12.3~~	~~17.7~~	~~5.4~~
~~6~~	~~4~~ ~~3~~	~~11~~ ~~1~~	~~13~~ ~~2~~	~~16~~ ~~4~~	~~13.1~~ ~~2.1~~	~~0.69~~ ~~0.25~~	~~19.6~~	~~19.6~~	~~0~~
~~5~~	~~3~~ ~~2~~	~~6~~ ~~2~~	~~8~~ ~~5~~	~~12~~ ~~10~~	~~8.3~~ ~~5.3~~	~~1.00~~ ~~1.78~~	~~13.6~~	~~33.9~~	~~20.3~~
~~4~~	~~1~~	~~5~~	~~6~~	~~10~~	~~6.5~~	~~0.69~~	~~6.5~~	~~6.5~~	~~0~~
~~3~~	~~1~~	~~3~~	~~5~~	~~9~~	~~5.3~~	~~1.00~~	~~5.3~~	~~27.5~~	~~22.2~~
~~2~~	~~1~~	~~4~~	~~6~~	~~8~~	~~6.0~~	~~0.44~~			

~~The Critical Path is 1–4–6–9–10–11 and the second most Critical Path is 1–4–7–9–10–11.~~

~~18) The Critical Path is determined to be 1–2–4–5–7–9–10, from which~~

~~*Z* from (*TL*–*TE*) /~~ $\sqrt{\text{sum of variances}}$ ~~=~~

~~(50.0 – 45.1) /~~ $\sqrt{0.69+0.25+0.44+0.44+0.11+1.0}$ ~~= 2.86~~

~~From Appendix D, Table D.3 on page 736, the probability of meeting the schedule time is 0.9979~~

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~~CHAPTER 12~~

~~DESIGN FOR RELIABILITY~~

~~1) *Reliability* may be simply defined as the “probability that a system or product will perform its designated mission in a satisfactory manner for a given period of time when used under specified operating conditions.” Inherent within this definition are the elements of **probability**, **satisfactory performance**, **time or mission related cycle**, and **specified operating conditions**. *Probability* is the fraction or percent of time that the system is available and is operating satisfactory. *Satisfactory performance* is the level of performance required for the system to successfully fulfill its mission requirements. *Time* is the measure against which the degree of performance can be related. *Specified operating conditions* refer to the overall environment in which the system is required to perform its intended function. Common measures include MTBF, MTTF, *R*, and failure rate (lambda). Reference: Section 12.1 (page 363).~~

~~2) Reliability must be considered as an inherent characteristic of design, and it is a key factor in determining whether or not the system will be able to perform its mission upon deployment and utilization; i.e., it dictates the length of time that the system will continue to perform in a satisfactory manner. The requirement for reliability, stated in terms of some design to **performance** measure (MTBF, MTTF, *R*, or failure rate), must be considered early during the conceptual design phase when the overall system level requirements are defined; i.e., from problem definition and needs analysis, feasibility analysis, operational requirements, and the definition of the maintenance concept. Reliability requirements must then be addressed throughout the system life cycle process through requirements allocation, the accomplishment of design trade offs, design review and evaluation, reliability test and system validation, and reliability assessment when the system is operating in the field.~~

~~The degree of reliability emphasis will vary depending on the type and complexity of the system and its mission. In some instances, reliability in design should be addressed on a level with many other performance related parameters; in other instances reliability in design will receive a greater degree of emphasis (e.g., space systems where the accomplishment of maintenance to meet an availability requirement is not possible.) Reference: Section 12.3 (page 374).~~

~~3) Mean time between failure (MTBF), mean time to failure (MTTF), reliability (*R*), failure rate (lambda), mean operating cycles between failure, failures per module of software, failures per line item of software code, personnel-induced failures per operating cycle, and so on. Reference: Section 12.2 (page 364).~~

~~4) When addressing *failure rate* from a total “systems” perspective, there are a number of factors that need to be considered; i.e., equipment failures, software failures, facility failures, personnel-induced failures, process failures, failures in information flow, failures per item of data, and so on. While the concentration is often on just equipment failures, all~~

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~~of the factors listed in Table 12.1 (page 370) should be considered. Reference: Section 12.2.2 (page 366).~~

~~5) Refer to Figure 12.4 (page 368). The assumption, for most instances in the past, is that the failure rate follows the exponential distribution and is relatively constant as shown by the flat portion of the "bathtub" curve. Many of the early predictions, providing an estimate of the MTBF, were related to electronic equipment, and the "bathtub" curve in the upper part of the figure was assumed as being representative of a "real world" condition. Given such, if the system/equipment is delivered early during the "infant mortality" period, the failure rate will likely be higher than originally predicted, and the resources required to support maintenance activities will be consumed earlier than initially planned. At the other end of the "bathtub" curve, the failure rate will increase as equipment/component wear-out and degradation take place. To extend the useful life (and shift the wear-out portion of the curve further out in time), it may be necessary to accomplish some preventive maintenance by replacing certain short term critical components at a point in time before a failure would normally occur. The objective is, of course, to maintain the desired level of reliability for a longer period of time. In sustainability terms, this leads to less environmental impact from delaying disposal. Reference: Section 12.2.2 (page 366).~~

~~6) Refer to Figure 12.5 (page 369). The continuing incorporation of software changes and modifications (upgrading for whatever reason), the ongoing maintenance of software, etc., often results in a reliability problem as failures are being introduced constantly. Reference: Section 12.2.2 (page 366).~~

~~7) $R_S = (R_A)(R_B)(R_C)(R_D)$~~

~~$R_S = (0.98)(0.85)(0.90)(0.88) = 0.6597$~~

~~8) $R_S = [1 - (1 - R_A)(1 - R_B)(1 - R_C)]$~~

~~$R_S = [1 - (1 - 0.98)(1 - 0.85)(1 - 0.88)]$~~

~~$R_S = [1 - (0.02)(0.15)(0.12)] = 0.99964$~~

~~9) Determine $R_{CD} = R_C + R_D - (R_C)(R_D) = 0.9952$~~

~~$R_{EF} = R_E + R_F - (R_E)(R_F) = 0.9880$~~

~~$R_{ABCDEF} = (R_A)(R_B)(R_{CD})(R_{EF}) = 0.90607$~~

~~$R_{ABCDEFG} = R_{ABCDEF} + R_G - (R_{ABCDEF})(R_G)$~~

~~$R_{SYSTEM} = 0.90607 + 0.98 - (0.90607)(0.98) = 0.99812$~~

~~10) MTBF = $\frac{n}{\lambda}$ and $n = 3$; then MTBF = $\frac{3}{\lambda}$~~

~~Convert the failure rate to failures per hour~~

~~MTBF = $\frac{3}{22\times 10^{-6}} = \frac{3\times 10^{6}}{22}$ = 136,364 hours~~

~~11) With one unit in standby~~

~~$R = e^{-\lambda t} + (\lambda t)e^{-\lambda t}$ or~~

~~$R = e^{-\lambda t}[1+\lambda t]$, where $\lambda t = (0.003)(200) = 0.6$~~

~~$R = e^{-0.6}[1+0.6]$, and $e^{-0.6} = 0.54881$~~

~~$R = 0.54881(1.6) = 0.878096$~~

~~12) Determine individual failure rates:~~

~~$\lambda_A = \frac{1}{10,540}$ = 0.0000949 failures per hour~~

~~$\lambda_B = \frac{1}{16,220}$ = 0.0000617 failures per hour~~

~~$\lambda_C = \frac{1}{9,500}$ = 0.0001053 failures per hour~~

~~$\lambda_D = \frac{1}{12,100}$ = 0.0000826 failures per hour~~

~~$\lambda_E = \frac{1}{3,600}$ = 0.0002778 failures per hour~~

~~The reliability (or probability of survival) of the series network is~~

~~$R = e^{-(\sum\lambda)(1,000)} = e^{-(0.0006223)(1,000)}$~~

~~$R = e^{-0.6223} = 0.53687$~~

~~13)~~

~~$\lambda = \frac{4\text{ failures}}{(1\times 30)+(1\times 85)+(1\times 220)+(1\times 435)+(6\times 500)}$~~

~~$\lambda = \frac{4}{3,770}$ = 0.001061 failures/hours~~

~~14) MTBF =~~ $\frac{1}{44.193\%/1000\text{ hrs}}$ ~~= 2,262.80~~

~~15) Configuration "A"~~

~~R_{BC} = (0.86) (0.89) = 0.7654~~

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~~R_{DE} = (0.86)(0.87) = 0.7482~~
~~R_{BCDE} = 0.7654 + 0.7482 – (0.7654)(0.7482) = 0.9409~~
~~R_{GH} = 0.87 + 0.88 – (0.87)(0.88) = 0.9844~~
~~$R_{BCDEFGHI}$ = (0.9409)(0.82)(0.9844)(0.89) = 0.6759~~
~~R_{KL} = 0.85 + 0.86 – (0.85)(0.86) = 0.9790~~
~~R_{OPQ} = 1 – [(1 – 0.84)(1 – 0.89)(1 – 0.89)] = 0.9981~~
~~$R_{JKLMNOPQ}$ = (0.86)(0.9790)(0.83)(0.85)(0.9981) = 0.5929~~
~~$R_{BCDEFGHIJKLMNOPQ}$ = 0.6759 + 0.5929 – (0.6759)(0.5929) = 0.8681~~
~~$R_S = (R_A)(R_{BCDEFGHIJKLMNOPQ})$ = (0.84)(0.8681) = 0.7292~~

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~~Configuration "B"~~

~~R_{CD} = 0.89 + 0.86 – (0.89)(0.86) = 0.9846~~

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~~R_{HIJ} = 1 – [(1 – 0.88)(1 – 0.89)(1 – 0.86)] = 0.9982~~
~~R_{KLM} = 1 – [1 – 0.85)(1 – 0.86)(1 – 0.83)] = 0.9964~~
~~R_{CDFG} = (0.9846)(0.82)(0.87) = 0.7024~~
~~R_{EHIJ} = (0.87)(0.9982) = 0.8683~~
~~$R_{CDFGEHIJ}$ = 0.7024 + 0.8683 – (0.7024)(0.8683) = 0.9608~~
~~$R_{CDFGEHIJKLM}$ = (0.9608)(0.9964) = 0.9573~~
~~R_{NO} = (0.85)(0.84) = 0.7140~~
~~$R_{CDFGEHIJKLMNO}$ = 0.7140 + 0.9573 – (0.7140(0.9573) = 0.9878~~
~~R_S = (0.84)(0.86)(0.9878) = 0.7136~~

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~~Configuration "C"~~

~~R_{BC} = (0.86)(0.89) = 0.7654~~

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~~R_{DE} = (0.86)(0.87) = 0.7482~~
~~R_{BCDEF} = 1 – [(1 – 0.82)(1 – 0.7654)(1 – 0.7482)] = 0.9894~~
~~R_{HI} = 0.88 + 0.89 – (0.88)(0.89) = 0.9868~~
~~R_{HIJ} = 0.9868 + 0.86 – (0.9868)(0.86) = 0.9982~~
~~R_{GK} = (0.87)(0.85) = 0.7395~~

~~$R_{BCDEFHIJ} = (0.9894)(0.9982) = 0.9876$~~

~~$R_{BCDEFHIJGK} = 0.9876 + 0.7395 - (0.9876)(0.7395) = 0.9968$~~

~~$R_{MN} = 0.83 + 0.85 - (0.83)(0.85) = 0.9745$~~

~~$R_S = (0.84)(0.9968)(0.86)(0.9745) = 0.7017$~~

~~Cost effectiveness for “A” = $\frac{0.7437}{\$42,000} = 0.0000177$~~

~~Cost effectiveness for “B” = $\frac{0.7136}{\$39,000} = 0.0000182$~~

~~Cost effectiveness for “C” = $\frac{0.7017}{\$57,000} = 0.0000123$~~

~~Select Configuration “B” (given that $R \geq 0.70$)~~

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~~16) The selection of common and standard components in design; selection of components with a long shelf life; incorporation of redundancy at the right level in design; incorporation of fail-safe provisions in the event of failure; application of “derating” methods in design (where a component may be selected and utilized in a “less-than-rated-value” application) to improve reliability; elimination of adjustable components in design; incorporation of modularization in design; incorporation of the essential environmental provisions within and between system components; elimination of any critical useful-life items in design; and so on. Reference: Sections 12.3.4 (page 380) and.12.3.5 (page 381).~~

~~17) A *reliability model* constitutes a description of the system in “functional” terms, identifies functional relationships and interfaces, and is used for the purposes of accomplishing a reliability allocation, reliability prediction, stress-strength analysis, and ultimately a reliability assessment. The model is usually developed from the system-level functional analysis (refer to Section 3.7 on page 86 and Section 4.3.1 on page 104), and may take the form of a functional flow block diagram (FFBD) such as illustrated in Figure 12.12 (page 378). Reference: Section 12.3.2 (page 377).~~

~~18) Reliability requirements at the *system* level should be defined as part of the system operational requirements and the maintenance concept (refer to Section 3.4 on page 61 and Section 3.5 on page 76, respectively). These requirements must be identified and related to one or a set of mission scenarios that are to be accomplished to meet the stated system need. Such requirements are then integrated and prioritized, along with other system-level requirements, through application of the QFD (or equivalent) process described in Section 3.6 (page 82 – also see Figure 3.17 on page 83). Reliability requirements at the *sub-system* level, *unit* level, and below are developed through the allocation process described in Sections 3.7.2 (page 91), 4.3.2 (page 105), and 12.3.3 (page 377). Reference: Section 12.3.1 (page 376) and Section 12.3.3 (page 377).~~

~~19) To improve the reliability of a system/product, it may be necessary to incorporate some *redundancy* in design. Redundancy, which can be applied at different levels in the system hierarchical structure, is accomplished by providing two or more functional “operating”~~

~~paths (or channels of operation) in areas that are critical for successful mission accomplishment. If one of the paths should fail for any reason, then an alternative path would be available in order for the system to continue its operation as intended. There are different categories of redundancy to include "active" redundancy (where if a failure occurs there will be an automatic switching of the function to another path) and "standby" redundancy (where in the event of failure one can switch to an alternative path but requiring a manually approach involving a human action to accomplish such). The application (whether "active" or "standby" redundancy is incorporated in the design) will depend on issues of "criticality" from a mission accomplishment perspective. In any event, the benefits obtained through redundancy include increased reliability. On the other hand, by incorporating redundancy, the system may require more components, extra space, added weight, added cost, and so on, which constitute some of the negative aspects. Reference: Section 12.3.5 (page 381).~~

~~20) Refer to Section 12.4 (pages 394–396):~~

~~(a) The *failure mode, effects, and criticality analysis (FMECA)* is a design technique (or analysis tool) that can be applied in the evaluation of a given system design configuration for the purposes of identifying design weaknesses. It includes the necessary steps for examining ways in which a system failure can occur, the particular modes of failure, causes of failure, potential effects of failure on system operation, anticipated frequency of occurrence, criticality of failure, and recommendations for corrective action. The FMECA can be applied early in the preliminary system design phase from a "functional" perspective, later on in the design and development process in evaluating equipment and other elements of the system, and downstream in the life cycle for the purposes of measurement and evaluation. Reference: Section 12.4.1 (page 385).~~

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~~(b) The *fault–tree analysis (FTA)* is an analytical and graphical method, used in early design evaluation, to determine different ways in which a system failure can occur and the anticipated frequency of such. It utilizes a mathematical approach in identifying the more critical symptoms of failure, developing a fault–tree structure, and "driving down" to the cause(s) and the frequency of such. It is much narrower in focus and scope than the FMECA, can be accomplished more expeditiously and economically, and can be applied early in the design process. A prime application is in conjunction with the safety/hazard analysis and the identification of "critical" failures early. On the other hand, the FTA is not as comprehensive as the FMECA, and not as complete in a total design evaluation effort. Both the FMECA and the FTA can be applied in a complementary manner. Reference: Section 12.4.2 (page 390).~~

~~(c) A *stress–strength analysis* is accomplished to assess the reliability of a system/product when utilized under conditions where additional stresses or material strength characteristics are being imposed. Quite often when additional stresses (above normal conditions) are added, unexpected failures may occur and the reliability of the system/product will be less than anticipated. The purpose of the analysis is to identify potential weaknesses and to improve the design to preclude early failures of this type. Reference: Section 12.4.3 (page 394).~~

~~(d) *Reliability prediction* is accomplished at various stages in and throughout the system design and development process to determine whether or not the design configuration at the time is likely to be in compliance with the reliability requirements that were specified in the beginning. For example, if a MTBF of 450 hours was initially specified as a firm design requirement from the beginning, one may wish to accomplish a "prediction" at various follow-on stages in the evolutionary design process to determine just how well the configuration (evaluated at the time) will meet the 450 hours (or better). If, from a prediction, it appears that the ultimate MTBF will be less than 450 hours, then corrective action will be needed to improve the situation in a timely manner (versus learning about a design problem later on when the potential cost of re-design is likely to be much greater). Reference: Section 12.4.4 (page 394).~~

~~(e) *Reliability growth analysis* is accomplished when a reliability prediction indicates that the specified MTBF (or equivalent requirement) is too low and that the ultimate design requirement will not be met. Given such, an analysis needs to be accomplished with the objective of determining just what needs to be done in design in order to improve system reliability and resulting in an increase in the MTBF. There may be a series of steps involving a design modification, a measurement, another design modification, and so on, until the required MTBF is realized. The results of the analysis and associated plan are illustrated in Figure 12.23 (page 397). Also, refer to the response for Question 22 below. Reference: Section 12.4.5 (page 396).~~

~~21) Student exercise. Refer to Section 12.4.1 (page 385) and the process illustrated in Figure 12.17 (page 387).~~

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~~22) One should accomplish a *reliability growth analysis* and develop and implement a *reliability growth plan* of some type (refer to Figure 12.23, page 397). Through past experience, one should be able to identify potential areas of weakness and be able to predict ways in which system design can be improved over time by accomplishing certain actions. Given this, the system configuration with a 400-hour MTBF should be evaluated, the areas that "cause" (contribute to) the low MTBF should be identified, possible ways for improvement should be considered, the appropriate modification(s) should be incorporated, the system should be re-tested, and hopefully the results will indicate a reliability improvement. This process can be repeated continuously until the required 500-hour MTBF is realized. The FMECA can be utilized as an aid in determining "cause-and-effect" relationships and reliability predication can be applied relative to assessing the reliability MTBF for a current design configuration. This iterative process is often referred to as a *test, analyze, and fix (TAAF)* approach. Reference: Section 12.4.5 (page 396).~~

~~23) As the requirements for the system (to include the requirements for reliability) are first determined during the conceptual design phase, one needs to determine just how the system will be evaluated at a later time to ensure that these previously-defined requirements have been met. Thus, the requirements for reliability testing are initially identified in conceptual design and included in the test and evaluation master plan (TEMP) – refer to Figure 2.4 (page 34), Section 3.4 (page 61), and Section 6.3 (page 157). As the design process evolves, reliability analyses and predictions are accomplished to assess current status with regard to the initially specified requirements, and finally "validation" is accomplished by~~

~~conducting various reliability tests as described in Sections 6.1 (page 151), 6.2 (page 153), and 6.5 (page 162). Validation is basically accomplished through a combination of Type 2 and Type 3 testing, described in Section 6.2.3 (page 154) and Section 6.2.4 (page 156). Reference: Section 12.5 (page 396).~~

~~24) In *sequential testing*, if the system/equipment being tested is highly reliable, the amount of testing (and the associated costs) could turn out to be much less than for a system/equipment where the reliability is marginal. Referring to Figure 12.24 (page 398), a desired goal in sequential is to enter into the “accept” region as early as possible. A disadvantage would pertain to the time and costs associated with testing that results in either truncation (at the end of the “continue to test” region) or in the “reject” region. Also, refer to Figure 12.27 (page 402). Reference: Section 12.5.1 (page 397).~~

~~*Life testing*, usually applied at the component level, refers to the selection of “questionable” and/or “critical” components and the subsequent operation of these components (in a realistic environment and under normal stress conditions) for a designated period of time equivalent to the projected “life” of these components. Reference: Section 12.5.3 (page 403).~~

~~*Accelerated testing* is testing under extreme (or higher level) stressed conditions. In conducting a test of a component with a high reliability, just testing the component under normal conditions may take a long time, particularly if the test continues until the first failure occurs. The question is—how can one shorten the duration of the test and still verify the reliability of the component? By adding more stresses, which can be equated to “x” years of life, one may be able to acquire the same desired results in a shorter period of time and at less cost. Reference: Section 12.5 (pages 396–403).~~

~~25) Accomplishing a sequential test on a “sampling” basis, throughout the production process, may be required to ensure that the same reliability characteristics are inherent and built into each of the items being produced. The sample may be based on a percentage of the total items being produced over the entire period of production, or a set number of items selected during a given time period. Even though reliability qualification testing has been accomplished successfully on a pre-production prototype as part of Type 2 testing, one needs to ensure that all of the “like” models being produced subsequently are equally as reliable. Reference: Section 12.5.2 (page 403).~~

~~26) *Producer's risk* is the probability of rejecting a system as a result of testing when the measured MTBF is equal to or better than the specified MTBF. *Consumer's risk* is the probability of accepting a system as a result of testing when the measured MTBF is less than the specified MTBF. Reference: Section 12.5.1 (page 399).~~

~~27)~~

~~Component~~	~~Original~~		~~Redesigned~~		~~Redesign Cost~~	~~Failure Rate Reduction~~	~~Cost Effectiveness Times 10^9~~	~~Redesign Priority~~
	~~MTBF~~	~~Failure Rate~~	~~MTBF~~	~~Failure Rate~~				

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~~1~~	~~9,100~~	~~0.000110~~	~~45,500~~	~~0.000022~~	~~$1,000~~	~~0.000088~~	~~88~~	~~1~~
~~2~~	~~12,500~~	~~0.000080~~	~~62,500~~	~~0.000016~~	~~$2,000~~	~~0.000064~~	~~32~~	~~3~~
~~3~~	~~5,000~~	~~0.000200~~	~~25,000~~	~~0.000040~~	~~$3,000~~	~~0.000160~~	~~53~~	~~2~~
~~4~~	~~14,300~~	~~0.000070~~	~~71,400~~	~~0.000014~~	~~$4,000~~	~~0.000056~~	~~14~~	~~4~~
~~5~~	~~25,000~~	~~0.000040~~	~~125,000~~	~~0.000008~~	~~$5,000~~	~~0.000032~~	~~6.4~~	~~5~~
~~System~~	~~2,000~~	~~0.000500~~	~~10,000~~	~~0.000010~~	~~$15,000~~			

~~Redesign Priority~~	~~Component~~	~~Cumulative MTBF~~	~~Cumulative Failure Rate~~	~~Cumulative Reliability~~	~~Cumulative Cost~~	~~Decision Criterion~~
~~0~~		~~2,000~~	~~0.000500~~	~~0.606~~	~~0~~	~~Reliability if no components are redesigned~~
~~1~~	~~1~~	~~2,427~~	~~0.000412~~	~~0.662~~	~~$1,000~~	
~~2~~	~~3~~	~~3,968~~	~~0.000252~~	~~0.777~~	~~$4,000~~	
~~3~~	~~2~~	~~5,319~~	~~0.000188~~	~~0.829~~	~~$6,000~~	~~Component redesign to achieve reliability of at least 0.8~~
~~4~~	~~4~~	~~7,576~~	~~0.000132~~	~~0.876~~	~~$10,000~~	~~Reliability obtainable for a maximum of $10,000~~
~~5~~	~~5~~	~~10,000~~	~~0.000100~~	~~0.905~~	~~$15,000~~	~~Reliability if all components are redesigned~~

~~The authors gratefully acknowledge that problem 27 and its solution were contributed by Professor Scott Jackson of the University of Southern California.~~

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~~CHAPTER 13~~

~~DESIGN FOR MAINTAINABILITY~~

~~1) *Maintainability* is a design characteristic dealing with the ease, accuracy, safety, and economy in the performance of maintenance functions. Maintainability is the *ability* of a system/product to be maintained, whereas *maintenance* constitutes a series of actions to be taken to restore or retain a system/product in an effective operating state. Maintainability is a design characteristic (design dependent parameter), while maintenance is the result of design. Maintainability can be expressed in terms of maintenance times, maintenance labor hour factors, maintenance frequency factors, and maintenance cost. Specific design objectives include maximum accessibility, maximum standardization, good functional packaging and modularization, good interchangeability, effective diagnostics, optimum levels of reparability, good labeling, and so on. Reference: Section 13.1 (page 411).~~

~~2) Good maintainability in design is necessary for the minimization of the need for maintenance (frequency, time, labor hours, and resources required), and for lower life-cycle cost. Maintainability, like reliability, must be addressed from the beginning, during the conceptual design phase where the greatest impact on availability and life-cycle cost can be realized. Refer to Figure 2.12 (page 49). Reference: Section 13.4 (page 429).~~

~~3) The measures of maintainability include~~ $\overline{M}ct$, ~~-~~▯Mct, $\overline{M}pt$, ~~-~~▯Mpt, $\overline{M}$, ~~Mmax, ADT, LDT, MDT, MLH/OH, MTBR, MTBM, and Maintenance Cost (\$). These factors, which reflect downtime, labor hours, and frequency, can be applied to hardware, software, people, and the system as an entity (or any element thereof). For software, such factors can be aligned to a given module of software or a software program (time and frequency of maintenance) or personnel labor hours per module/program, number of lines of code, and so on. Reference: Section 13.2 (pages 412–426).~~

~~4) MTBF is the "mean time between failure" and often includes only "primary" and "secondary" failures, although all failure factors should really be included (refer to Table 12.1, page 370). MTBM is the "mean time between maintenance" for ALL maintenance actions and may be broken down into MTBMu (for unscheduled maintenance) and MTBMs (for scheduled maintenance). MTBMu should equate to MTBF **if** all of the factors in Table 12.1 are included in the MTBF factor. MTBR includes only those maintenance actions which result in a "removal and replacement" action, and may include both scheduled and unscheduled replacements. Reference: Section 12.2.2 (page 366), and Section 13.2.3 (page 423).~~

~~5) (a) The range of observation is 47 – 11 = 36 minutes.~~

~~(b) The number of class intervals is the range of observation divided by the class interval width, or 36 ÷ 4 = *9 intervals*. The distribution as illustrated has a *log normal pattern*.~~

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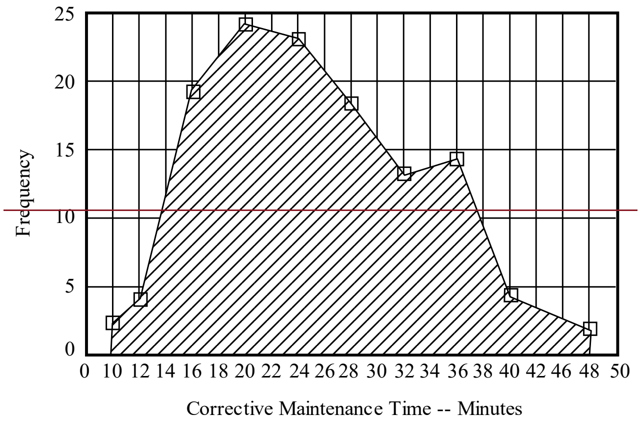

~~(c) The mean corrective maintenance time ($\overline{M}ct$) is (using Equation 13.1, page 415):~~

$$\overline{M}ct = \frac{\sum_{i=1}^{n} Mct_i}{n} = \frac{\cancel{3.169}}{126}$$ ~~= 25.151, or $\overline{M}ct \cong 25$ minutes.~~

~~(d) Calculation for Mct, (Equation 13.6, page 420):~~

~~Mct_i~~	~~Log Mct_i~~	~~$(\text{Log } Mct_i)^2$~~	~~Frequency~~
~~11~~	~~1.041~~	~~1.084~~	~~2~~
~~13~~	~~1.114~~	~~1.241~~	~~3~~
~~15~~	~~1.176~~	~~1.383~~	~~8~~
~~17~~	~~1.230~~	~~1.514~~	~~12~~
~~19~~	~~1.279~~	~~1.635~~	~~12~~
~~21~~	~~1.322~~	~~1.748~~	~~14~~
~~23~~	~~1.362~~	~~1.854~~	~~13~~
~~25~~	~~1.398~~	~~1.954~~	~~10~~
~~27~~	~~1.431~~	~~2.049~~	~~10~~
~~29~~	~~1.462~~	~~2.139~~	~~8~~
~~31~~	~~1.491~~	~~2.224~~	~~7~~
~~33~~	~~1.519~~	~~2.306~~	~~6~~
~~35~~	~~1.544~~	~~2.384~~	~~5~~
~~36~~	~~1.556~~	~~2.422~~	~~5~~
~~37~~	~~1.568~~	~~2.459~~	~~4~~
~~39~~	~~1.591~~	~~2.531~~	~~3~~
~~41~~	~~1.613~~	~~2.601~~	~~2~~
~~47~~	~~1.672~~	~~2.796~~	~~2~~
~~Total~~	~~23.369~~	~~36.324~~	~~126~~

~~$\sum(\log Mct_i)(\text{frequency})$ = 173.806~~

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~~$\sum(\log Mct_i)^2$ (frequency) = 242.116~~

~~$\overline{Mct}$ = antilog $\frac{\sum \log Mct_i}{n}$ = antilog $\frac{173.806}{126}$~~

~~$\overline{Mct}$ = antilog 1.3794 = 23.956 minutes~~

~~(e) The standard deviation (σ) of the sample data is~~

~~$\sigma = \sqrt{\frac{\sum(Mct_i - \overline{M}ct)^2}{n-1}}$~~

~~Mct_i~~	~~$(Mct_i - \overline{M}ct)$~~	~~$(Mct_i - \overline{M}ct)^2$~~	~~Frequency~~	~~(Freq.) × $(Mct_i - \overline{M}ct)^2$~~
~~11~~	~~+14~~	~~196~~	~~2~~	~~392~~
~~13~~	~~+12~~	~~144~~	~~3~~	~~432~~
~~15~~	~~+10~~	~~100~~	~~8~~	~~800~~
~~17~~	~~+8~~	~~64~~	~~12~~	~~768~~
~~19~~	~~+6~~	~~36~~	~~12~~	~~432~~
~~21~~	~~+4~~	~~16~~	~~14~~	~~224~~
~~23~~	~~+2~~	~~4~~	~~13~~	~~52~~
~~25~~	~~0~~	~~0~~	~~10~~	~~0~~
~~27~~	~~−2~~	~~4~~	~~10~~	~~40~~
~~29~~	~~−4~~	~~16~~	~~8~~	~~128~~
~~31~~	~~−6~~	~~36~~	~~7~~	~~252~~
~~33~~	~~−8~~	~~64~~	~~6~~	~~384~~
~~35~~	~~−10~~	~~100~~	~~5~~	~~500~~
~~36~~	~~−11~~	~~121~~	~~5~~	~~605~~
~~37~~	~~−12~~	~~144~~	~~4~~	~~576~~
~~39~~	~~−14~~	~~196~~	~~3~~	~~588~~
~~41~~	~~−16~~	~~256~~	~~2~~	~~512~~
~~47~~	~~−22~~	~~484~~	~~2~~	~~968~~
~~Total~~		~~1981~~	~~126~~	~~7653~~

~~$\sigma = \sqrt{\frac{\sum(Mct_i - \overline{M}ct)^2}{n-1}} = \sqrt{\frac{7653}{125}}$ = 7.82 minutes~~

~~(f) The value for Mmax is determined from Equation 13.9 (page 421).~~

~~Mmax = antilog [$\overline{\log Mct} + z\sigma_{\log Mct_i}$]~~

~~Specify a value for "Z" (assume 90%) where $\sigma_{\log Mct_i}$ is determined from Equation 13.10 (page 421).~~

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$$\sigma_{\log Mct_i} = \sqrt{\frac{242.116 - (173.806)^2/126}{125}}$$ ~~= 0.138~~

~~Mmax = antilog [1.3794 + (1.28)(0.138)]~~

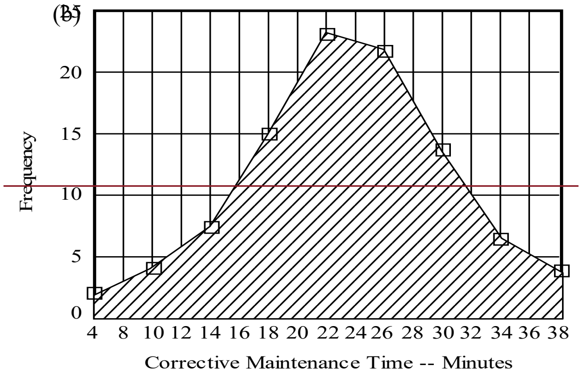
~~Mmax = antilog 1.556 = 35.98 minutes~~

~~6) (a) In the textbook problem statement, substitute “below” for “on page xxx”.~~

~~Mct_i~~	~~Frequency~~	~~(Mct_i) (Freq)~~	~~$(Mct_i - \overline{Mct})$~~	~~$(Mct_i - \overline{Mct})^2$~~	~~Freq× $(Mct_i - \overline{Mct})^2$~~
~~9~~	~~1~~	~~9~~	~~+14~~	~~196~~	~~196~~
~~12~~	~~2~~	~~24~~	~~+11~~	~~121~~	~~242~~
~~13~~	~~3~~	~~39~~	~~+10~~	~~100~~	~~300~~
~~15~~	~~4~~	~~60~~	~~+8~~	~~64~~	~~256~~
~~17~~	~~6~~	~~102~~	~~+6~~	~~36~~	~~216~~
~~19~~	~~10~~	~~190~~	~~+4~~	~~16~~	~~160~~
~~21~~	~~12~~	~~252~~	~~+2~~	~~4~~	~~48~~
~~23~~	~~13~~	~~299~~	~~0~~	~~0~~	~~0~~
~~25~~	~~12~~	~~300~~	~~−2~~	~~4~~	~~48~~
~~27~~	~~10~~	~~270~~	~~−4~~	~~16~~	~~160~~
~~29~~	~~8~~	~~232~~	~~−6~~	~~36~~	~~288~~
~~31~~	~~6~~	~~186~~	~~−8~~	~~64~~	~~284~~
~~33~~	~~3~~	~~99~~	~~−10~~	~~100~~	~~300~~
~~35~~	~~2~~	~~70~~	~~−12~~	~~144~~	~~288~~
~~37~~	~~1~~	~~37~~	~~−14~~	~~196~~	~~196~~
~~Total~~	~~93~~	~~2169~~		~~1097~~	~~3082~~

~~The range of observation is 37 - 9 = 28 minutes~~

~~(b)~~



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~~The distribution of repair times appears to approximately normal.~~

~~(c) $\overline{M}ct = \frac{\sum_{i=1}^{n} Mct_i}{n} = \frac{2.169}{93}$ = 23.32 minutes (assume 23)~~

~~(d) The standard deviation (σ) of the sample data is~~

~~$\sigma = \sqrt{\frac{\sum(Mct_i - \overline{M}ct)^2}{n-1}} = \sqrt{\frac{3.082}{92}}$ = 5.79 minutes~~

~~(e) Refer to Equation 13.3 (page 417).~~

~~Upper limit = $\overline{M}ct + z\frac{\sigma}{\sqrt{n_c}}$ = 23.32 + $\frac{(1.65)(5.79)}{\sqrt{93}}$~~

~~Upper limit = 23.32 + 0.99 = 24.31 minutes~~

~~This is less than the specified requirement of 25 minutes; therefore, *the specified requirement will be met.*~~

~~7) Refer to Equation 13.14 (page 427).~~

~~$\overline{M}ct = \frac{400(1-0.990)}{0.990}$ = 4.04 hours~~

~~8) (a) Determine MTBF = $\frac{1}{\lambda} = \frac{1}{0.004}$ = 250 hours.~~

~~(b) Determine $\overline{M}$. Assume that the mean down time of 50 hours less the mean logistics plus administrative time of 30 hours is equivalent to $\overline{M}$, or $\overline{M}$ = 20 hours.~~

~~(c) Determine the corrective and preventive maintenance frequencies. Assume that the corrective maintenance frequency equals λ, or 0.004. The quantity of corrective maintenance actions is (10,000 hours)(0.004), or 40. Thus, the quantity of preventive maintenance actions is 50 – 40, or 10. The preventive maintenance frequency fpt is 10 divided by 10,000 or 0.001.~~

~~(d) Determine $\overline{M}ct$, given $\overline{M}$ = 20, fpt = 0.001, and λ = 0.004, using Equation 13.8 on page 421:~~

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$$\overline{M} = \frac{\overline{M}ct(\lambda) + (\overline{M}pt)(\text{fpt})}{\lambda + \text{fpt}}, \text{ or } 20 = \frac{\overline{M}ct(0.004) + (6)(0.001)}{0.005}, \text{ or } \overline{M}ct = 23.5$$

~~hours~~

~~(e) Determine MTBM. MTBM is 10,000 hours divided by 50, or 200 hours.~~

~~(f) Determine~~ A_i ~~from Equation 13.14 (page 427).~~

$$A_i = \frac{250}{250 + 23.5} = 0.9141$$

~~(g) Determine~~ $A_a = \frac{200}{200 + 20} = 0.9091$

~~(h) Determine~~ $A_0 = \frac{200}{200 + 20} = 0.8000$

~~(i) One cannot legitimately derive~~ MTTR_g ~~(equivalent to~~ $\overline{M}ct$~~) and Mmax without some additional data or assumptions.~~

~~9) Determine MTBM. From Equation 13.13 (page 424):~~

$$\text{MTBM} = \frac{1}{1/2.0 + 1/1,000} = 1.996 \text{ hours}$$

~~Determine~~ $\overline{M}$~~. Given that~~ $\lambda = 0.5$ ~~and~~ $\text{fpt} = 0.001$, $\overline{M}$ ~~is from Equation 13.8 on page 421:~~

$$\overline{M} = \frac{(0.5)(0.5) + (0.001)(2.0)}{0.501} = 0.503 \text{ hours}$$

$$A_a = \frac{\text{MTBM}}{\text{MTBM} + \overline{M}} = \frac{1.996}{1.996 + 0.503} = 0.7987$$

~~10) *Maintainability allocation* is the process of allocating or apportioning one or more system-level requirements down to the various sub-systems, units, assemblies, and so on. Given design-to requirements at the top, the next step is to break these requirements down to the various applicable elements of the system and as an "input" to the design of these elements. Allocation should be accomplished to the degree necessary to "control" the design of the system and its various elements. The process is illustrated in Tables 13.7 and 13.8 (pages 432–433). Reference: Section 13.4.2 (page 431).~~

~~11) Refer to Table 13.7 (page 432).~~

~~Item~~	~~Number of Items~~	~~Failure Rate (λ)~~	~~Contribution of Total Failures~~	~~Percent Contribution (%)~~	~~Average~~ $\overline{Mct}$ ~~*~~	~~Contribution of Total Corrective Maint. Time (Minutes)~~
~~Assy A~~	~~1~~	~~0.05~~	~~0.05~~	~~0.07~~	~~2.0~~	~~1.00~~
~~Assy B~~	~~2~~	~~0.16~~	~~0.32~~	~~0.42~~	~~0.6~~	~~0.192~~
~~Assy C~~	~~1~~	~~0.27~~	~~0.27~~	~~0.35~~	~~0.9~~	~~0.243~~

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~~Assy D~~	~~1~~	~~0.12~~	~~0.12~~	~~0.16~~	~~1.5~~	~~0.180~~
~~TOTAL~~			~~0.76~~	~~100~~		~~0.715~~

~~*Estimate appropriate values depending on the anticipated degree of maintenance contribution.~~

~~From Equation 13.23 (page 433),~~ $\overline{Mct} = \frac{0.715}{0.760}$ ~~= 0.94~~

~~This is less than the specified 1 hour requirement for System ABC. Thus, the customer may wish to relax the requirement for any of the designated assemblies (without allowing the~~ $\overline{Mct}$ ~~value to exceed 1 hour). On the other hand, if there are risks associated with the overall system requirement (or that imposed on any of the four assemblies), then one may wish to remain with the specified allocated values in order to provide some margin for error. In summary, there are numerous trade offs that may be appropriate, and the results here represent only *one* approach. Reference: Section 13.4.2 (page 431).~~

~~12) Determine the total number of hours, or (40 hours)(50 weeks)(15 years) = 30,000 hours. Divide the 30,000 hours by the MTBF of 400, or 75 maintenance actions. For each MA, there will be 2 maintenance technicians for the 2 hour maintenance period, or the MLH/OH = (75 MAs)(2 hours)(2 technicians) = 300 MLH/30,000 = 0.01 MLH/OH.~~

~~13) *Maintainability prediction* is accomplished at various points in the design process to assess the system design configuration (at the time of prediction) in terms of whether or not the configuration evaluated is likely to meet the maintainability requirements as initially specified. If a 450 hour MTBM, or a 30 minute~~ $\overline{Mct}$~~, is the requirement included in the system specification, then one needs to assess just how the design is doing relative to meeting this requirement. Predictions are usually made in conjunction with formal design reviews and/or when there have been significant changes in design. Predictions are based on available design data, drawings, component part lists, the results from various analyses, etc. Reference: Section 13.5.2 (page 437).~~

~~14) Refer to Section 13.5 (pages 436 456):~~

~~(a) The *reliability centered maintenance analysis* (*RCM*) is a systematic approach to developing a focused, effective, and cost efficient preventive maintenance program and control plan for the system. Past experience is replete with examples where either too much or too little preventive maintenance has been accomplished on systems in operational use. The RCM method is intended to identify and justify the need for PM based on solid reliability information/data (i.e. type and frequency of PM required, etc). Accomplishing a RCM analysis is usually based on the FMECA as a pre requisite (refer to Section 12.4.1, page 385), and may be implemented during the preliminary system design phase and subsequently as required. Reference: Section 13.5.3 (page 439).~~

~~(b) The *level of repair analysis* (*LORA*) is accomplished to determine whether (in the event of failure) it is more economical to accomplish "repair" of the item in question, or to "discard" the item all together (i.e., not accomplish repair). In the event that "repair" is recommended, the next step is to determine whether it is more feasible to accomplish repair~~

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~~at the intermediate level of maintenance or at the depot or manufacturer or supplier. Both economic and non economic screening criteria are used to aid in the process, although the LORA per se is oriented more to the economic issues involved. The LORA should be accomplished initially (at a top level) during the conceptual design phase as decisions are made, particularly in the selection of COTS items, that can greatly influence the development of the maintenance concept (refer to Section 3.5, page 76). The analyst needs to acquire an early feeling as to what functions are likely to be accomplished at each level of maintenance and the estimated resources required. The LORA will then be subsequently accomplished as the design definition process evolves through the preliminary system design and detail design and development phases. Reference: Section 13.5.4 (page 440).~~

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~~(c) The *maintenance task analysis (MTA)* constitutes the process of evaluating a given design configuration (whether preliminary or final) for the purposes of (a) assessing the design for inclusion of system supportability characteristics and the incorporation of good reliability and maintainability features (attributes), and (b) determining the maintenance resources required for support of the system throughout its planned life cycle (i.e., personnel and training, spares/repair parts and associated inventories, transportation, facilities, computer resources, data/information, etc.). The MTA evolves from the system functional analysis, and the specific maintenance tasks in the MTA are an extension of the maintenance functional flow block diagrams (i.e., maintenance functions, sub functions, tasks, sub tasks, etc.). The MTA may be accomplished at a gross level during the conceptual design phase, and then expanded and refined during the subsequent phases of system design and development. Reference: Section 13.5.5 (page 446).~~

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~~15) Refer to Figure 13.16 (page 445). In general, if the system operating time is increased, with all other factors remaining the same (including the reliability MTBF), there are likely to be more replacements required, and there is likely be a shift in the direction of "repair at the intermediate level." In other words, it might be more economical to set up a repair capability at the intermediate level if the number of MA were to increase (an increase in the number of replacements). This assumes that there are no other external and non economic factors that would dictate otherwise. Reference: Section 13.5.4 (page 440).~~

~~16) *Total productive maintenance* (*TPM*) refers to a methodology for evaluating the overall effectiveness of a production/manufacturing capability, and for identifying major problem areas which, in turn, would lead to follow on system/process modification(s) for improvement. The specific objectives of TPM are to (a) maximize the availability and overall effectiveness of the production process; (b) establish a life cycle approach in determining the requirements for preventive maintenance; (c) involve all organizational aspects of a production plant in the care and maintenance of that plant; and (d) to promote organizational efficiency through good "motivation management." The prime TPM measure is *overall equipment effectiveness* (*OEE*), which is a function of *availability* (*A*), *performance rate* (*P*), and *quality rate* (*Q*). Reference: Section 13.5.6 (page 454).~~

~~17) Determine OEE, which is a function of *availability*, *performance rate*, and *quality rate*. Referring to Equation 13.25 (page 456), $A = 460 - 100/460 = 0.783$. From Equation 13.26, $P = 0.555$. From Equation 13.27, $Q = 22 - 2/22 = 0.909$. From Equation 13.24, $OEE =$~~

~~(0.783)(0.555)(0.909) = 0.395, or about 40%. If this turns out to be below the desired benchmark, the analyst can construct a functional flow diagram describing the production system, identify the functions where downtime occurs, identify the functions where cycle time is impacted, identify the areas where defects occur, and initiate the necessary recommendations for design improvement in the applicable areas of operation where degradation has been detected. Reference: Section 13.5.6 (page 454).~~

~~18) Good accessibility to components/areas requiring maintenance will reduce the maintenance time (Mcti), turnaround time (TAT), and tend to preclude the introduction of errors in accomplishing the required maintenance tasks; good modularization and interchangeability will reduce the active maintenance time (Mcti), turnaround time (TAT), and remove/replace time; the installation of common and standard components (i.e., standardization) will reduce maintenance time (Mcti), reduce the special resources required for maintenance (i.e., special tools, special procedures), and reduce the frequency of maintenance (increase in MTBM) by simplifying the tasks and precluding the introduction of failures during the accomplishment of these maintenance tasks; accurate and complete diagnostics (particularly for electronic equipment) will enable the rapid and positive identification of faulty items, thus reducing the active repair time (Mcti) and precluding the probability of removing and replacing the wrong items (i.e., promoting the costly "maintenance by substitution" possibility); simplicity in design will likely reduce maintenance time (Mcti), maintenance frequency (MTBM), maintenance labor hours (MLH), and personnel training requirements; good labeling will reduce maintenance times, personnel labor hours, and maintenance training requirements; and so on. The fulfillment of all of these design objectives will, of course, result in a reduction of maintenance cost and, thus, system life-cycle cost. Reference: Section 13.4.3 (page 434).~~

~~19) Response to this problem basically constitutes a student exercise where, in the evaluation of each of the seven items listed, the student should accomplish an abbreviated level of repair analysis (LORA). The major input factors include the initial acquisition cost for a replacement, anticipated reliability and frequency of maintenance for the item in question, and the projected cost of maintenance and repair. It is a trade off between the "cost of replacement" and the "cost of repair." Reference: Section 13.5.4 (page 440).~~

~~20) *Preventive maintenance (PM)* requirements should initially be determined from the results of the FMECA, where the accomplishment of PM will improve the reliability of an item and/or the system (refer to Section 12.4.1, page 385). Although the preference is to avoid PM if at all possible, the accomplishment of such may be the only solution in response to a specific design problem; i.e., replace critical components at designated scheduled intervals in order to extend the reliability and avoid failures. Additionally, preventive maintenance requirements may be identified through the reliability centered maintenance (RCM) analysis, which is an extension of the FMECA (refer to Section 13.5.3, page 439).~~

~~21) The RCM usually depends on the completion of the FMECA as an input. The FMECA will initially aid in the identification of specific preventive maintenance (PM) requirements, and the RCM analysis aids in the verification of these (and other) PM requirements and in the~~

~~development of an overall PM plan. Both the FMECA and the RCM analysis are very complementary. Reference: Section 12.4.1 (page 385) and Section 13.5.3 (page 439).~~

~~22) Student exercise. Refer to Figures 13.20 and 13.21 (pages 451–453).~~

~~23) The purpose in accomplishing a *maintainability demonstration* is to verify that the initially specified requirements (i.e., MTBM,~~ $\overline{M}ct$, $\overline{M}pt$, ~~MLH/OH) have been met. The demonstration usually includes conducting a planned series of simulated maintenance tasks on a pre-production or prototype model of the system/equipment. As the tasks are accomplished, data are collected to measure task sequences, task times, the resources required in task accomplishment, and so on.~~

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~~While elapsed-time factors are the main point of emphasis, other elements of the system can be verified/validated in the process (i.e., maintenance personnel quantities and skills, test and support equipment compatibility, adequacy of maintenance facilities, verification of maintenance procedures, and validation of technical data). Maintainability demonstration can initially be accomplished during the preliminary system design phase with the aid of simulation and the generation of three-dimensional models using CAD tools. However, the main thrust in doing a maintainability demonstration is during Type 2 testing, conducted in the latter part of the detail design and development phase. Reference: Section 6.2 (page 153) and Section 13.6 (pages 457–463).~~

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~~24) Refer to Section 13.6.1 (page 457) for the approach to be followed in accomplishing maintainability demonstration:~~

~~(a) The selection of tasks is based on the expected percent contribution toward the total maintenance requirements. The maintenance tasks associated with those items that reflect high failure rates and will require a large percentage of the corrective maintenance and/or utilize more resources than usual should be demonstrated to a greater extent than those requiring less maintenance. Additionally, there may be some tasks, where the frequency of accomplishment is relatively low but where such are considered to be "critical" (with regard to the mission of the system), that must be demonstrated. Reference: Section 13.6.1 (page 457).~~

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~~(b) The selection of personnel quantities and skill levels for maintainability demonstration is based on the results of the maintenance task analysis (MTA). Reference: Section 13.5.5 (page 446) and Figure 13.21 Sheet 1 (page 452 – blocks 15-18 in the figure).~~

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~~(c) The requirements pertaining to the other resources for maintainability demonstration (i.e., test and support equipment, spares/repair parts and associated inventories, facilities, and technical data) are also derived from the maintenance task analysis (MTA). Reference: Section 13.5.5 (page 446) and Figure 13.21 Sheet 2 (page 453).~~

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~~25) Yes, the equipment did pass maintainability demonstration.~~

~~Determine the demonstrated $\overline{Mct}$~~

$$\overline{M}ct = \frac{\sum_{i=1}^{n} Mct_i}{n} = \frac{3.074}{50}$$ ~~= 61.48 minutes (assume 61)~~

~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~	~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~	~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~
~~39~~	~~484~~	~~63~~	~~4~~	~~49~~	~~144~~
~~42~~	~~361~~	~~96~~	~~1225~~	~~42~~	~~361~~
~~64~~	~~9~~	~~74~~	~~169~~	~~32~~	~~841~~
~~74~~	~~169~~	~~74~~	~~169~~	~~48~~	~~169~~
~~92~~	~~961~~	~~47~~	~~196~~	~~32~~	~~841~~
~~57~~	~~16~~	~~68~~	~~49~~	~~62~~	~~1~~
~~43~~	~~324~~	~~45~~	~~256~~	~~85~~	~~576~~
~~82~~	~~441~~	~~67~~	~~36~~	~~50~~	~~121~~
~~67~~	~~36~~	~~63~~	~~4~~	~~86~~	~~625~~
~~91~~	~~900~~	~~40~~	~~441~~	~~56~~	~~25~~
~~70~~	~~81~~	~~70~~	~~81~~	~~64~~	~~9~~
~~54~~	~~49~~	~~58~~	~~9~~	~~75~~	~~196~~
~~36~~	~~625~~	~~73~~	~~144~~	~~73~~	~~144~~
~~71~~	~~100~~	~~66~~	~~25~~	~~36~~	~~625~~
~~75~~	~~196~~	~~53~~	~~64~~	~~58~~	~~9~~
~~51~~	~~100~~	~~52~~	~~81~~	~~62~~	~~1~~
~~65~~	~~16~~	~~82~~	~~441~~	—	—
~~Total~~				~~3,074~~	~~12,950~~

$$\sigma = \sqrt{\frac{\sum (Mct_i - \overline{M}ct)^2}{n-1}} = \sqrt{\frac{12,950}{49}}$$ ~~= 16.26 minutes~~

~~Upper Limit =~~ $\overline{M}ct + z\frac{\sigma}{\sqrt{n}}$ ~~= 61.48 +~~ $\frac{(1.28)(16.26)}{\sqrt{50}}$

~~Upper Limit = 61.48 + 2.94 = 64.42 minutes~~

~~The Upper Limit is less than the specified $\overline{Mct}$ of 65 minutes. Therefore, the equipment did pass the maintainability demonstration test.~~

~~26) No, the equipment did not pass the maintainability demonstration.~~

~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~	~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~	~~Mct_i~~	~~$(Mct_i - \overline{M}ct)^2$~~
~~150~~	~~2500~~	~~159~~	~~3481~~	~~102~~	~~4~~
~~144~~	~~1936~~	~~152~~	~~2704~~	~~69~~	~~961~~
~~82~~	~~324~~	~~129~~	~~841~~	~~78~~	~~484~~

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~~78~~	~~484~~	~~89~~	~~121~~	~~67~~	~~1089~~
~~113~~	~~169~~	~~114~~	~~196~~	~~102~~	~~4~~
~~120~~	~~400~~	~~135~~	~~1225~~	~~106~~	~~36~~
~~133~~	~~1089~~	~~136~~	~~1296~~	~~172~~	~~5184~~
~~131~~	~~961~~	~~148~~	~~2304~~	~~112~~	~~144~~
~~98~~	~~49~~	~~115~~	~~225~~	~~118~~	~~324~~
~~101~~	~~1~~	~~112~~	~~144~~	~~65~~	~~1225~~
~~133~~	~~1089~~	~~108~~	~~64~~	~~117~~	~~289~~
~~121~~	~~441~~	~~86~~	~~196~~	~~161~~	~~3721~~
~~122~~	~~484~~	~~118~~	~~324~~	~~91~~	~~81~~
~~144~~	~~1936~~	~~122~~	~~484~~	~~103~~	~~9~~
~~94~~	~~36~~	~~181~~	~~6561~~	~~115~~	~~225~~
~~92~~	~~64~~	~~95~~	~~25~~	~~115~~	~~225~~
~~101~~	~~1~~	~~113~~	~~169~~	—	—
~~Total~~				~~5,757~~	~~46,329~~

$$\sigma = \sqrt{\frac{\sum (Mct_i - \overline{M}ct)^2}{n-1}} = \sqrt{\frac{5757}{50}}$$ ~~= 115.14 minutes~~

$$\sigma = \sqrt{\frac{\sum (Mpt_i - \overline{M}pt)^2}{n-1}} = \sqrt{\frac{46,329}{49}}$$ ~~= 30.75 minutes~~

~~Upper Limit =~~ $\overline{M}ct + z\frac{\sigma}{\sqrt{n}}$ ~~= 115.14 +~~ $\frac{(1.28)(30.75)}{\sqrt{50}}$

~~Upper Limit = 115.14 + 5.57 = 120.71 minutes~~

~~The Upper Limit is greater than the specified~~ $\overline{M}pt$ ~~of 100 minutes; therefore, the equipment did not pass the maintainability demonstration test.~~

~~27) The system will not meet the specified~~ $\overline{M}ct$ ~~requirement of 65 minutes. Referring to Equations 13.29 and 13.31 (pages 460 and 461):~~

$$\overline{M}ct + z\frac{\sigma}{\sqrt{n}} > \overline{M}ct \text{ (specified)}$$

$$62 + \frac{(1.65)(17.5)}{\sqrt{50}} > 65$$

~~66.084 > 65; hence, reject the system~~

~~28) Reliability and maintainability in design are very closely related, and the consideration of both on an integrated basis is required in order to meet certain system "availability" requirements. As a first objective, it would be great if **all** systems were so reliable as to be~~

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~~able to accomplish their respective missions 100% of the time. However, building into the design the required amount of reliability will likely be quite costly. On the other hand, the requirements for reliability may be relaxed somewhat providing that, when a failure does occur, the system can be repaired quickly, effectively, and efficiently so as to meet an overall availability requirement for the system. Such a rapid turnaround will require the incorporation of good maintainability characteristics in the design. In order to meet a higher-level "availability" requirement, there must be a proper balance between reliability and maintainability characteristics in design.~~

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~~In the design of space systems, for example, the importance of building reliability into the design becomes obvious and is critical, since the accomplishment of maintenance will likely be impossible. On the other hand, for many aircraft systems, production systems, and the like, while reliability is important, maintainability assumes a greater degree of importance, since the accomplishment of maintenance is more feasible, with the end objective of meeting an overall system availability objective at the system level.~~

~~Refer to Section 13.5.1 (and Figure 13.11, page 436) for a good illustration of a reliability-maintainability trade-off study. Some examples at a more detailed level — if reliability is high, the requirements for accessibility and thorough diagnostics will not be as great. Conversely, if the reliability of a system is on the low side, then there needs to be greater emphasis on accessibility, good self-test and diagnostics, modularization and interchangeability, good labeling, and so on.~~

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~~CHAPTER 14~~

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~~DESIGN FOR USABILITY (HUMAN FACTORS)~~

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~~1) *Human factors* refer to those characteristics that are associated with the human being that must be considered in the design of systems where there are humans (i.e., operators and maintainers) involved in the operation, maintenance, and/or support of the system. Consideration must be given to the human's *anthropometric* characteristics (i.e., human physical dimensions – both static and dynamic), *sensory* factors (i.e., hearing, sight, feel, smell, etc.), *physiological* factors (i.e., impact on the human from external environmental forces such as temperature extremes, vibration, noise, radiation, toxicity), *psychological* factors (i.e., human needs, expectations, motivation, attitude, etc.), and their interrelationships. It is essential that the "human" be considered as a major element of the system (along with hardware, software, facilities, data/information, elements of support), and that these factors be addressed from the beginning in the early stages of conceptual design. Referring to Figures 2.6 (page 38), 4.4 (page 107), 4.9 (page 116), and 5.3 (page 132), human factors and *human system integration (HSI)* requirements must be properly integrated with other design requirements to include reliability (Chapter 12, page 362), maintainability (Chapter 13, page 410), supportability (Chapter 15, page 497), and so on. Reference: Figure 2.6 (page 38), Section 4.4 (page 112), and Section 14.1 (pages 469–481).~~

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~~2) *Human functional requirements* evolve from the "functional analysis" for the overall system, described in Sections 3.7 (page 86) and 4.3 (page 104). Referring to Section 3.7.1 (page 86), operator and maintenance *functional flow block diagrams (FFBDs)* are developed for the system, which lead to the development of individual lower-level *operational* FFBDs and *maintenance* FFBDs. Each block in the overall functional description of the system is evaluated in terms of the resources required to perform the given function (refer to Figure 4.2, page 105). Such resource requirements are based on the accomplishment of trade-off studies leading to the best "mix" of hardware, software, human, and other resources to accomplish the function, evolving from the "whats" to the "hows." Figure 4.4 (page 107) provides an illustration of hardware, software, and human requirements (and their respective life cycles) evolving as a result of the "functional analysis" (i.e., blocks 0.2 and 1.1 in Figure 2.4, page 34). This, then, leads to the process, illustrated in Figure 14.1 (page 470), where the human functions are broken down into job operations, duties, tasks, sub-tasks, and task elements. Reference: Section 14.1 (page 469).~~

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~~3) *Anthropometric factors* deal primarily with the physical dimensions of the human body, and these dimensions are critical in the design of operator and maintenance work stations. Referring to Figures 14.2 (page 472), 14.3 (page 473), 14.4 (page 474), and 14.5 (page 475), the human body measurements are important in designing work stations, determining the height, location and sequences of controls, sizes and position of access openings, and so on. Further, these dimensions will vary depending on whether the human body is in a "static" (fixed) or "dynamic" (with motion) state. Operators/maintainers must be able to accomplish their assigned functions accurately, reliably, in a minimum period of time, and without introducing errors in the process. Reference: Section 14.1.1 (pages 471–476). It~~

~~should be noted that the specific dimensions shown in the figures included in the text are for the purposes of illustration, and that the instructor is advised to refer to some of the references in the Selected Bibliography, Appendix *G*, Section G.6 (page 760), for a more comprehensive coverage of the human factors discussed in the text.~~

~~*Human sensory factors* pertain to the capabilities of the human being to perform operator and maintenance functions when considering: (a) **sight** (distances of vision, clarity of vision at different angles, ability to see different colors, ability to work with different levels of illumination and so on — refer to Figures 14.6, 14.7, and Table 14.1 on pages 477–478); (b) **hearing** (audibility or ability to detect and understand messages/signals, ability to perform tasks with different levels of noise, etc.); (c) **feel/touch** (sensitive to sizes, shapes, material characteristics, etc.); and **smell** (ability to detect various odors, identification of gases, etc.). Reference: Section 14.1.2 (pages 476–479).~~

~~*Physiological factors* pertain to the effects of external environmental conditions on the human being in the performance of operator and maintenance tasks; i.e., temperature extremes, humidity, noise, vibration, toxicity, etc. If the environmental conditions are "extreme" (very high or very low temperature, high humidity, high noise level, high level of vibration, high toxicity), human performance is likely to be influenced negatively and system degradation will occur. The system must be designed such that errors will not be introduced (as a result of the external environment) in the performance of operator and maintenance tasks. Reference: Section 14.1.3 (page 479).~~

~~*Psychological factors* pertain to the human mind and the aggregate of emotions, traits, and behavior patterns as they relate to job performance. If an individual is emotionally upset, or lacks the proper motivation for some reason, this will certainly tend to affect job performance which, in turn, will result in system degradation. The system design must be such that the accomplishment of human tasks is not too "simple" (causing "boredom" and the subsequent introduction of errors) or too "complex" (causing "frustration" and the subsequent introduction of errors). Reference: Section 14.1.4 (page 480).~~

~~4) With regard to *physiological factors*, if the temperature is either too hot or too cold, if there is high humidity, if there is excessive vibration, or if the noise level is too high, then the operator/maintainer is likely to induce errors in the accomplishment of his/her tasks. Pertaining to *psychological factors*, if the human has a poor attitude or is not motivated to perform for some reason, then errors are likely to be introduced in the performance of assumed tasks.~~

~~If a task is too routine or "simple" to accomplish, the human is likely to become bored and, thus, introduce errors in the performance of his/her tasks. On the other hand, if the task is too "complex" and difficult to accomplish, this is likely to lead to "frustration" and errors will be introduced as a result. Relative to their interrelationships, physiological factors (e.g., temperature extreme) can certainly have a negative impact on attitude and motivation, and psychological factors (a negative attitude) can have an impact on the immediate working environment. Reference: Sections 14.1.3 and 14.1.4 (pages 479–481).~~

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~~5) If an operator/maintainer is *undertrained*, the various assigned tasks may appear to be too difficult or complex, will take longer to accomplish, frustration will occur, and errors will be introduced in the process. Additionally, the operator/maintainer may introduce errors just from a lack of knowledge of the proper procedures/steps in accomplishing an assigned task. On the other hand, if an individual is *overtrained*, the tasks to be accomplished will likely appear to be too simple and routine, boredom will set in, and careless errors are likely to be introduced in the process. A good design objective might be to include some “automation” in this latter incidence. Reference: Section 14.5 (page 492).~~

~~6) Refer to Figure 14.8 (page 481). The ability of the human being to *recognize* or *sense* the requirements for information processing (through vision, hearing, feeling, and other senses), the ability or *capacity* of the human to process certain types and quantities of information, the ability of the human to both *store* and *recall* certain types of information on a timely basis (short term and long term memory), and the ability of the human to *distribute* the right information, in the proper quantity and format, reliably, to the right location(s). This will lead to the design of work stations and operator consoles/panels with the proper layout of controls, the proper meters/gauges, visual readout devices, and so on. Reference: Section 14.1 (page 469) and Figure 14.8 (pages 481).~~

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~~7) Some *measures* that might be applicable in specifying “design-to” criteria for the human element of a system are noted in Section 14.2 (pages 481-482). These, “tailored” to the specific system requirement(s), may include personnel types, quantities and skill levels, elapsed time factors, labor hour factors, cost factors, and so on. For example, the system shall be designed such that it can be operated by a human with “abc” dimensions at the 95th percentile or less; the accomplishment of operator tasks in performing a given mission shall require no more than “x” OLH/OH; the accomplishment of maintenance tasks shall require no more than “y” MLH/OH and by an individual with “basic” skills; the elapsed time that it takes to conduct a specific mission scenario shall take no longer than “z” time; the cost per maintenance action ($/MA) shall be “w” or less; and so on. Reference: Section 14.2 (page 481).~~

~~8) With the human as a critical element of the system, he/she can significantly impact system reliability (refer to Table 12.1, page 370, and the failure rates attributed to operator-induced and maintenance-induced failures). The incorporation of good design characteristics for human factors can either enhance or degrade system reliability. If the design is overly complex, this may result in the introduction of personnel-induced failures and a subsequent degradation of system reliability. Conversely, the selection of components, the degree of redundancy incorporated in the design, the degree of automation incorporated, etc., in the design for reliability can significantly impact human factors and the ease and simplicity of performing operator and maintenance tasks. There is a close interrelationship between the goals and objectives discussed both in Chapters 12 and 14. Likewise, the same interrelations exist between the maintainability objectives in Chapter 13 and the human factors objectives in Chapter 14. In maintainability, a prime objective is to design for minimum personnel quantities and skill levels, minimum MLH/OH, and minimum training requirements in the performance of maintenance activities. If, in the performance of maintenance tasks, accessibility is poor, panel layouts are poor for~~

~~diagnostics, component removal and replacement is difficult, and so on, it is likely that maintenance induced failures will be introduced which will impact reliability, maintainability, and human factors. All three of these engineering design related disciplines should be well integrated from the beginning. Reference: review of the basic design objectives in reliability, maintainability, and human factors.~~

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~~9) The *Operator Task Analysis (OTA)* involves a systematic study of the tasks that must be accomplished for the operation of the system in the performance of its various assigned missions. "Operator" tasks are derived initially from the system *functional analysis* and the development of *operational functional flow block diagrams (FFBDs)*. Referring to Figure 14.11 (page 488), the OTA includes such information as a description of a task, the task stimulus from some initiated physical action, feedback from the given action, allowable task time, potential error(s) in accomplishing the task, assignment of a task to a designated work station, and so on. The objectives are to: (a) assess the system design configuration for the incorporation of good human factors characteristics; and (b) to determine personnel quantities and skill level requirements. The OTA may be accomplished, at a top level, during the preliminary system design phase after the functional analysis has identified the initial requirements for human involvement, and then amplified and refined throughout the detail design and development phase. Reference: Section 14.4.1 (page 486).~~

~~The *Operational Sequence Diagram (OSD)*, which often is used in conjunction with the operator task analysis, aids in evaluating the *flow of information* (in the accomplishment of an operational scenario) and the major interfaces between the human operator and equipment (consoles, control panels, work stations). Referring to Figure 14.12 (page 490), this illustration shows the flow of information between two operators and two operator-control stations. The objective is to evaluate the interfaces, particularly with regard to human control panel actions; i.e., the method for transmitting information (via audio or visual means), the type of readouts and displays, the accuracy and time for information transmittal, the sequence of steps in the process, and so on. The OSD is generally implemented as a design analysis tool during the detail design and development phase. Reference: Section 14.4.2 (page 489).~~

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~~The purposes of the *error analysis* are to conduct an assessment of the tasks that will be required in the operation and maintenance of the system and to identify areas where possible "errors" can be induced (i.e., errors of omission and errors of commission). Initially, this may be accomplished analytically. Later, this may be accomplished through a series of demonstrations or tests where a properly trained individual will perform certain tasks while being monitored for accuracy, completeness, etc., with any errors noted in the process. An error analysis is often accomplished in conjunction with the OTA, MTA, and often included as part of a maintainability demonstration, technical procedures verification, and other Type 2 tests (refer to Section 6.2.3, page 154). Reference: Section 14.4.3 (page 489).~~

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~~The purpose of the *safety/hazard analysis* is to evaluate a given system design configuration with the objective of identifying potential safety and hazardous conditions which could cause system/equipment damage and/or human injury or death. The analysis,~~

~~which is closely aligned with the reliability FMECA and FTA, identifies potential hazards, hazard classifications (negligible, marginal, critical, and catastrophic), cause(s) of the hazard, anticipated frequency of occurrence, and recommended corrective action or preventive measures. The safety/hazard analysis (also a prime tool utilized in the implementation of safety engineering program) constitutes a design analysis tool which can be utilized throughout the preliminary system design and detail design and development phases. Reference: Section 14.4.4 (page 491).~~

~~10) Student exercise. Refer to Figures 14.1 (page 470) and 14.11 (page 488).~~

~~11) Student exercise. Refer to Figure 14.12 (page 490).~~

~~12) The purpose of the OTA is to enable the assessment of a system design configuration from an *operational* perspective, and to aid in the determination of operator personnel requirements (i.e., personnel quantities and skill levels). Refer to Section 14.4.1 (page 486). The purpose of the MTA (described in Chapter 13) is to enable the assessment of a system design configuration from a *maintainability* and *maintenance* perspective, and to aid in the determination of maintenance and support resource requirements (i.e., maintenance personnel quantities and skill levels, spares/repair parts and associated inventories, test and support equipment, transportation, maintenance facilities, maintenance software, technical data). Refer to Section 13.5.5 (page 446). While the format for each is quite different, the OTA and MTA can be rather complementary if properly coordinated.~~

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~~13) The FMECA and the safety/hazard analysis are quite similar in many respects. System failures/hazards are identified, there are various classifications of failures/hazards in terms of criticality, the cause and effect relationships of failures/hazards are determined, the anticipated frequency of occurrence is estimated, and recommended approaches for possible corrective action and/or prevention are noted. On many occasions, the FMECA is accomplished as a prerequisite for, and input to, the safety/hazard analysis. In any event, these two analysis efforts should be closely coordinated. Refer to Section 12.4.1 (page 385) for the FMECA and Section 14.4.4 (page 491) for the safety/hazard analysis.~~

~~14) Personnel quantities and skill level requirements are defined through the OTA, OSD, and MTA (for maintenance personnel). The OTA, with the support of "timeline" and "workload" analyses, leads to the identification of operator personnel quantities and skills. The requirements for each task/function are combined, integrated, and assigned to specific "job positions" or "work stations," leading to the total number of positions by skill level. The MTA is used for the purposes of determining maintenance personnel quantities and skills. Potential problem areas are noted when the quantity of personnel is high and/or when high skill levels are required to accomplish a task/function. Reference: Section 13.5.5 (page 446) and Section 14.4.1 (page 486).~~

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~~15) Student exercise. It is anticipated that the student will develop a set of descriptions similar to what is presented for *basic*, *intermediate,* and *high skill levels* in Section 14.5 (pages 492-493).~~

~~16) The personnel requirements relative to the quantities and skill levels for the new system (based on the results of the OTA, OSD, and MTA) are evaluated in terms of the current "baseline" organizational capability; i.e., those individuals (background and skills) who are presently in the user's organization and who will be expected to operate and maintain the new system in the future. The objective is to plan and implement a training program that will bring the anticipated "user" personnel up to the skill levels required for the new system. Included in the plan are the initial requirements for training, the specific types of training (e.g., special degree granting program, continuing education, seminar, and/or OJT), training format and schedule, training material and equipment, software, facilities, and so on. The basic plan is developed for: (a) the initial training required for operator and maintenance personnel as the system is first introduced into the user's inventory; (b) the periodic upgrading of those individuals who have been operating and maintaining the system on a daily basis; and (c) the training of replacement personnel as required. A proposed personnel development and training plan is prepared to cover each individual in the user's organization. Reference: Section 14.5 (pages 492-494).~~

~~17) Each individual in the organization will likely exhibit different skills in the accomplishment of his/her functions/tasks, based on individual background, formal education level, and experience. The objective is to enable each individual to acquire the necessary skills required in order to first accomplish his/her current job in an effective and efficient manner and, second, to enable the individual to grow in the organization over the long term. The manager must sit down with each individual in the organization and design a specific development plan, "tailored" to the needs of the individual. Such training may include any combination of formal degree granting programs, continuing education, seminars and workshops, special self-paced programs, and/or on-the-job training (OJT). Such a plan should be implemented for each new individual entering into the organization. Reference: Section 14.5 (pages 492-495). Also, refer to "Staffing the Systems Engineering Organization" (Section 18.3.4, page 669) for application in a Systems Engineering Organization.~~

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~~18) The effectiveness of a training program may be measured at the "output" stage in terms of the number of functions/tasks completed, the number of individuals involved in the process, and the number and type of errors made as a result. This type of information can be acquired from an overall organizational standpoint. More specifically, the adequacy of personnel training can be assessed through a~~ ~~*personnel test and evaluation*~~ ~~exercise (refer to Section 6.2.3 on page 154 and Section 14.6 on page 494), an~~ ~~*error analysis*~~ ~~(Section 14.4.3, page 489), or some activity of an equivalent nature. Operator/maintenance personnel, in accomplishing their assigned functions/tasks, are monitored in terms of their level of performance; i.e., accuracy, timeliness, and the consumption of resources in the performance of a task. In the event that errors are introduced in the process, the possible "causes" for such will be investigated, and the results will be evaluated in terms of the adequacy of the training program for the individuals involved. This may result in some changes in training coverage and emphasis. Reference: Section 14.5 (page 492).~~

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~~19) To verify the adequacy (in terms of quantities and skills) of personnel in the performance of system operational and maintenance support functions. The requirements for personnel~~

~~are initially established as a result of the functional analysis in the conceptual design phase, and the initial requirements for "personnel test and evaluation" are determined as these personnel requirements are established. Later, personnel requirements for the subsystem level (and below) are identified, and the overall requirements for the system are refined accordingly. This is accomplished, through allocation and through trade- off studies, on an iterative basis throughout the preliminary system design and detail design and development phases. Later, and as part of Type 2 testing (refer to Section 6.2.3, page 154), individual "personnel test and evaluation" exercises are accomplished to verify "human" adequacy in the performance of various functions/tasks. The objective is to be able to accomplish any given function/task effectively, efficiently, in a timely manner, and without the introduction of any errors. In the accomplishment of tasks where an excessive number of personnel are required, where high skill levels are required, where the consumption of resources appears to be excessive, etc., the design should possibly be changed for improvement. Reference: Section 6.2.3 (page 154) and Section 14.6 (page 494).~~

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~~20) If, during reliability qualification testing, there are personnel performing functions/tasks that replicate those which are likely to be accomplished later on during the system utilization and support phase, then there may be a possibility of verifying certain operational and maintenance tasks (performed by the human) in the process. Refer to Section 6.2.3 (page 154) and Section 12.5 (page 396) for reliability testing. As part of maintainability demonstration, selected maintenance tasks are accomplished that should replicate those that are likely to be accomplished later on for supporting the system in the field. As this is accomplished, it may be possible to perform some of the "personnel test and evaluation" effort at the same time. Refer to Section 6.2.3 (page 154) and Section 13.6 (page 457) for maintainability demonstration requirements.~~

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~~CHAPTER 15~~

~~DESIGN FOR LOGISTICS AND SUPPORTABILITY~~

~~1) *Logistics* can be defined differently, depending on whether one is addressing the subject in the context of the *commercial* sector or in the *defense* sector. Referring to Section 15.1 (page 498), in the commercial sector it can be defined as "that part of the supply chain process that plans, implements, and controls the efficient and effective forward and reverse flow and storage of goods, services, and related information between the point of origin and the point of consumption in order to meet customer requirements." Figure 15.2 (page 500) illustrates the activities in this area, which primarily pertain to the flow of relatively small consumable items (versus large-scale systems).~~

~~In the defense sector (refer to pages 501-502), logistics may be defined as a "disciplined, unified, and iterative approach to the management and technical activities necessary to (a) integrate support considerations into system and equipment design; (b) develop and support requirements that are related consistently to readiness objectives, to design, and to each other; (c) acquire the required support; and (d) provide the required support during the operational phase at minimum cost." This definition, which evolved from the Integrated Logistic Support (ILS) concept in the mid 1960s, pertains to the total spectrum of logistics (to include the commercial-related activities in Figure 15.2) as it pertains to systems, from a total life-cycle perspective.~~

~~Logistics, as defined and emphasized throughout this textbook, deals with *systems* in terms of their respective life cycles where there are requirements in design and development, production and/or construction, transportation and distribution, system operation and sustaining maintenance support, and system retirement and material recycling/disposal. In other words, logistics includes both the commercial-related activities illustrated in Figure 15.2 (page 500) and the maintenance and support infrastructure and related activities shown in Figure 3.14 (page 77), as a major element of a system and from a total life cycle integrated perspective.~~

~~Referring to Figure 15.4 (page 505), the elements of logistics include (a) logistics, maintenance, and support personnel; (b) personnel training and training support; (c) supply support — spares/repair parts and related inventories; (d) computer resources and maintenance software; (e) technical data; (f) maintenance and support facilities; (g) packaging, handling, storage, transportation, and distribution; (h) test, measurement, and support equipment; and (i) logistics information.~~

~~2) Logistics, as it is practiced in the *commercial sector*, primarily deals with the supply chain (SC), supply chain management (SCM), and the flow of materials from the various sources of supply, through manufacturing and production, distribution, and delivery of the applicable product(s) to the ultimate consumer. The materials included in the "flow" primarily refer to small components and consumable items, along with the associated data/information and business processes that support this flow. Generally, logistics is not~~

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~~addressed in the system design process, nor are the products involved in the flow addressed from a follow-on maintenance and support perspective. In other words, logistics in this application is not addressed from a total life-cycle perspective.~~

~~Logistics, as it is practiced in the *defense sector*, deals with *systems* from a total life-cycle perspective. Specific "design to" requirements are established in conceptual design from the beginning, requirements pertaining to the "design for supportability" are addressed throughout the system design and development process, the various elements of support are identified and acquired, the required maintenance and support infrastructure (and its elements) is sustained throughout the planned period of system utilization, and logistics requirements are addressed during system retirement and the subsequent recycling and/or disposal of materials as required. The commercial-related logistics activities, illustrated in Figure 15.2 (page 500), are inherent within the defense approach to logistics, particularly as the system and its elements are in production and being distributed to the customer. A total life-cycle approach to logistics (to include system design considerations and follow-on maintenance and support) is assumed. The emphasis throughout this book stresses the importance of addressing logistics (and its various elements) in the system design process, and the potential impact that this can have on the later phases of production, distribution, operation, and the sustaining maintenance and support of the system throughout its life cycle. Reference: Section 15.1 (pages 498-503).~~

~~3) Referring to Section 15.1 (page 498), a *supply chain (SC)* and *supply chain management (SCM)* can be referred to as "a process-oriented, integrated approach to procuring, producing, and delivering end products and services to customers. It includes sub-suppliers, suppliers, internal operations, trade customers, and end users. It covers the management of materials, information, and funds flow." From a historical perspective, the various activities associate with commercial or "business logistics" are reflected in the upper part of Figure 15.2 (page 500); i.e., the "technical-related" activities associated with physical supply, manufacturing, and physical distribution. More recently, and with the advent of new technologies, there has been a great deal of emphasis on information technology (IT), electronic data interchange (EDI), electronic commerce (EC), and associated "business processes," which were not adequately addressed within the context of commerce/business logistics in the past. The application of these various technologies has added an extra dimension to logistics, with the total spectrum of activity (both upper and lower part in Figure 15.2) being included under the broad term of "supply chain management (SCM)." While there are still some variations in definition, SCM basically covers the entire management framework, including all of the activities in Figure 15.2, and the elements of "business logistics" fit within this framework. For the latest, it is suggested that one visit the web site for the "Council of Supply Chain Management Professionals (CSCMP)" described in Appendix *H* (page 766). Reference: Section 15.1 (pages 498-503).~~

~~4) Given that a *system* is mission-related and that it must respond to some functional objective, its "make-up" should include all of those "elements" that are necessary to successfully accomplish this! This includes all of those activities and material items that are necessary in the initial acquisition of new (or re-engineered) systems, and those required for the follow-on sustaining maintenance and support of systems in operational~~

~~use, in the event of failure and for as long as required. Thus, the approach emphasized throughout this text is that the "logistics and maintenance support infrastructure" constitutes an inherent element of the system, and not something that is considered after-the-fact and somewhat unrelated. Reference: Sections 15.1 and 15.2 (pages 498-503).~~

~~5) Logistics is inherent within and throughout each phase of the system life cycle. Referring to Figure 15.10 (page 527), logistics and supportability requirements are initially established during the conceptual design phase (refer to Section 15.5.1, page 526); these requirements are then allocated downward to the various elements of the maintenance and support infrastructure during preliminary system design (refer to Section 15.5.2, page 528); day-to-day design participation, review, and evaluation takes place during the preliminary system design and detail design and development phases (refer to Section 15.5.3, page 530); the on-going and iterative supportability analysis (SA) process is implemented throughout the overall system design and development effort (refer to Section 15.6, page 532); the test, evaluation, and validation of supportability requirements in the design is accomplished during the latter phases of the detail design and development phase (refer to Section 15.7, page 535); the requirements for the sustaining maintenance and support of the system throughout its operational utilization phase is provided as required; and logistics requirements are implemented during the retirement and material recycling/disposal phase. Reference: Section 15.5 (pages 526).~~

~~6) The *logistics and maintenance support infrastructure*, as referenced throughout this text, refers to all of the logistics activities and associated materials that are reflected in Figures 3.14 (page 77), 15.2 (page 500), 15.4 (page 505), integrated in such as manner as to be considered as a major sub-system or element of the higher-level system. It basically is a term used to embrace all of what is included in Chapter 15. Reference: Section 3.5 (page 76), Section 15.1 (page 498), and Section 15.2 (page 503).~~

~~7) *Design for supportability* refers to the designing of a system configuration that incorporates the essential characteristics and attributes such that the system can later be supported effectively and efficiently throughout its planned life cycle. Some examples relative to design objectives may include the use of common and standard components, the use of high-reliable components, the incorporation of functional and physical interchangeability, accurate self-test and the incorporation of good diagnostics, good accessibility, functional modularization and ease of component removal/replacement, good labeling, and so on. The objective is to design a highly reliable and maintainable system that is easy and economical to support, requiring a minimum expenditure of resources, and where the system life-cycle cost is minimum. Supportability objectives, in this instance, apply not only to the prime mission-related elements of the system, but to all of the elements of the logistics and maintenance infrastructure described in Sections 15.1 and 15.2. Reference: Figure 2.6 (page 38), Section 4.4 (page 112), and Section 15.1 (pages 498-503).~~

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~~8) Many of the goals and objectives pertaining to the *design for supportability, design for reliability, design for maintainability,* and the *design for human factors (usability)* are mutually complementary. For "supportability," the objective is to design a system that can be easily and economically supported. For "reliability," the objective is to design a system~~

~~that is reliable and will require a minimum of support. For "maintainability," the objective is to design a system that will be easy and economical to support should the requirements for maintenance prevail. For "human factors," the objective is to design a system that can be operated and maintained easily, with personnel of minimum skill levels, and at minimum cost. If one is to design a system for the desired reliability, maintainability, and human factors, then it is likely that it will be designed for supportability as a result. All four of these objectives must be addressed, be well integrated, and be mutually supportive. Reference: Figure 2.6 (page 38), Section 4.4 (page 112), Chapter 12 (page 362), Chapter 13 (page 410), Chapter 14 (page 468), and Chapter 15 (page 497).~~

~~9) The consideration of *logistics* and the *design for supportability* must be inherent within the systems engineering process commencing in conceptual design from and beginning and extending through all subsequent phases of the system life cycle. The "design to" requirements for logistics and supportability must be established in conceptual design, allocated during the preliminary system design phase, and must be considered in the continuing day-to-day design process along with the other important characteristics such as functionality, reliability, maintainability, human factors, safety, producibility, disposability, sustainability, and so on. Reference: Figure 2.6 (page 38), Section 4.4 (page 112), Section 15.4 (page 507), and Section 15.5 (page 526).~~

~~10) Refer to Section 15.4 (pages 507-526). While there may be more than three "measures" in each of the areas listed, only three are included herein. It should be noted that whatever measures are considered, they must be "tailored" to the specific system and its mission.~~

~~(a) *Supply chain*: response time, item processing time, cost of operation and support. Reference: Section 15.4.1 (page 508).~~

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~~(b) *Purchasing and material flow*: quantity of materials processed, time to initiate and process a purchase order, cost of materials processed. Reference: Section 15.4.2 (page 509).~~

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~~(c) *Transportation and packaging*: availability of transportation, transportation time, transportation cost. Reference: Section 15.4.3 (page 510).~~

~~(d) *Warehousing and distribution*: the time that it takes to ship a product, the cost of each product shipped, the cost of inventory holding and management. Reference: Section 15.4.4 (page 512).~~

~~(e) *Maintenance organization*: maintenance labor hours per maintenance action (MLH/MA), maintenance labor hours per mission cycle (MLH/mission segment), maintenance cost per month. Reference: Section 15.4.5 (page 513).~~

~~(f) *Training and training support*: personnel training time, personnel training rate, cost per individual trained. Reference: Section 15.4.5 (page 513).~~

~~(g) *Spares, repair parts, and related inventories*: spares availability, spares demand rate, inventory level. Reference: Section 15.4.6 (page 514).~~

~~(h) *Test and support equipment*: test equipment availability, support equipment reliability, mean time between maintenance (MTBM). Reference: Section 15.4.7 (page 522).~~

~~(i) *Maintenance facility*: facility utilization, turnaround time (TAT), cost per maintenance action. Reference: Section 15.4.8 (page 523).~~

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~~(j) *Computer resources and maintenance software*: software reliability, computer availability, software complexity. Reference: Section 15.4.9 (page 524).~~

~~(k) *Technical data and logistics information*: logistics response time, information processing time, cost per logistics action. Reference: Section 15.4.10 (page 525).~~

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~~Refer to Figure 15.11 (page 529) where the various measures (metrics) associated with each of the elements of logistics are noted.~~

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~~11) Spare/repair part demand rates, criticality of spare/repair part, location of inventories, inventory levels and economical order quantities, sources of supply, and total cost are factors that need to be considered in determining supply support requirements. Type of items requiring maintenance, frequency of anticipated maintenance, maintenance processing time, availability of test and support equipment, availability of required personnel skills and facilities, contractual and proprietary matters, and the cost of maintenance are factors that need to be considered in determining test and support equipment requirements. Complexity of system operation and maintenance, frequency and duration of operation and maintenance, personnel turnover rates, and cost are important in determining personnel requirements. The number of people required for operation and support, the complexity of tasks, the number and type of configuration design changes incorporated, personnel turnover rate, and the availability of training facilities and resources are factors that need to be considered in determining training requirements. The items/products/personnel to be transported, the type and direction of transportation, the frequency and time required, availability, and cost are factors in determining transportation and handling requirements. Type and number of items requiring support, the nature of the support required (requiring normal maintenance facility or clean room laboratory), the frequency of support, the space and utilities required for support, material storage and inventory processing requirements, and cost are factors in determining facility requirements. The type of operator and maintenance tasks to be performed, the quantity and complexity of tasks, the location where the tasks are to be accomplished, the number and skill levels of the personnel operating and maintaining the system, requirements for special maintenance and overall procedures, and cost are factors needed in determining technical data requirements. Reference: Section 15.4 (page 507).~~

~~12) Referring to Equation 15.2, page 515, the probability of having a spare available is (with a component reliability of 0.85, the value of λt is 0.163).~~

~~$P = e^{-\lambda t} + (\lambda t)e^{-\lambda t} = 0.85 + (0.163)(0.85) = 0.9886$~~

~~13) Referring to Equation 15.3, page 515, the probability is~~

~~$P = e^{-\lambda t}[1 + \lambda t + \frac{(\lambda t)^2}{2!}]$~~

~~$P = 0.85\ [1 + 0.163 + \frac{(0.163)^2}{(2)(1)}] = 0.9998$~~

~~14) Referring to Equation 15.4 (page 516), the probability is (with a component reliability of 0.875, the value of λt is 0.134).~~

~~$P = e^{-2\lambda t}[1 + 2\lambda t + \frac{(2\lambda t)^2}{2!}]$~~

~~$P = e^{-0.268}[1 + 0.268 + \frac{(0.268)^2}{2}] = 0.9974$~~

~~($e^{-0.268}$ is equivalent to a reliability of 0.7649)~~

~~15) Referring to Section 15.4.6 (page 516), "Probability of mission completion"; n = 10, λ = 0.01, and t = 20 hours.~~

~~$n\lambda t$ = (10(0.01)(20) = 2.0~~

~~Enter Figure 15.7 (page 517) where $n\lambda t$ equals 2.0, and proceed to the intersection where "n" equals 2. The probability value is approximately 0.68. Thus, there is a 68% confidence that at least 8 systems will operate successfully.~~

~~16) Referring to Section 15.4.6 (page 518), "Spare part quantity determination"; K = 30, λ = 0.0001, T = 3 months, P = 0.95, Hours of Operation = (24) (30) = 720. Then $K\lambda T$ = (30) (0.0001) (24) (30) (3) = 6.48. Using the nomograph in Figure 15.8 (page 519), approximately 9 spares are required.~~

~~17) Referring to Equation 9.42 (page 264), the EOQ or Q^* is:~~

~~$Q^* = \sqrt{\frac{2C_pD}{C_h}} = \sqrt{\frac{(2)(25)(200)}{(0.25)(100)}} = 20$ units~~

~~18) Referring to Equation 9.42 (page 264),~~

~~$Q = \sqrt{\frac{(2)(160)(4)}{2}}$ $Q = 8$~~

~~Referring to Equation 9.40 (page 264),~~

~~$TC = (12)(4) + \frac{(16)(4)}{(8)} + \frac{(2)(8)}{(2)}$ or $TC = \$64$~~

~~19) The EOQ model is generally applicable in instances where there are relatively large quantities of common and standard spares and repair parts. The objective is to determine the proper balance between the costs of procurement and the costs of inventory maintenance. The anticipated Demand (D) is a prime factor here. On the other hand, application of the EOQ principle may not be appropriate when acquiring mission related~~

~~"critical" spares (where mission success and safety are more predominant than anything else), when dealing with "high value" items (items where the initial cost of acquisition is significantly high), and/or when dealing with items under warranty. Reference: Section 9.2.4 (page 258) and Section 15.4.6 (page 521).~~

~~20) Some spares/repair parts may be classified as being "high priority" if they are needed to fulfill a requirement immediately in order for the system to properly complete its mission. If an item fails and that failure precludes the system from accomplishing its mission, or causes major personal injury, then there is a "criticality" issue. Referring to Section 12.4.1 (page 385), one of the outputs from the FMECA is to identify areas of "criticality" and where system failures can significantly impact mission success. This, in turn, leads to the identification of "critical" spares, which are usually purchased via some high priority means (or equivalent). There may be other factors that also determine whether a "high priority" is required. One such instance may constitute an order that must be initiated earlier than usual because of the limited life of the future "source of supply." Reference: Section 15.4.6 (page 514).~~

~~21) The establishment of a good data collection, feedback, analysis, and reporting capability, with the objective of assessing the day to day operations of the intermediate level maintenance shop, will aid in verifying the adequacy of the type and quantity of test equipment required. This includes an assessment of the number and frequency of items arriving in the shop for both corrective and preventive maintenance, the length of the queue (if any), item process times (e.g., test equipment utilization), the thoroughness of testing, reliability and maintainability characteristics inherent within the test equipment itself, maintenance turnaround time(s), and cost. Adequacy, from a technical *performance* perspective (e.g., test equipment accuracies for electronic equipment in particular), may be verified through periodic "calibration" and the traceability of requirements back to a *transfer, secondary,* or *primary standard*. Various items may be periodically "calibrated" against some standard which, in turn, is calibrated against some higher-level standard, and so on. Reference: Section 15.4.7 (page 522).~~

~~22) If the test equipment (particularly electronic and other equipment with high accuracy requirements) is faulty, not properly maintained, or properly calibrated, then the item being supported (or checked out) will not likely perform as it should. The measurements will be incorrect and, in some instances, a failure may be induced as a result. This, of course, will likely have a negative impact on the system when the item that has been maintained in the shop is reinstalled in the system. Basically, the test equipment must be more reliable than the item(s) being tested – an accuracy of 10 to 1 would be desirable if it can be acquired, although 3 to 1, or 2 to 1, is more realistic. Reference: Section 15.4.7 (page 522).~~

~~23) The type and quantity (volume) of anticipated maintenance for the desired period of time or planning horizon need to be considered; i.e., quantity of items being returned for maintenance, the specific type of maintenance and whether corrective or preventive, the allocated time for processing these items for maintenance, the complexity of the tasks that will need to be accomplished, the requirement frequency, and so on. This will lead to determining the personnel quantities and skill levels, and the supporting resources~~

~~facilities, support equipment, software, data/information) that will be required to support the organization in accomplishing its assigned function(s). These basic requirements, and the process for determining such, are developed with the aid of the supportability analysis (SA) described in Section 15.6 (page 532). Given a "functioning" organization, the authors recommend an approach similar to that described in Section 19.4 (page 681) for the purposes of "evaluation" and the periodic assessment of the organization's capabilities and effectiveness. The authors recommend an attempt to develop a model similar to the SE-CMM, but tailored to a "maintenance" organization. Reference: Section 15.4.5 (page 513).~~

~~24) Selecting a specific mode of transportation would depend on the item(s) being transported, the distance and direction of transportation, the anticipated frequency, the allocated transportation time, the availability and reliability of the transportation capability, national and international regulatory requirements, safety and security issues, and cost. The selected approach may constitute any one of the five modes of transportation shown in Figure 15.6 (page 511), or a combination thereof (i.e., intermodal transportation). Reference: Section 15.4.3 (page 510).~~

~~25) Good *packaging* design is required, in the transporting of products from one place to another, in order to ensure that the reliability of the system (which will ultimately incorporate the product) is retained. Poor packaging design can lead to product damage, while in transit, and can cause a significant degradation in the ultimate performance and reliability of the system in which the package is installed. Damage can be induced through the lack of protection against extreme environments (e.g., temperature extremes, high humidity, vibration, shock, sand and dust, salt spray) and against illegal pilferage and sabotage. Reference: Section 15.4.3 (page 511 for packaging criteria).~~

~~26) There may be any number of different types of systems, each with a somewhat different and unique logistics and maintenance support infrastructure and operating within the same overall higher-level system of systems (SOS) configuration. As an initial step, the specific design requirements for the new system being developed should be determined on a preliminary basis. Next, these requirements need to be addressed in the context of the total SOS configuration. From an interoperability perspective, are there conflicting requirements? Are there any logistics and supporting resources that can be shared with the other systems in the network? Are there any negative impacts from the proposed support capability for the newly developed system on the other systems in the SOS configuration, or from the other systems on the newly developed system? If there are any sharing opportunities, then the designers of the new system should work with their counterparts associated with the other applicable systems in the network. There may be opportunities available for the overall reduction of support requirements (and life-cycle cost) in the event that some sharing is possible. If there are any "conflicting" requirements, the designers need to work with their counterparts associated with the other systems where the conflicts exist and determine whether a resolution is possible. As this process evolves, design trade-offs are accomplished and compromises may occur as a result. Care must be taken to ensure that the requirements for the new system are not compromised in any way. In any event, this becomes an iterative process in arriving at a final design configuration. Reference: Section 15.2 (page 503).~~

~~27) Referring to the answer in response to Question 26, the basic design approach in developing a new system in a system-of-systems (SOS) configuration is discussed. The “challenges” pertain to the possible “conflicting” requirements among the various different and unique systems within a given SOS configuration network and the subsequent process in arriving at an agreeable solution for all concerned. First, there may be a negative impact on the new system being designed caused by one or more of the other systems in the SOS configuration. The designer of the new system may either be forced into a re-design effort for the new system or an effort to convince his/her counterparts associated with the other system(s) in question to initiate a design change at their end. Second, there may be “conflicting” requirements relative to certain aspects of the support structure such as the supply chain. Referring to Figure 15.3 (page 504), there could be conflicts in major supplier requirements, particularly with regard to priorities in cases where an individual supplier is providing support for several different systems within the same SOS network. Conflicts may involve technical discrepancies or organizational and management political issues. Care must be taken to ensure that all supplier requirements are being met for each of the systems in a given SOS network. In any event, the “challenges” could be numerous. Reference: Section 15.2 (page 503).~~

~~28) The logistics and maintenance support infrastructure, as a total entity, can actually be "validated" only after the system is delivered and in operational use by the customer (user), as part of Type 4 Testing (refer to Section 6.2.5, page 157). The "infrastructure," as a major element of the system, must be fully installed and functioning in an "operational" sense. Prior to this time, various elements of the infrastructure (e.g., personnel quantities and skills, support equipment, maintenance software, technical data) can be validated, on a relatively independent basis, through the accomplishment of Types 1, 2, and 3 Testing, described in Section 6.2 (page 153). For example, refer to eleven (11) categories of testing in Section 6.2.3 (page 154) within the spectrum of Type 2 Testing. Reference: Section 15.7 (pages 535-537).~~

~~29) In recent years, the field of logistics and maintenance support has expanded tremendously with the advent and utilization of many relatively new "technologies" to include the implementation of electronic commerce (EC) methods, information technology (IT) and data processing methods, electronic data interchange (EDI), global positioning systems (GPS), radio frequency identification (RFID) tags, various communications tools (internet, web sites, cell phones, iPods), high speed transportation capabilities, and so on. Of significance is the application of both “active” and “passive” RFID tags being used in inventory (i.e., product) identification and “tracking.” In summary, through selective implementation of these and related methods/techniques, the field of logistics has and can continue to take on a truly *global* and *international* perspective. The student can expand on this with some specific examples. Reference: Section 15.1 (page 501) and Section 15.3 (page 506).~~

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~~CHAPTER 16~~

~~DESIGN FOR PRODUCIBILITY, DISPOSABILITY, AND SUSTAINABILITY~~

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~~1) To bring a system *into being* is to achieve a high degree of organization and order; to *cease being* is to return a system to a state of disorganization and disorder, as in the concept of entropy. The **degree of order exhibited by an engineered system is a remarkable manifestation of system design**; design that is largely responsible for the realized outcome of producibility and disposability, as well as all other design dependent parameters.~~

~~2) The interconnections among producibility, disposability, and sustainability are subtle but real. A good level of *producibility* comes from the use of standard materials and processes and results in enhanced product reliability; promotes ease of product assembly and disassembly which, in turn, enhances product maintainability and disposability; results in "simplicity" of operations, thereby reducing personnel skill requirements; and leads to minimum requirements for maintenance and support, which enhances system supportability. Good producibility and disposability tend to minimize material use, energy use, and waste production, thereby increasing sustainability. Of course, sustainability also depends heavily on well-engineered system behavior during utilization and design for extended life. Refer to Figure 16.1 (page 543).~~

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~~3) Technological services sustain human existence in the physical sense, in that their utility is physically manifested. All that has utility is physically manifested, with utility defined as the power to satisfy human wants. Ecological services have physical aspects too, but extend into the **biological and environmental aspects of the natural world** in which humans must live. Refer to Section 16.1.1 (page 542).~~

~~4) The most prominent incentive promoting *green engineering* is realization by the producer that there exists an expectation originating with the customer or consumers. This expectation is generally external to the producer and inherent in the market. Good will and the profit motive of the producer will drive some degree of internal response. But organized pressure through government legislation is needed too. Although social in its origin, customer expectations of green products, structures, and services can only be effectively met by acting on factors amenable to design. Refer to Section 16.1.2 (page 543).~~

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~~5) ECDM is an *evolutionary design paradigm* that starts with consideration of environmental impacts caused by products and product-related processes during the system design and development process. It is essentially a "model" which can be broken down into two categories: (a) design for environment (DFE) and (b) environmental management (EM). The DFE approach is a proactive activity that aims to prevent environmental impacts, whereas EM is remedial in nature. Refer to Section 16.2.2 (page 547) and to Figure 16.4 (page 555) for an illustration of the ECDM activity flow process.~~

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6) ~~*Producibility* is a measure of the relative ease and economy with which a product or service may be produced by the production or service system. The characteristics of design must be such that the entity can be produced easily and economically, using conventional and advanced manufacturing methods and processes without sacrificing functionality, performance, effectiveness, or quality. *Simplicity* and *flexibility* are overarching objectives, and the goal is to minimize the use of critical materials and critical processes, the use of proprietary items, the use of special production tooling and facilities, the application of unrealistic tolerances in fabrication and assembly, the use of special test systems, and the use of high skills in manufacturing. Producibility is a design-dependent parameter and must be addressed in the early stages of preliminary design.~~

7) ~~Refer to Section 16.3.1 (page 547) for a listing and discussion of the *measures* of producibility and Section 16.3.2 (pages 549-552) for approaches to *modeling manufacturing progress*. The degree of manufacturing progress depends directly on product or service producibility. Higher levels of production progress mean lower labor and energy requirements per unit of output.~~

8) ~~*Disposability* pertains to the degree to which an item can be broken down and recycled for other uses or disposed of without causing undue environmental degradation; i.e., without resulting in the generation of solid waste, toxic substances (air pollution), water pollution, noise pollution, and so on. Disposability is a design-dependent parameter and must be addressed from the beginning. It also relates to producibility, because a product that incorporates standard components and is easy to assemble should be relatively easy to disassemble for reuse or disposal. Without the consideration of disposability in design, environmental problems and human health hazards are likely to be present. Refer to Section 16.5 (pages 556-558).~~

9) ~~Measures of disposability may include both *time* and *cost* factors associated with the disposal of a given item. Additionally, there may be some measures associated with the various environmental issues; i.e., the amount of solid waste generated in the disposal of an item, the amount of air pollution generated, the amount of water pollution generated, the amount of noise pollution generated, and so on. Refer to some technology categories for the eco-factory in Figure 16.5 (page 558).~~

10) ~~*Producibility* is an *internality* because it refers to the ease with which *the factors of production* are combined and employed within the firm. Production factors are entirely under control of the producing organization or manufacturer and the costs thereof are of great concern to corporate profitability and those concerned with the "bottom line". *Disposability* is normally *external* to the firm, in that the concern for environmental impact and the societal cost thereof is not under the direct control and not directly of interest to the producing enterprise. As a design-dependent parameter, however, disposability is one more factor inherent in the design that should be considered during the early phases of design.~~

11) ~~Incentives that make disposability somewhat of an internality are: (a) the corporate image and esteem among stakeholders, (b) the good will generated by care directed to the disposal of process waste and product remains, (c) the value of reclaimable and recyclable~~

~~materials, and (d) the saving in prospect for customers over the life cycle of a product or system that is easily disposed of. When internal incentives are insufficient, government can and probably will levy a tax, a fee, or a fine on discarded product and/or on process waste discharged into the environment. This will get the attention of the producer through a *forcing function* encouraging greater consideration of design for disposability.~~

~~12) *Environmental quality* is a general term that refers to a "level of goodness" as it applies to the overall environment in which humans live. It is a relative term and can be measured on the basis of the degree of "cleanliness" as it pertains to air quality, water quality, noise level, and so on. The objectives are to maximize air and water quality, minimize noise levels, and to eliminate the introduction of harmful substances into the environment. Refer to Section 16.6.1 (page 559).~~

~~13) Within the context of the eco-design of products and processes, the ECDM approach seeks to *discover product innovations* that will result in reducing harmful environmental impacts at any or all stages of the life cycle, while satisfying cost and performance as well as quality objectives. For ECDM to be implemented and integrated effectively into the eco-product development process, several key elements are required throughout the life-cycle stages: life-cycle synthesis, life-cycle analysis, and life-cycle evaluation, all needed to determine the best alternative that balances competing design considerations. Figure 16.6 (page 561) summarizes ECDM-related problems.~~

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~~14) A part of functional analysis includes the combining and grouping of similar functions into logical subdivisions, identifying major subsystems, configuration items, physical units, assemblies, and so on. The approach used and the results from system "packaging" can have a great impact on the ease and economy of being able to produce various subsystems and system elements in multiple quantities. Refer to Section 4.3 (page 104).~~

~~15) *Demanufacturing* pertains to the design of an item so that it can be easily and economically disassembled (taken apart) or broken down to the level required such that like materials and residue can be either recycled or disposed of without significant degradation to the environment. An example is the disassembly of an automobile engine in preparation for rebuilding. The disassembly and rebuilding can be called *remanufacturing*, with demanufacturing being the first part of the process. Refer to Section 16.4.3, Figure 16.4 and Footnote 6 all on page 555.~~

~~16) Goals for the elimination of waste depend upon where one is in the life cycle. For new systems under development, an objective is to design a product where most of its content can be reused and/or recycled without causing undue degrading effects on the environment. For those systems already in being, accomplishing a functional analysis and evaluating each of the functions in terms of input/output/waste/cost can lead to the identification of high cost / high risk areas where the degree of waste could be excessive. These functional areas are then subject to redesign to goals and timetables.~~

~~17) If a product is designed to be *producible*, it should be easy to assemble and/or disassemble which, in turn, should enhance its mobility and facilitate the process of transportation.~~

~~Producibility, mobility, and transportability are all related and mutually supportive. Refer to Market Measures (page 548-549) and Section 15.3 (pages 503-507).~~

~~18) Refer to Section 16.4.1 (page 552) for guidance. Pick five and describe each one briefly.~~

~~19) In the production of an item or batch, a series of operations is required. An estimate establishes the anticipated time and cost associated with the process. As these steps are repeated in the production of additional units of the same item (or in the provision of like service activities), learning takes place and the time and cost factors usually become less than experienced initially. Further, each time that the process is repeated improvement will be obtained until a leveling off occurs where little additional improvement is realized. The plot of such progress displays an empirical learning curve. Theoretical learning "models" for a range of parameters exist. Refer to Figure 16.3 (page 551) for one such model.~~

~~Learning curves may be classified as *unit* or *cumulative*. For example, a 70% unit learning curve is realized when the cost of producing the first item is $100, the cost of producing the second is $70, the cost of producing the fourth is $49, and the cost of producing the eighth is $34. For an 80% cumulative learning curve, if the cost of producing the first ten items is $100 each and the cost of producing the next twenty items is $80 each, then the cost of producing the next forty items is $64 each. Learning curves are applicable when there are repetitive tasks or activities anticipated and there is a need to predict the projected costs over additional units and time. Refer to Section 16.3.2 (pages 549-552).~~

~~20) The *eco-factory* is another name for an "ecology-based production system". The objective is to *design for environment* (*DFE*). Refer to Section 16.1.3 (page 544) for a definition and description and to Figure 16.5 (page 558) for some technology categories.~~

~~21) *Green engineering* refers to an engineering endeavor that is involved in the design of a system, product, or process that is intended to be "environmentally friendly". The objective is to produce a product or a process that will not degrade the environment in any significant way. Design for sustainability subsumes the intent of green engineering if recognized as being both internal and external. Refer to Section 16.6.1 (page 559).~~

~~22) Referring to Figure 2.2 (page 30), the four life cycles represent the activities that must be addressed when making plans pertaining to system design and development, production, operation, support, and/or retirement. They are interactive in that decisions in any one will impact the others. It is the fourth life cycle that includes the activities necessary to enable the retirement, recycling, and/or disposal of those elements of the system, the production capability, and maintenance and support infrastructure that have become obsolete and need to be "retired" and phased out. Accordingly, a plan pertaining to the design of the prime system elements (e.g., selection of technologies, selection of materials, packaging of components) could have a significant impact on the production capability (manufacturing process selected) and on the degree of supportability; a plan pertaining to the development of the production capability (e.g., assembly process) could have a significant impact on supportability and on demanufacturing (for disposal), and so on.~~

~~23) Student exercise requiring reference to the web sites for ISIE ***http://www.is4ie.org*** and ISSP ***http://sustainabilityprofessionals.org***~~

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~~CHAPTER 17~~

~~DESIGN FOR AFFORDABILITY~~
~~(LIFE - CYCLE COSTING)~~

~~1) *Life cycle cost* (*LCC*) includes **the total cost of a system over its entire life cycle**. LCC includes all of the costs associated with the activities identified in Figure 17.1 (page 568), including the visible and the not so visible as in Figure 17.2 (page 569). When performing a LCC analysis, all "future" research and development costs, production and/or construction costs, operation and maintenance and support costs, retirement and material recycling/disposal costs are to be identified and considered in the evaluation process. "Past" (or "sunk") costs while providing a good historical view are not to be considered. Sunk costs have no place in an analysis as they will have no effect on decisions in the future. Reference: Section 17.1 (page 567).~~

~~2) Refer to Section 3.6 (page 82). *Design to cost* (*DTC*) refers to an economic "design to" requirement; i.e., the system shall be designed so that the ultimate LCC will not exceed "x" dollars per unit or "y" present equivalent, annual equivalent, or future equivalent dollars per system. In the past, the emphasis on "design to cost" has been applied to the final manufacturing or production cost of an item, but it should includes *all* costs included in the DTC figure of merit; i.e., design and development, production, deployment, operation, support, and retirement.~~

~~The DTC factor or some equivalent economic design to parameter should be included as a TPM as first identified in Section 3.6 (page 82). DTC factors must be specified when the requirements for a system are initially defined during the early phases of conceptual design, where the greatest benefit can be realized by influencing the ultimate costs of the system. Refer to Figure 17.3 (page 571).~~

~~3) When involved in the decision making process (whether for a "design" situation or for an operational activity), one should address the *total* cost impact of each proposed alternative prior to making a final decision to enable the assessment of associated risks. Even if a decision is made based on some specific facet of cost (i.e., initial procurement price), the consequences from a life cycle cost perspective should be the basis for decision. Often what is initially perceived as being a low cost investment turns out to be very costly when considering operating, maintenance, disposal and other downstream costs.~~

~~4) Refer to Sections 3.7 (page 86) and 4.3 (page 104). *Functional costing* refers to determining the total cost associated with the accomplishment of a given "function" (independent of how that function is to be performed). What does it cost to accomplish Function "X"? There may be various feasible approaches possible in responding to a given functional requirement, each resulting in a different cost due to the different resources required in each instance (i.e., combination of hardware, software, people, etc.) Trade off studies should be conducted, with the objective of minimizing the ultimate cost per function.~~

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~~5) There are twelve basic steps in conducting a life-cycle cost analysis as identified in Figure 17.5 (page 575), although there certainly may be some variations depending on the nature of the problem, situation, system, etc. The 12 sub-headings in Section 17.3 (beginning on page 574) describe the basic process that is recommended.~~

~~6) A *cost breakdown structure* (*CBS*) constitutes a logical subdivision of costs by functional area of activity, major elements of a system, and/or discrete classes of common or like items. It includes **all costs**, broken down to the depth required for the purposes of gaining "visibility" relative to the system being evaluated. Refer to Figure 17.6 (page 577) and Figure 17.7 (page 579) for examples.~~

~~The CBS can be related directly to the Summary Work Breakdown Structure (SWBS) as long as the SWBS includes all costs. A Contract Work Breakdown Structure (CWBS), which will reflect the activities and costs for a given negotiated contract, may not include all of the costs required by the CBS and, thus, the CBS and CWBS may not directly related to each other. Refer to Section 17.3.3 and Footnote 7 on page 576.~~

~~7) There should be a direct relationship between the CBS and the functional analysis, and one should be able to identify each of the functions (in the functional analysis) within the CBS. Refer to Section 17.3.3 and Footnote 9 on page 576.~~

~~8)Referring to Figure 17.9 (page 581), cost estimating methods may be categorized as *direct engineering/manufacturing estimates* (*standard factors*), *analogous estimates*, and *parametric estimates*. Obviously, as one progresses through a program, the task of cost estimating becomes simpler as more becomes known about the system and its associated activities. However, it is at the early stages of system development when cost estimating (particularly in conducting life-cycle cost analyses) is particularly important. It is at this point when the availability of good cost data is limited (if it exists at all). Thus, the dependence on various estimating methods to provide needed information.~~

~~What is referred to as the "direct estimating" approach involves the collection of data from past experience and the development of specific discrete factors to use in the estimates; e.g., \$/labor hour, \$/volume of material, \$/pound/mile of distance, \$/cubic volume of utilized space, \$/pound of fuel, \$/item of inventory, \$/procurement action, etc. Basically, one uses factors that are usually applied in a typical "cost to complete" exercise for a given project.~~

~~When desired cost information is not readily available, one might have to rely on "analogous cost estimating". This involves the estimation of costs by comparing the current product/system configuration with a similar configuration from the past (where, hopefully, the costs are known) and using a combination of complexity and other factors to adjust the cost for the new item. For example, this item is twice as complex as a similar item in the past; therefore, the costs will likely be twice as great.~~

~~A third approach may involve the use of "parametric" estimates. From past experience, one attempts to relate cost to some physical or functional parameter of the system; e.g., cost related to aircraft weight, cost per unit volume of material, cost per mile transported, and so~~

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~~on. Such factors may be similar to those used in direct estimating, but perhaps not as precisely applied, particularly in the early stages of conceptual design. When using "parametric" methods, care must be taken to ensure that the relationships that have been developed in the past represent an application similar to the current situation. For example, parametric relationships for a ship may not be applicable to an aircraft.~~

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~~9) *Activity based costing (ABC)* is a method for collecting cost data, tracing costs back to their actual "causes," and for determining the specific costs associated with a given product or process. To be effective, total cost management (and the accomplishment of life-cycle cost analyses) requires *full-cost visibility* allowing for the traceability of all costs back to the activities, processes, or products that generate the costs. The principles of ABC are given on pages 581-582, specifically the six point list on page 582. The ABC approach is different from the conventional accounting method(s) in that the latter is more oriented to the "short-term" (in response to year-end business reporting needs) and the fact that it is difficult (if not impossible) to trace all costs back to their respective "causes." For example, "overhead" or "indirect" costs, which often constitute more than 50% of the total, are not easily traceable or easily allocated.~~

~~10) When evaluating a system overall, one should address the issue of *total value*, considering both the "technical factors" and the "economic factors." Within the economic domain are "revenues" and "costs," Refer to Figure 17.1 (page 568). While "revenues" are generally viewed to be positive values, there can be a "cost" involved when the expected revenues turn out to be less than initially anticipated. For example, if a production capability is inefficient, then the production rate, or the number of items to be produced, will be less than anticipated. This will result in less revenue which can be considered to be a "cost" capable of affecting its applicable program phase as in Figure 17.9 on page 581.~~

~~11) Refer to the CBS in Figure 17.6 on page 577. This structure may not be adequate in the performance of life-cycle cost analyses across the entire system life cycle. The CBS must be "tailored" to the particular application, providing the necessary visibility in critical areas. It must include the proper relationships as conveyed in the sample of Figure 17.7 on page 579, and so on. For example, if the system being evaluated is very "operator-personnel intensive," then the analyst should probably expand Category (Coo), while combining some other categories. If there are numerous transportation needs, a greater depth of coverage will be required within Category (Cod) to provide the necessary visibility. While the top-tier structure in Figure 17.6 may be adequate, the nature (specific cost categorization) and depth of coverage at the lower levels will likely be somewhat inadequate.~~

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~~12) Refer to the answer for Problem 8 addressing *parametric cost estimating*. These relationships may be developed from data derived from similar systems in the past, wherein costs can be related to the physical and functional parameters of the systems. Each life-cycle cost profile shown in Figure 17.13 (page 591) is a "signature" of sort for a particular type of system and may be used to estimate the cost profile for a similar system. Figure 17.9 (page 581) indicates that parametric cost estimating will be applicable mostly during~~

~~the early phase of the life cycles (left portions) shown in Figure 17.13, whereas the other estimating methods will be applicable later on.~~

~~13) Refer to Section 16.3.2 (page 549) and Figure 16.3 (page 551). Learning curves can be applied to estimating costs for any activity which is repetitious in nature; e.g., the production of a multiple quantity of products where learning takes place as manufacturing progresses. In general, learning curves are applied to show a savings in time and cost as multiple quantities of an item are produced. However, there are instances when a multiple quantity of items are produced and where the cost of the second is higher than the cost of the first, the cost of the fourth is higher than the cost of the second, etc. In this situation, there is a failure to achieve the assumed learning curve savings on which manufacturing costs estimates were originally based. This can occur when there are numerous design changes initiated during initial production, when there are changes in management structure and/or lower level personnel, and/or when there are numerous changes in procedures.~~

~~14) In performing a life cycle cost analysis, it may be appropriate to first develop a profile (such as shown conceptually in Figure 7.1 on page 177, or in Figure 17.11 on page 588) in "constant" units; e.g. in current year dollars for each year in the life cycle (without including inflation or making other adjustments). As "cause and effect" is analyzed from year to year, it is often easier to proceed if given a known baseline for comparative purposes. Then, a second profile should be developed in order to show 2014 dollars in 2014, 2015 dollars in 2015, 2016 dollars in the year 2016, and so on. This "inflated" profile will include inflationary effects, the effects of learning, projected cost growth from year to year, and so on. This is similar to a normal "cost to complete" exercise for a typical project, except that the objective is to project~~ ~~*all life cycle costs*~~~~. The third profile is one where all future costs are related back to the "present time," or the common point in time when decisions are being made (i.e., present equivalent, annual equivalent, or future equivalent). In the evaluation of alternatives, one must compare the profiles for each on an~~ ~~*equivalent*~~ ~~basis to incorporate the "time value of money" as developed in Chapter 8 (page 204).~~

~~15) An advantage in presenting the costs in a format similar to what is shown in Figure 17.10 on page 586 is to be able to relate the costs back to a specific function (or block) in the cost breakdown structure (CBS), and to be able to quickly determine the "high cost contributors." In some cases, particularly when attempting to implement a continuous product/process improvement initiative for cost reduction purposes, the presentation of costs in terms of "percent of total" is often more meaningful than worrying about the specific "bottom line" value. Simply pick the highest, then the next highest, etc., initiating recommendations for improvement at each step in the process. The format of Figure 17.10 may be used as the basis for creating a PC based spreadsheet model.~~

~~16) The goal is to find out how sensitive the results of an LCC analysis are in terms of the input factors and the underlying assumptions that have been made. On occasion, the input data may be highly "suspect" (not based on good assumptions or good historical information); yet, the results of the analysis (and the decision to be made) may be heavily dependent on this early input. By varying input factors (e.g., MTBM), the degree of variation will~~

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~~become visible at the output stage (e.g., variation in LCC). Will a relatively small variation in the input result in a large variation at the output? How much variation at the input can be accommodated before the ultimate decision shifts to favor a different alternative? What parameters have the greatest impact on the results of a LCC analysis, and what is the magnitude of this impact? The results of a *sensitivity analysis* lead into the identification of the *risks* associated with the decision making process. Refer to Section 17.3.9 on page 589.~~

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~~17) Referring to Figure 17.12 on page 590, a *Pareto analysis* is accomplished to show the relative degrees of importance (or priorities) that one should address in the solving of problems, in the assignment of resources, and so on. In the figure, for example, the areas that need the most attention are indicated. Refer to Section 17.3.10 (page 590).~~

~~18) Student exercise directed to a personal automobile. Although no design and development costs are involved, all costs beginning with acquisition and ending with net salvage value or net trade in value should be considered. Include such hidden costs as taxes and insurance. Include quantifiable hidden benefits such as additional net job income. Also, it is appropriate to ponder the offer received from a friend to pay for needed gasoline for joining you for a trip home. How should the true cost to you be determined? How would you explain this true cost to your friend?~~

~~19) In the given table, it appears initially that *Configuration A* is preferred, as it seems to be significantly more cost effective than Configuration B. However, prior to making a final decision, the analyst needs to do a "breakeven analysis" to determine the future point in time when Configuration A assumes a "preferred position" (see the example of Figure 17.21 on page 616 where Alternative A assumes the preferred position at about 9 years out). If the cross over point is early enough in the life cycle, then one would still select *Configuration A*. If not, Configuration B might be selected instead.~~

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~~20)(a) If the MTBF is *decreased*, the frequency of maintenance is likely to increase, and the LCC is likely to increase as well; (b) If the $\overline{M}ct$ is *increased*, the system downtime will likely increase, the supporting resources will likely increase (e.g., more maintenance labor hours will be needed), and the LCC will likely increase as well; (c) If the MLH/OH is *increased*, the cost for maintenance people will probably increase, and the resulting LCC will likely increase as well. There may be a situation where an increase of MLH/OH could result in a lower overall life cycle cost (when "X" MLHs of "high skills" where the cost is high are replaced by a greater number of "Y" MLHs of "low skills" where the cost is lower); (d) If the system utilization is *increased* (and all other factors to include reliability and revenue remain the same), there will be more hours in which the system is being used (i.e., stressed), there will probably be more maintenance actions required, and the LCC will likely increase; (e) If the system fault isolation capability is *inadequate*, there will be more "false alarms," more of a "trial by error" maintenance approach, more consumption of materials, and LCC will likely increase.~~

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~~The steps that one should take to reduce some of the costs discussed above are as follows: (a) identify the high cost contributors by developing a table like the one in the textbook on page 586; (b) determine the cause and effect relationships using an Ishikawa or similar~~

~~approach; (c) propose recommendations for design or operational improvement which will modify the system as appropriate to lower the overall LCC. The above should be done on a continuous improvement basis over time.~~

~~21) Table 1 exhibits the information given in this problem over a 10-year evaluation horizon.~~

~~Problem 21 - Table 1. BAF Corporation costs by program year.~~

~~Evaluation Category~~	~~Cost by Program Year ($)~~										~~Total Cost ($)~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~											
~~1. Manufacturing Cost~~	~~9,875~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~19,750~~	~~187,625~~
~~2. Distribution Cost~~	~~1,975~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~3,950~~	~~37,525~~
~~3. Operating Cost~~	~~3,240~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~6,480~~	~~61,560~~
~~4. Maintenance Cost~~											
~~a. Scheduled~~											
~~b. Unscheduled~~	~~1,300~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~2,600~~	~~24,700~~
~~Total Cost~~	~~16,390~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~32,780~~	~~311,410~~
~~Configuration "B"~~											
~~1. Manufacturing Cost~~	~~7,875~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~15,750~~	~~149,625~~
~~2. Distribution Cost~~	~~2,625~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~5,250~~	~~49,875~~
~~3. Operating Cost~~	~~648~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~1,296~~	~~12,312~~
~~4. Maintenance Cost~~											
~~a. Scheduled~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~500~~	~~5,000~~
~~b. Unscheduled~~	~~1,200~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~2,400~~	~~22,800~~
~~Total Cost~~	~~12,848~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~25,196~~	~~239,612~~
~~Configuration "C"~~											
~~1. Manufacturing Cost~~	~~10,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~20,000~~	~~190,000~~
~~2. Distribution Cost~~	~~2,500~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000~~	~~5,000q~~	~~47,500~~
~~3. Operating Cost~~	~~540~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~1,080~~	~~10,260~~
~~4. Maintenance Cost~~											
~~a. Scheduled~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~800~~	~~8,000~~
~~b. Unscheduled~~	~~1,238~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~2,475~~	~~23,513~~
~~Total Cost~~	~~15,078~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~29,355~~	~~279,273~~

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~~Problem 21 – Table 2. Evaluation of alternative configurations for the BAF Corporation.~~

~~Program year, n~~	~~(P/F, 10%,n)~~	~~Configuration “A”~~		~~Configuration “B”~~		~~Configuration “C”~~	
		~~Revenues ($)~~	~~Cost ($)~~	~~Revenues ($)~~	~~Cost ($)~~	~~Revenues ($)~~	~~Cost ($)~~
~~0~~	~~1.0000~~	~~—~~	~~15,000~~	~~—~~	~~28,000~~	~~—~~	~~23,000~~
~~1~~	~~0.9091~~	~~35,910~~	~~14,900~~	~~47,228~~	~~11,680~~	~~45,455~~	~~13,707~~
~~2~~	~~0.8265~~	~~65,294~~	~~27,093~~	~~86,783~~	~~20,824~~	~~82,650~~	~~24,262~~
~~3~~	~~0.7513~~	~~59,353~~	~~24,628~~	~~78,887~~	~~18,930~~	~~75,130~~	~~22,054~~
~~4~~	~~0.6830~~	~~53,957~~	~~22,389~~	~~72,715~~	~~17,209~~	~~68,300~~	~~20,049~~
~~5~~	~~0.6209~~	~~49,051~~	~~20,353~~	~~65,195~~	~~15,644~~	~~62,090~~	~~18,227~~
~~6~~	~~0.5645~~	~~44,596~~	~~18,504~~	~~59,273~~	~~14,223~~	~~56,450~~	~~16,571~~
~~7~~	~~0.5132~~	~~40,543~~	~~16,823~~	~~53,886~~	~~12,931~~	~~51,320~~	~~15,065~~
~~8~~	~~0.4665~~	~~36,854~~	~~15,292~~	~~48,983~~	~~11,754~~	~~46,650~~	~~13,694~~
~~9~~	~~0.4241~~	~~33,504~~	~~13,902~~	~~44,531~~	~~10,686~~	~~42,410~~	~~12,449~~
~~10~~	~~0.3856~~	~~30,462~~	~~12,640~~	~~40,488~~	~~9,716~~	~~38,560~~	~~11,319~~
~~Salvage~~	~~0.3505~~	~~351~~	~~—~~	~~876~~	~~—~~	~~771~~	~~—~~
~~Totals~~		~~449,875~~	~~201,524~~	~~598,845~~	~~171,597~~	~~569,786~~	~~190,397~~

~~Present equivalent value of Configuration “A” = $449,875 – $201,524 = $248,351~~

~~Present equivalent value of Configuration “B” = $598,845 – $171,597 = $427,248~~

~~Present equivalent value of Configuration “C” = $569,786 – $190,397 = $379,389~~

~~Configuration “B” is the recommended Alternative~~

~~22) (a) Assume that System XYZ is “isolated” in terms of external interaction affects; address System XYZ as an entity.~~

~~There are two mutually exclusive configurations being proposed for System XYZ, and each configuration will meet the required mission needs in terms of performance. The objective is to make a selection in terms of the lowest life cycle cost.~~

~~Throughout the program time span of 10 years, there are events associated with the design and development, test and evaluation, production, operation and maintenance. These events give rise to individual costs which are identified on a year to year basis, total for each year, and discounted to the present value. Discounting is accomplished based on the assumption that other alternatives exist, and that the various configurations of System XYZ are being evaluated on an equivalent basis.~~

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~~An initial step involves developing a matrix for collecting the various costs each year in terms of their inflated values. These costs are subdivided into: 1. Design and Development; 2. Production; and 3. Operations and Maintenance as shown in the table below.~~

~~Problem 22 - Table 1. System XYZ Life Cycle Cost Summary ($)~~

	~~Life-Cycle Year~~										~~Total~~
~~Item~~	~~1~~	~~2~~	~~3~~	4	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	~~Cost ($)~~
~~Configuration "A"~~											
~~1. Design and Development~~											
~~a. Prime Equipment~~	~~50,000~~	~~30,000~~									~~80,000~~
~~b. Special Support Equip.~~	~~20,000~~	~~10,000~~									~~30,000~~
~~2. Production~~											
~~a. Prime Equipment~~	—	~~210,000~~	~~210,000~~	~~420,000~~	~~420,000~~						~~1,260,000~~
~~b. Special Support Equip.~~	—	~~26,000~~	~~13,000~~	~~26,000~~	~~13,000~~						~~78,000~~
~~3. Operations and Maint.~~	—	~~42,000~~	~~66,290~~	~~133,115~~	~~203,597~~	~~274,111~~	~~274,111~~	~~274,111~~	~~159,870~~	~~114,201~~	~~1,541,406~~
~~Total Discounted Cost (15%)~~	~~70,000~~ ~~60,872~~	~~318,000~~ ~~240,440~~	~~289,290~~ ~~190,208~~	~~579,115~~ ~~331,138~~	~~636,597~~ ~~316,516~~	~~274,111~~ ~~118,498~~	~~274,111~~ ~~103,038~~	~~274,111~~ ~~89,607~~	~~159,870~~ ~~45,451~~	~~114,201~~ ~~28,230~~	~~2,989,406~~ ~~1,523,998~~
~~Configuration "B"~~											
~~1. Design and Development~~											
~~a. Prime Equipment~~	~~70,000~~	~~30,000~~									~~100,000~~
~~b. Special Support Equip.~~	~~17,000~~	~~6,000~~									~~23,000~~
~~2. Production~~											
~~a. Prime Equipment~~	—	~~230,000~~	~~230,000~~	~~460,000~~	~~460,000~~						~~1,380,000~~
~~b. Special Support Equip.~~	—	~~24,000~~	~~12,000~~	~~24,000~~	~~12,000~~						~~72,000~~
~~3. Operations and Maint.~~	—	~~46,000~~	~~59,601~~	~~119,222~~	~~168,458~~	~~219,235~~	~~219,235~~	~~219,235~~	~~127,415~~	~~91,800~~	~~1,270,201~~
~~Total Discounted Cost (15%)~~	~~87,000~~ ~~75,655~~	~~336,000~~ ~~244,050~~	~~301,601~~ ~~198,303~~	~~603,222~~ ~~344,922~~	~~640,458~~ ~~318,436~~	~~219,235~~ ~~94,775~~	~~219,235~~ ~~82,410~~	~~219,235~~ ~~71,668~~	~~127,415~~ ~~36,224~~	~~91,800~~ ~~22,693~~	~~2,845,201~~ ~~1,499,136~~

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~~Next, costs in each of the categories of Design and Development, Production (Investment), and Operations and Maintenance should be developed for use in populating Table 1. This is accomplished as follows and verifies the values already entered:~~

~~1. Design and Development Costs~~

~~Non-recurring costs associated with the design and development of System XYZ (and for special support equipment) are presented in raw form in the problem statement and entered in Table 1 without showing computations involved.~~

~~2. Production Costs (Investment)~~

~~The costs of operational systems and special support equipment are provided in the problem statement. These costs include both recurring production costs and amortized non-recurring costs, including initial setup. The development of these costs is presented in Table 2 and then entered in Table 1.~~

~~Problem 22 - Table 2. Production Costs~~

	~~Year~~				
~~Item~~	~~2~~	~~3~~	~~4~~	~~5~~	~~Total~~
~~Configuration "A"~~	~~(10 Systems)~~	~~(10 Systems)~~	~~(20 Systems)~~	~~(20 Systems)~~	~~(60 Systems)~~
~~System XYZ~~	~~$210,000~~	~~$210,000~~	~~$420,000~~	~~$420,000~~	~~$1,260,000~~
~~Support Equipment~~	~~26,000~~	~~13,000~~	~~26,000~~	~~13,000~~	~~78,000~~
~~Total~~	~~$236,000~~	~~$223,000~~	~~$446,000~~	~~$433,000~~	~~$1,338,000~~
~~Configuration "B"~~	~~(10 Systems)~~	~~(10 Systems)~~	~~(20 Systems)~~	~~(20 Systems)~~	~~(60 Systems)~~
~~System XYZ~~	~~$230,000~~	~~$230,000~~	~~$460,000~~	~~$460,000~~	~~$1,380,000~~
~~Support Equipment~~	~~24,000~~	~~12,000~~	~~24,000~~	~~12,000~~	~~72,000~~
~~Total~~	~~$254,000~~	~~$242,000~~	~~$484,000~~	~~$472,000~~	~~$1,452,000~~

~~3. Operations and Maintenance Costs~~

~~Operational and maintenance costs are based primarily on the frequency of maintenance (or the number of maintenance actions per year) and the logistic support resources required to perform that maintenance. The number of maintenance actions (particularly corrective maintenance) is a function of system utilization (total hours of system operation) and the MTBM factor. Total system operating hours by year (assuming a 365-day year) are given in Table 3.~~

~~Problem 22 - Table 3. System Operating Hours~~

~~Year 1~~	~~Year 2~~	~~Year 3~~	~~Year 4~~	~~Year 5~~	~~Year 6~~	~~Year 7~~	~~Year 8~~	~~Year 9~~	~~Year 10~~
~~0~~	~~0~~	~~14,600~~	~~29,200~~	~~58,400~~	~~87,600~~	~~87,600~~	~~87,600~~	~~51,100~~	~~36,500~~

~~The assumed average number of maintenance actions for System XYZ is based on operating hours divided by MTBM factors and the results are given in Table 4.~~

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~~Problem 22 - Table 4. Corrective Maintenance Actions~~

~~Configuration~~	~~Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~											
~~Unit "A"~~	~~0~~	~~0~~	~~18~~	~~37~~	~~73~~	~~110~~	~~110~~	~~110~~	~~64~~	~~46~~	~~568~~
~~Unit "B"~~	~~0~~	~~0~~	~~29~~	~~58~~	~~117~~	~~175~~	~~175~~	~~175~~	~~102~~	~~73~~	~~904~~
~~Unit "C"~~	~~0~~	~~0~~	~~7~~	~~14~~	~~29~~	~~44~~	~~44~~	~~44~~	~~26~~	~~18~~	~~226~~
~~Total~~	~~0~~	~~0~~	~~54~~	~~109~~	~~219~~	~~329~~	~~329~~	~~329~~	~~192~~	~~137~~	~~1,698~~
~~Configuration "B"~~											
~~Unit "A"~~	~~0~~	~~0~~	~~18~~	~~37~~	~~73~~	~~110~~	~~110~~	~~110~~	~~64~~	~~46~~	~~568~~
~~Unit "B"~~	~~0~~	~~0~~	~~15~~	~~29~~	~~58~~	~~88~~	~~88~~	~~88~~	~~51~~	~~37~~	~~454~~
~~Unit "C"~~	~~0~~	~~0~~	~~6~~	~~12~~	~~23~~	~~35~~	~~35~~	~~35~~	~~20~~	~~15~~	~~181~~
~~Total~~	~~0~~	~~0~~	~~39~~	~~78~~	~~154~~	~~233~~	~~233~~	~~233~~	~~135~~	~~98~~	~~1,203~~

~~To determine maintenance factors (as needed in this example problem), a good approach is to calculate the maintenance actions for each unit of each configuration that is applicable to intermediate level maintenance. Then a summary of these actions will provide the total number of maintenance actions at the level of Systems XYZ (or the level of the operational aircraft).~~

~~From the above, the maintenance actions are based on a function of the operating time and the MTBM/MTBM~~$_S$ ~~for each unit. (Refer to Tables 5 and 6).~~

~~Problem 22 - Table 5. Preventive Maintenance Actions~~

~~Configuration~~	~~Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~ ~~Unit "A"~~	~~0~~	~~0~~	~~20~~	~~40~~	~~80~~	~~120~~	~~120~~	~~120~~	~~70~~	~~50~~	~~620~~
~~Configuration "B"~~ ~~Unit "A"~~	~~0~~	~~0~~	~~20~~	~~40~~	~~80~~	~~120~~	~~120~~	~~120~~	~~70~~	~~50~~	~~620~~

~~Problem 22 - Table 6. Total Maintenance Actions (Systems Level)~~

~~Configuration~~	~~Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~	~~0~~	~~0~~	~~74~~	~~149~~	~~299~~	~~499~~	~~499~~	~~499~~	~~262~~	~~187~~	~~2,318~~
~~Configuration "B"~~	~~0~~	~~0~~	~~59~~	~~118~~	~~234~~	~~353~~	~~353~~	~~353~~	~~205~~	~~148~~	~~1,823~~

~~After determining the number of maintenance actions (estimated over the life cycle), the next step is to determine the expected resource consumption per maintenance action. Resources include both human and material resources. Human resources (in this instance) are measured in terms of maintenance labor-hours needed per maintenance action.~~

~~Maintenance labor-hours are developed and recorded in Tables 7 and 8.~~

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~~Problem 22 - Table 7. Maintenance labor hours (Low Skill Technician)~~

~~Configuration~~	~~Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~	~~0~~	~~0~~	~~37~~	~~74~~	~~150~~	~~225~~	~~225~~	~~225~~	~~130~~	~~93~~	~~1,159~~
~~Configuration "B"~~	~~0~~	~~0~~	~~29~~	~~59~~	~~117~~	~~117~~	~~117~~	~~117~~	~~102~~	~~74~~	~~912~~

~~Maintenance labor hours = (Maintenance Actions) $(\bar{M})$ (Number of Personnel)~~

~~Table 8 includes both the low skilled and high skilled technicians for corrective maintenance (split evenly). For instance, the corrective maintenance labor hours for Unit "A" of Configuration "A" for Year 3 is (18 Maintenance Actions) (5 hrs.) (2 Technicians) = 180 MLH. This is from MMH = (Maintenance Actions) $(\bar{M}ct$ or $\bar{M}pt)$ (Number of People).~~

~~Problem 22 - Table 8. Maintenance Labor Hours at Intermediate Level~~

~~Item~~	~~Life Cycle Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~ ~~Corrective Maintenance~~											
~~Unit "A"~~	~~0~~	~~0~~	~~180~~	~~370~~	~~730~~	~~1,100~~	~~1,100~~	~~1,100~~	~~640~~	~~460~~	~~5,680~~
~~Unit "B"~~	~~0~~	~~0~~	~~232~~	~~464~~	~~936~~	~~1,400~~	~~1,400~~	~~1,400~~	~~816~~	~~584~~	~~7,232~~
~~Unit "C"~~	~~0~~	~~0~~	~~28~~	~~56~~	~~116~~	~~176~~	~~176~~	~~176~~	~~104~~	~~72~~	~~904~~
~~Total~~	~~0~~	~~0~~	~~440~~	~~890~~	~~1,782~~	~~2,676~~	~~2,676~~	~~2,676~~	~~1,560~~	~~1,11~~	~~13,816~~
~~Preventive Maintenance~~ ~~Unit "A"~~	~~0~~	~~0~~	~~320~~	~~640~~	~~1,280~~	~~1,920~~	~~1,920~~	~~1,920~~	~~1,120~~	~~800~~	~~9,920~~
~~Configuration "B"~~ ~~Corrective Maintenance~~											
~~Unit "A"~~	~~0~~	~~0~~	~~180~~	~~370~~	~~730~~	~~1,100~~	~~1,100~~	~~1,100~~	~~640~~	~~460~~	~~5,680~~
~~Unit "B"~~	~~0~~	~~0~~	~~150~~	~~290~~	~~580~~	~~880~~	~~880~~	~~880~~	~~510~~	~~370~~	~~4,540~~
~~Unit "C"~~	~~0~~	~~0~~	~~36~~	~~72~~	~~138~~	~~210~~	~~210~~	~~210~~	~~120~~	~~90~~	~~1,086~~
~~Total~~	~~0~~	~~0~~	~~366~~	~~732~~	~~1,448~~	~~2,190~~	~~2,190~~	~~2,190~~	~~1,270~~	~~920~~	~~11,306~~
~~Preventive Maintenance~~ ~~Unit "B"~~	~~0~~	~~0~~	~~240~~	~~480~~	~~960~~	~~1,440~~	~~1,440~~	~~1,440~~	~~840~~	~~600~~	~~7,440~~

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~~In addition to maintenance labor hour consumption, the labor hours associated with the *operation* of System XYZ must be determined. The determination is developed in Table 9 considering that Operator Labor Hours = (System Operating Hours)(1%).~~

~~Problem 22 - Table 9. System XYZ Operator Labor Hours~~

~~Item~~	~~Year~~										~~Total~~
	~~1~~	~~2~~	~~3~~	4	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~System XYZ~~	~~0~~	~~0~~	~~146~~	~~292~~	~~584~~	~~876~~	~~876~~	~~876~~	~~511~~	~~365~~	~~7,300~~

~~The next step is to determine operator and maintenance personnel costs by applying the above MLH and Maintenance Action values, and the individual cost factors stated in the problem. The results are given in Table 10.~~

~~For corrective maintenance at the intermediate level, one half of the maintenance labor hours are at $20 per hour and one half are at $30 per hour.~~

~~Maintenance facility costs are based on the total corrective and preventive maintenance labor hours at the intermediate facility multiplied by the given burden rate (for each configuration).~~

~~Maintenance data costs are based on the number of corrective and preventive maintenance actions multiplied by the dollar rate per maintenance action.~~

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~~Problem 22 - Table 10. Personnel Costs ($)~~

	~~Life-Cycle Year~~										
~~Item~~	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	~~Total Cost ($)~~
~~Configuration "A"~~											
~~1. Operator Cost~~	~~0~~	~~0~~	~~5,840~~	~~11,680~~	~~23,360~~	~~35,040~~	~~35,040~~	~~35,040~~	~~20,440~~	~~14,600~~	~~181,040~~
~~2. Maintenance Cost~~											
~~Organization~~	~~0~~	~~0~~	~~740~~	~~1,480~~	~~3,000~~	~~4,500~~	~~4,500~~	~~4,500~~	~~2,600~~	~~1,860~~	~~23,180~~
~~Intermediate~~											
~~a. Corrective Maint.~~	~~0~~	~~0~~	~~11,00~~	~~22,250~~	~~44,550~~	~~66,900~~	~~66,900~~	~~66,900~~	~~39,000~~	~~27,900~~	~~345,400~~
~~b. Preventive Maint.~~	~~0~~	~~0~~	~~9,600~~	~~19,200~~	~~38,400~~	~~57,600~~	~~57,600~~	~~57,600~~	~~33,600~~	~~24,000~~	~~297,600~~
~~Total~~	~~0~~	~~0~~	~~27,180~~	~~54,610~~	~~109,310~~	~~164,040~~	~~164,040~~	~~164,040~~	~~95,640~~	~~68,360~~	~~847,220~~
~~Configuration "B"~~											
~~1. Operator Cost~~	~~0~~	~~0~~	~~5,840~~	~~11,680~~	~~23,360~~	~~35,040~~	~~35,040~~	~~35,040~~	~~20,440~~	~~14,600~~	~~181,040~~
~~2. Maintenance Cost~~											
~~Organization~~	~~0~~	~~0~~	~~580~~	~~1,180~~	~~2,340~~	~~4,540~~	~~3,540~~	~~3,540~~	~~2,040~~	~~1,480~~	~~18,240~~
~~Intermediate~~											
~~a. Corrective Maint.~~	~~0~~	~~0~~	~~9,150~~	~~18,300~~	~~36,200~~	~~54,750~~	~~54,750~~	~~54,750~~	~~31,750~~	~~23,000~~	~~282,650~~
~~b. Preventive Maint.~~	~~0~~	~~0~~	~~7,200~~	~~14,400~~	~~28,800~~	~~43,200~~	~~43,200~~	~~43,200~~	~~25,200~~	~~18,000~~	~~223,200~~
~~Total~~	~~0~~	~~0~~	~~22,770~~	~~45,560~~	~~90,700~~	~~136,530~~	~~136,530~~	~~136,530~~	~~79,430~~	~~57,080~~	~~705,130~~

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~~Personnel costs are entered for each configuration in Table 11.~~

~~Problem 22 – Table 11. Summary of Operations and Maintenance Cost ($)~~

~~Item~~	~~Life Cycle Year~~										~~Total Cost ($)~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~											
~~1. Personnel Cost~~	—	—	~~27,180~~	~~54,610~~	~~109,310~~	~~164,040~~	~~164,040~~	~~164,040~~	~~95,640~~	~~68,360~~	~~847,220~~
~~2. Material Cost~~											
~~a. Spare Units~~	—	~~42,000~~	~~21,000~~	~~42,000~~	~~21,000~~	—	—	—	—	—	~~126,000~~
~~b. Component Spares~~	—	—	~~15,500~~	~~31,250~~	~~62,750~~	~~94,250~~	~~94,250~~	~~94,250~~	~~55,000~~	~~39,250~~	~~486,500~~
~~3. Maintenance Facilities~~	—	—	~~760~~	~~1,530~~	~~3,062~~	~~4,596~~	~~4,596~~	~~4,596~~	~~2,680~~	~~1,916~~	~~23,736~~
~~4. Maintenance Data~~	—	—	~~1,850~~	~~3,725~~	~~7,475~~	~~11,225~~	~~11,225~~	~~11,225~~	~~6,550~~	~~4,675~~	~~57,950~~
~~Total~~	—	~~42,000~~	~~66,290~~	~~133,115~~	~~203,597~~	~~274,111~~	~~274,111~~	~~274,111~~	~~159,870~~	~~114,201~~	~~1,541,406~~
~~Configuration "B"~~											
~~1. Personnel Cost~~	—	—	~~22,770~~	~~45,560~~	~~90,700~~	~~136,530~~	~~136,530~~	~~136,530~~	~~79,430~~	~~57,080~~	~~705,130~~
~~2. Material Cost~~											
~~a. Spare Units~~	—	~~46,000~~	~~23,000~~	~~46,000~~	~~23,000~~	—	—	—	—	—	~~138,000~~
~~b. Component Spares~~	—	—	~~11,750~~	~~23,500~~	~~46,500~~	~~70,250~~	~~70,250~~	~~70,250~~	~~40,750~~	~~29,500~~	~~362,750~~
~~3. Maintenance Facilities~~	—	—	~~606~~	~~1,212~~	~~1,408~~	~~3,630~~	~~3,630~~	~~3,630~~	~~2,110~~	~~1,510~~	~~18,746~~
~~4. Maintenance Data~~	—	—	~~1,475~~	~~2,950~~	~~5,850~~	~~8,825~~	~~8,825~~	~~8,825~~	~~5,125~~	~~3,700~~	~~45,575~~
~~Total~~	—	~~46,000~~	~~59,601~~	~~119,222~~	~~168,458~~	~~219,235~~	~~219,235~~	~~219,235~~	~~127,415~~	~~91,800~~	~~1,270,201~~

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~~Spare part costs are related to Unit spares (one set per intermediate level maintenance shop and one set at the depot), and Component spares which are a function of individual maintenance actions. Spares cost are summarized in Table 12.~~

~~Problem 22 - Table 12. Spares Cost ($)~~

~~Item~~	~~Life-Cycle Year~~										~~Total Cost ($)~~
	~~1~~	~~2~~	~~3~~	~~4~~	~~5~~	~~6~~	~~7~~	~~8~~	~~9~~	~~10~~	
~~Configuration "A"~~ ~~Spare Units~~	~~—~~	~~42,000~~	~~21,000~~	~~42,000~~	~~21,000~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~126,000~~
~~Component Spares~~ ~~Corrective Maintenance~~ ~~Preventive Maintenance~~	~~—~~ ~~—~~	~~—~~ ~~—~~	~~13,500~~ ~~2,000~~	~~27,250~~ ~~4,000~~	~~54,750~~ ~~8,000~~	~~82,250~~ ~~12,000~~	~~82,250~~ ~~12,000~~	~~82,250~~ ~~12,000~~	~~48,000~~ ~~7,000~~	~~34,250~~ ~~5,000~~	~~424,500~~ ~~62,000~~
~~Total~~	~~—~~	~~42,000~~	~~36,500~~	~~72,250~~	~~83,750~~	~~94,250~~	~~94,250~~	~~94,250~~	~~55,000~~	~~39,250~~	~~612,500~~
~~Configuration "B"~~ ~~Spare Units~~	~~—~~	~~46,000~~	~~23,000~~	~~46,000~~	~~23,000~~	~~—~~	~~—~~	~~—~~	~~—~~	~~—~~	~~138,000~~
~~Component Spares~~ ~~Corrective Maintenance~~ ~~Preventive Maintenance~~	~~—~~ ~~—~~	~~—~~ ~~—~~	~~9,750~~ ~~2,000~~	~~19,500~~ ~~4,000~~	~~38,500~~ ~~8,000~~	~~58,250~~ ~~12,000~~	~~58,250~~ ~~12,000~~	~~58,250~~ ~~12,000~~	~~33,750~~ ~~7,000~~	~~24,500~~ ~~5,000~~	~~300,750~~ ~~62,000~~
~~Total~~	~~—~~	~~46,000~~	~~34,750~~	~~69,500~~	~~69,500~~	~~70,250~~	~~70,250~~	~~70,250~~	~~40,750~~	~~29,500~~	~~500,750~~

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~~On the basis of the Present Equivalent of the estimated Life-Cycle Cost, Configuration "B" is Preferred (refer to Table 13).~~

~~Problem 22 - Table 13. Summary of Results (i = 15%)~~

~~Year~~	~~Configuration "A"~~		~~Configuration "B"~~	
	~~Undiscounted Cost ($)~~	~~Discounted Cost ($)~~	~~Undiscounted Cost ($)~~	~~Discounted Cost ($)~~
~~1~~	~~70,000~~	~~60,872~~	~~87,000~~	~~75,655~~
~~2~~	~~318,000~~	~~240,440~~	~~336,000~~	~~254,050~~
~~3~~	~~289,290~~	~~190,208~~	~~301,601~~	~~198,303~~
~~4~~	~~579,115~~	~~331,138~~	~~603,222~~	~~344,922~~
~~5~~	~~636,597~~	~~316,516~~	~~640,458~~	~~318,436~~
~~6~~	~~274,111~~	~~118,498~~	~~219,235~~	~~94,775~~
~~7~~	~~274,111~~	~~103,038~~	~~219,235~~	~~82,410~~
~~8~~	~~274,111~~	~~89,607~~	~~219,235~~	~~71,668~~
~~9~~	~~159,870~~	~~45,451~~	~~127,415~~	~~36,224~~
~~10~~	~~114,201~~	~~28,230~~	~~91,800~~	~~22,693~~
~~Total~~	~~$2,989,406~~	~~$1,523,998~~	~~$2,845,201~~	~~$1,499,136~~

~~It should be noted that the alternatives are relatively close; thus, one may wish to go back and challenge some of the underlying assumptions (in terms of initial inputs) and perform a sensitivity analysis. The object is to vary some of the input values (i.e., high cost "drivers") to determine and evaluate the resulting impact.~~

~~Problem 22 - Table 14. Cost Breakdown — System XYZ (Configuration "B")~~

~~Cost Category~~	~~Undiscounted Cost ($)~~	~~Percent (%)~~
~~Design and Development~~		
• ~~Prime Equipment~~	~~100,000~~	~~3.52~~
• ~~Support Equipment~~	~~23,000~~	~~0.81~~
~~Sub-Total~~	~~123,000~~	~~4.33~~
~~Production~~		
• ~~Prime Equipment~~	~~1,380,000~~	~~48.50~~
• ~~Support Equipment~~	~~72,000~~	~~2.53~~
~~Sub-Total~~	~~1,452,000~~	~~51.03~~
~~Operations and Maintenance~~		
• ~~Personnel Cost~~	~~705,130~~	~~24.78~~
• ~~Spare Units~~	~~138,000~~	~~4.85~~
• ~~Component Spares~~	~~362,750~~	~~12.75~~
• ~~Maintenance Facilities~~	~~18,746~~	~~0.66~~
• ~~Maintenance Data~~	~~45,575~~	~~1.60~~
~~Sub-Total~~	~~1,270,201~~	~~44.64~~
~~Total~~	~~$2,845,201~~	~~100%~~

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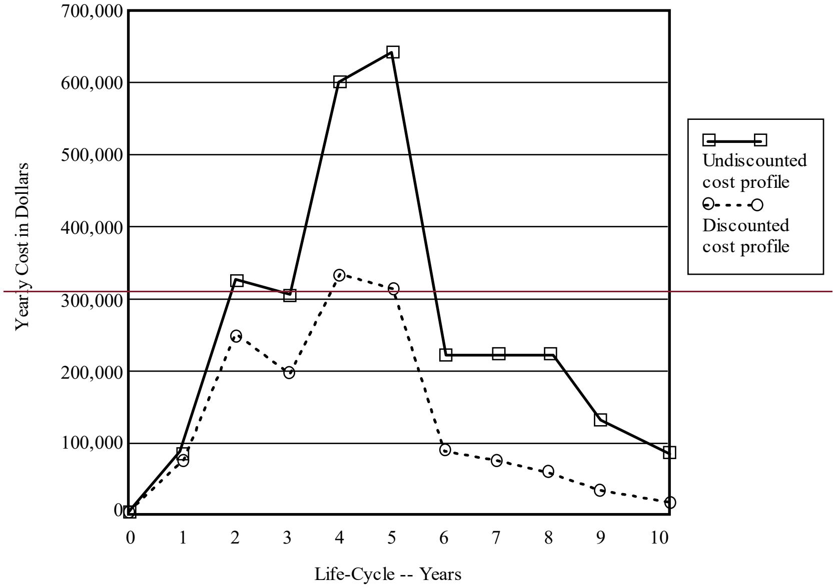
~~(b) Problem 22 - Figure 1. System XYZ Configuration “B” Cost Profile~~



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~~(c) Problem 22 - Figure 2. Break Even Analysis for System XYZ giving the preferred Configuration as Alternative B, which exhibits a minimum LCC.~~

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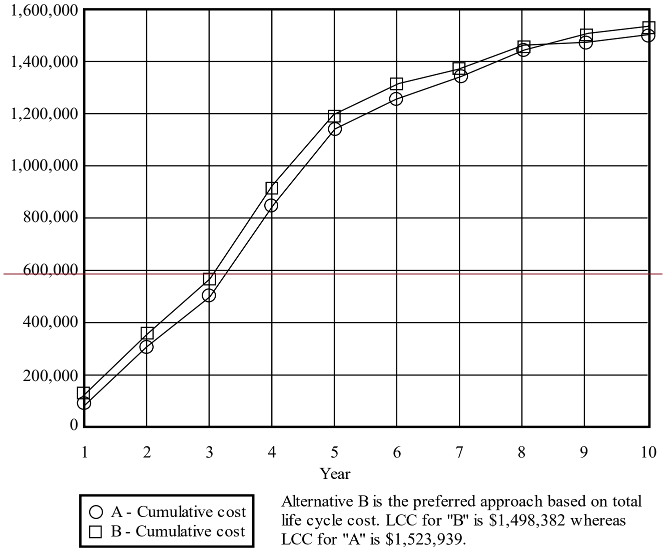

Alternative B is the preferred approach based on total life cycle cost. LCC for "B" is $1,498,382 whereas LCC for "A" is $1,523,939.

~~23) Refer to the figure on page 647. Two configurations (B and C) within the budget also meet the minimum MTBF requirement. However, Configuration B is 60% more expensive than Configuration C. The authors would select *Configuration C*, since it meets the MTBF requirement and does so at the lowest overall unit cost.~~

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~~24) Refer to the figure on page 648. Identify the high-cost contributors; do a sensitivity analysis and identify those inputs that seem to have the greatest impact on the output results; ensure that these input values are as accurate as possible and based on some valid historical experience; vary these input parameters over a designated and realistic range and measure the output in terms of delta cost. The risk may be stated in terms of a combination of technical and cost factors.~~

~~25) Student exercise. Pick something simple that includes an up-front acquisition cost in addition to purchase price.~~

~~26) The applications and benefits are identified in Section 17.6 (page 628). The big benefit is that of *total cost visibility*, but other benefits can be identified.~~

~~27) The objective is to find the optimal values for the controllable variables in the face of system parameters. For a deployed population already in being and deployed, an evaluation function in the form of Equation 7.2 (page 177) is applicable. Specifically, $E = f(X, Y)$ where:~~

~~E = measure of evaluation, which is usually to minimize the sum of the costs associated with the system.~~

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~~X = policy variable concerning the number of units to deploy, the replacement age of the units, and the number of replacement channels.~~

~~Y = system parameters of the arrival rate, the service rate, the waiting cost, and the service facility cost. All of these are predetermined by prior design.~~

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~~28) Here the focus shifts to designing the best candidate system. An evaluation function in the form of Equation 7.3 (page 178) is applicable. Specifically, $E = f(X, Y_d, Y_i)$ where:~~

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~~E = measure of evaluation, which is usually to minimize the sum of the costs associated with the system.~~

~~Y_d = design-dependent parameters (such as design MTBF and MTTR, the energy efficiency of equipment units, the design life of these units, and the first cost and the salvage value of units).~~

~~Y_i = design-independent parameters (such as demand, shortage penalty costs, cost of providing repair capability, and the time value of money).~~

~~29) With the system parameters given in Table 17.10 (page 622), follow the method given in Section 17.5.4 (page 622):~~

~~Annual equivalent population cost = $195,185~~

~~Annual repair facility cost = $180,000~~

~~Annual operation cost = $46,000~~

~~MTBF = 0.2225 and MTTR = 0.045 giving $\lambda / \mu = 1/5$~~

~~Next, compute C_n for $n = 0, 1, 2, ..., 20$ from Equation 10.39 (page 312) as:~~

~~$C_0 = 1,\ C_1 = 4,\ C_2 = 7.6,\ C_3 = 9.12,\ ...,\ C_{20} \cong 0.00$~~

~~Now, $\sum_{n=0}^{20} C_n = 47.71$~~

~~And from Equation 10.38 (page 312):~~

~~$P_0 = 1/\sum_{n=0}^{20} C_n = 1/47.71 = 0.02096$~~

~~P_n for $n = 0, 1, 2, ..., N$ can now be computed from $P_n = P_0 C_n = (0.02096)\, C_n$ as:~~

~~$P_0 = 0.02096,\ P_1 = 0.08384,\ P_2 = 0.01593,\ ...,\ P_{20} = 0.0000$~~

~~Now, the expected number of units short can be calculated from Equation 17.16 (page 622) as:~~

~~$E(S) = \sum_{j=1}^{D} jP_{(N-D+j)} = 0.5905$~~

~~From which the annual shortage cost is $47,640.~~

~~The total system annual equivalent cost may now be summarized as:~~

~~$TC = PC + OC + RC + SC = \$195{,}185 + \$46{,}000 + \$180{,}000 + \$47{,}640 = \underline{\$468{,}825}$~~

~~30) Download REPS from **www.a2i2.com** and use it to verify that the probability of one or more short is truly 0.27.~~

~~31) Student exercise using LCCC after downloading **www.a2i2.com** .~~

~~32) Student exercise using REPS after downloading from **www.a2i2.com**.~~

~~33) Student exercise using REPS and Figure 17.25 (page 627).~~

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~~CHAPTER 18~~

~~SYSTEMS ENGINEERING PLANNING AND ORGANIZATION~~

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~~1) Systems engineering requirements should be initiated at program inception: i.e., during the early stages of conceptual design when a "need" for a system is first identified. It is at this time when system requirements are first identified, system architecture is initially defined, program tasks are initially described, and a proposed management approach is assumed. A *top down*, *integrated*, *life cycle* approach to system design and development must be established from the beginning. Otherwise, the requirements may not be well established from the beginning, the various program activities and elements of the system may not be well integrated, there may be undue waste and high costs, and the ultimate system/product may not perform and/or fulfill the customer requirements as intended. Reference: Sections 2.2 (page 29), 2.3 (page 33), 3.1 (page 57), and Section 3.2 (page 58).~~

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~~2) The purpose of the *System Engineering Management Plan (SEMP)* is to describe the key activities/tasks and milestones necessary to accomplish the objectives discussed throughout this textbook; i.e., those tasks necessary to implement the requirements for the implementation of an effective systems engineering program. The objectives are to provide the structure, policies, and procedures to foster the integration of the various engineering-related activities needed for system design and development. The SEMP, which evolves from and supports the *Program Management Plan (PMP)*, must be developed during the conceptual design phase and completed/implemented at Milestone I shown in Figure 2.4, page 34 (also refer to Figures 3.1 on page 59 and 18.2 on page 642). Two different proposed outlines for the SEMP are shown in Figures 18.3 (page 644) and 18.4 (page 645). Reference: Section 18.2 (page 643).~~

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~~(a) The SEMP evolves from and supports the PMP, or whatever top level planning document is relevant and is equivalent (refer to Figure 3.1 on page 59 and Figure 18.2 on page 642).~~

~~(b) The SEMP may either include a *Reliability Program Plan* as one of its major sections, or will include a strong statement describing the plan and a reference to the actual plan (which may be included elsewhere and as a reliability engineering task refer to Section 12.3, page 374).~~

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~~(c) The *Integrated Logistics Support Plan (ILSP)* includes all of the requirements, policies and procedures, and activities/tasks associated with the initial identification of system maintenance and support requirements, supply chain (SC) and supply chain management (SCM) requirements, the design of the system and its elements for supportability, the procurement and acquisition of the various elements of support (i.e., spares and repair parts, test and support equipment, maintenance personnel, facilities, transportation and handling requirements, computer resources, data and information), and the sustaining maintenance and support of the system throughout its planned life cycle (to include system retirement and material recycling/disposal). While the ILSP often represents a separate and independent level of effort, there are system "design related" activities included within that~~

~~also must be included within the SEMP. In other words, the ILSP must directly support the SEMP, and the two plans must "talk to each other." Reference: Sections 15.3 (page 503) and 15.5 (page 526). Also see Figure 18.2 on page 642.~~

~~(d) The *Configuration Management Plan (CMP)* covers all of the requirements, policies, and procedures that are necessary to ensure a *baseline management* approach as the system design and development process proceeds from one level of design definition to the next; e.g., from Milestone I to Milestone II, from Milestone II to Milestone III, etc., in Figure 2.4 (page 34). Configuration Control (CC) is an inherent part of the system engineering process (refer to Section 5.9 on page 146 and Figure 5.11 on page 147). While the CM Plan is often represented as a separate document and level of effort, the elements of configuration control (detailed definition of the system status and configuration at any given time) must be referenced within the SEMP. In other words, the CMP and the SEMP must "talk to each other." Reference: Section 5.9 (page 146) and Figure 18.2 (page 642).~~

~~(e) The *Test and Evaluation Master Plan (TEMP)* must cover the requirements, policies, and procedures for the accomplishment of all system tests for the purposes of verifying and validating that the initially specified requirements for the system are being met. As the requirements are initially defined for the system during conceptual design, a method for measurement and validation must be established at the same time. Referring to Figure 2.4 (page 34), the TEMP is initially prepared at the end of the Conceptual Design Phase, and is later updated as the requirements for test and validation for the system become more refined. The TEMP and the SEMP must be complementary and mutually supportive, with the appropriate cross-referencing throughout. Reference: Section 6.3 (page 157) and Figure 6.2 (page 153).~~

~~(f) Each major system supplier should prepare a *Supplier Engineering and Acquisition Plan*, or something of an equivalent nature. The plan must defined the requirements and describe the policies and procedures for all activity pertaining to the design and development, production, and delivery of the applicable subsystem or element of the system for which the supplier is responsible. This plan must directly support the requirements for suppliers as specified in the SEMP. Reference: Section 18.3 (page 658). Supplier requirements are described further in Section 19.2 (page 676).~~

~~3) The *System Specification (Type A)* is the top-level specification and includes all of the *technical* requirements for the system and its design. Refer to Section 3.9 (page 95) and Figure 3.27 (page 96) for the material that would likely be included. The SEMP constitutes a *management* plan implemented to ensure that the appropriate tasks, organization, and resources are applied in order to comply with the requirements in the system specification (refer to Figures 18.2, 18.3, and 18.4 on pages 642-645). The two documents are closely related, mutually supportive, and must "communicate" with each other as conveyed in Figures 3.1 (page 59) and 18.2 (page 642). Reference: Sections 3.9 (page 95) and 18.2 (page 643).~~

~~4) Student exercise. Reference: Section 18.2 and Figures 18.2 – 18.4 (pages 642-645).~~

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~~5) Referring to Section 18.2.2 (page 646), the eleven (11) tasks identified might serve as an initial point of reference, although the specific requirements may vary from one program to the next. The goal is to identify tasks that are directly oriented to the system and are critical relative to meeting the requirements described in the system specification and the SEMP (as applicable). The tasks must be *tailored* to the system/program need. Reference: Section 18.2.2 (page 646). Also, refer to the different systems engineering texts included in the Bibliography in Appendix G (page 755).~~

~~6) The *work breakdown structure (WBS)* is a product-oriented family tree that leads to the identification of the functions, activities, tasks, subtasks, work packages, and so on, that must be performed for the completion of a given program. An overall top-level structure, a *Summary Work Breakdown Structure (SWBS)*, portrays ALL of the elements of work that must be accomplished. A *Contract Work Breakdown Structure (CWBS)* is one that identifies all of the functions, activities, tasks, work packages, etc., that are covered under a specific "contract." The relationships between a SWBS and a CWBS are illustrated in Figure 18.5 (page 649), an example of a SWBS is shown in Figure 18.6 (page 650), and an example of a CWBS is presented in Figure 18.7 (page 651). In the event of "outsourcing" when a particular contractual arrangement is in place, the CWBS would be utilized as part of the contact with the supplier. Reference: Section 18.2.3 (page 648).~~

~~7) The authors would, in most instances, select a *networking* method for scheduling (similar to PERT/CPM), and then superimpose cost information on top of this network (refer to Figures 18.9 (page 654) and 18.12 (page 657). In managing a systems engineering program, there are many interfaces with which one must deal, numerous organizational activities that must be integrated, and many remotely located suppliers upon which one must depend. Further, the accomplishment of many systems engineering tasks occurs early in a program during conceptual and preliminary system design (including some research and development activities) where there are still many "unknowns." The networking method of scheduling is readily adaptable to advanced planning, is probabilistic in nature, and forces the precise definition of tasks, task sequences, and task interrelationships. The technique enables management and engineering to predict, with some degree of certainty, the probable time that it will take to achieve an objective and the estimated resources required in accomplishing such. Additionally, it enables the rapid assessment of progress and the detection of problems and delays. More specifically, the network method facilitates the early identification of potential areas of risk. Reference: Section 18.2.4 (page 651) and Figures 18.9 – 18.12 (pages 654-657).~~

~~8) Student exercise. Reference: Section 18.2 (page 643) and Figures 18.9-18.11 (pages 654-656).~~

~~9) Student exercise. Reference: Section 18.2 (Figure 18.12, page 657). It might be appropriate to first develop the network (Figure 18.9, page 654); determine the costs for each of the schedule lines (Figure 18.12); develop a *cost breakdown structure (CBS)*; tie the costs for the various activities in the network to the applicable block in the CBS; and then develop a cost projection for the overall project (look ahead at Figure 19.5 on page 683). Reference: Section 18.2.4 (page 651).~~

~~10) Analyze the situation and determine the "causes" for the delay in schedule (or cost overrun); determine a proposed approach for correcting the deficiency; and implement the necessary change applying the needed additional resources as required. Such resources can be taken away from those tasks in the network which reflect an "up-to-date" schedule and which indicate a "slack" situation (i.e., those tasks that could be delayed further without causing the entire project output to be delayed). Reference: Section 18.2 (page 643), and refer to the time-cost option illustrated in Figure 18.12 (page 657).~~

~~11) The basic objectives in *organizing for systems engineering* are noted in Section 18.3 (page 658). The prime top-level objective is, of course, to establish a structure that is compatible with the company's (or institution's, or agency's) overall structure and one that will facilitate the accomplishment of the specified systems engineering tasks in an effective and efficient manner. More specifically, the systems engineering organization must assume a leadership role in the determination and establishment of system level requirements; it must create an environment that will foster a top-down, life-cycle approach in system design and development; it must cause the proper integration of various design and support activities (to include supplier activities); and it must assume a leadership role in accomplishing each of the eleven (11) tasks identified in Section 18.2.2, page 646 (*Systems Engineering Program Tasks*), or those tasks necessary to fulfill the objectives described throughout this text. The establishment of good communications across the board is critical. The role of the systems engineering organization and the specific structure (whether functional, project or product line, matrix, or a combination thereof) may vary somewhat depending on the nature and complexity of the system being developed, the balance between internal company and supplies activities, and the particular program phase of activity being addressed (e.g., whether conceptual design, preliminary system design, etc.). Reference: Section 18.3 (page 658).~~

~~12) Some of the advantages/disadvantages associated with a *functional*, *project*, and a *matrix* organizational structure are noted below:~~

~~Functional Organization (Figure 18.14, page 662) *Advantages*:~~

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~~(a) Enables the development of a better technical capability. Specialists can be grouped to share knowledge. Experience from one project can be readily transferred to other projects through personnel exchange. Cross-training is relatively easy.~~

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~~(b) The organizations can respond quicker to a specific requirement through the careful assignment (or reassignment) of personnel. There are a larger number of personnel in the organization with the required skills in a given area. The manager has a greater degree of flexibility in the utilization of personnel and a broader human-power base with which to work. Greater technical control can be maintained.~~

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~~(c) Budgeting and cost control is easier due to the centralization of areas of expertise. Common tasks for different projects can be integrated, and it is easier not only to estimate costs but to monitor and control costs.~~

~~(d) The channels of communication are well established, the reporting structure is vertical, and there is no question as to who is the "boss."~~

~~Functional Organization — *Disadvantages*:~~

~~(a) It is difficult to maintain a strong identity with a specific project. No single individual is responsible for the total project or the integration of its activities. It is hard to pinpoint specific project responsibilities.~~

~~(b) Concepts and techniques tend to be functionally oriented with little regard to project requirements. The "tailoring" of technical requirements to a particular project is discouraged.~~

~~(c) There is little customer orientation or focal point. Response to specific customer needs is slow. Decisions are made on the basis of the strongest functional area of activity.~~

~~(d) Because of the group orientation relative to a specific area of expertise, there is less personal motivation to excel and to be innovative concerning the generation of new ideas.~~

~~Project Organization (Figure 18.15, page 663) — *Advantages*:~~

~~(a) The lines of authority and responsibility for a given project are clearly defined. Project participants work directly for the project manager, communication channels within the project are strong, and there is no question as to priorities. A good and strong project orientation is provided.~~

~~(b) There is a strong customer orientation, a company (institution, or agency) focal point is readily identified, and the communication processes between the customer and the contractor (or supplier) are relatively easy to maintain. A rapid response to the customer is facilitated.~~

~~(c) Personnel assigned to the project generally exhibit a high degree of loyalty to the project, there is strong motivation, and personal morale is usually better with project identification and affiliation.~~

~~(d) There is greater visibility relative to all project activities. Cost, schedule, and performance progress can be easily monitored, and potential problem areas (with the appropriate follow on corrective action) can be identified earlier.~~

~~Project Organization — *Disadvantages*:~~

~~(a) The application of new technologies tends to suffer without strong functional groups and the opportunities for technical interchange between projects. As projects go on, those technologies that are applicable at project inception continue to be applied on a repetitive basis. There is no perpetuation of technology, and the introduction of new methods and procedures is discouraged.~~

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~~(b) In contractor organizations where there are many different projects, there is often a duplication of effort, personnel, and the use of equipment and facilities. The overall operation of the company is inefficient and the results can be quite costly. There are times when a complete decentralized approach is not as efficient as centralization.~~

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~~(c) From a managerial perspective, it is sometimes difficult to effectively utilize personnel in the transfer from one project to another. Good qualified workers assigned to projects are usually retained by the project managers for as long as possible (whether they are being effectively utilized or not), and the reassignment of such personnel usually requires approval from a higher level of authority which can be quite time consuming. The shifting of personnel in response to short term needs is essentially impossible.~~

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~~(d) The continuity of an individual's career, his or her own growth potential, and the opportunities for promotion are often not as good when assigned to a project for an extended period of time. Project personnel are limited in terms of opportunities to be innovative relative to the acquisition of new technologies, the introduction of changes for improvement, etc. The repetitiveness of tasks sometimes results in stagnation.~~

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~~Matrix Organization (Figure 18.16, page 663) — *Advantages*:~~

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~~(a) The project manager can provide the necessary strong controls for the project while having ready access to the resources from many different functionally oriented departments.~~

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~~(b) The functional organizations exist primarily as support for the projects. A strong technical capability can be developed and made available in response to project requirements in an expeditious manner.~~

~~(c) Technical expertise can be exchanged between projects with a minimum of conflict. Knowledge is available for all projects on an equal basis.~~

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~~(d) Key personnel can be shared and assigned to work on a variety of problems across project lines. From a company top management perspective, a more effective utilization of technical personnel can be realized and program costs can be minimized as a result.~~

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~~Matrix Organization — *Disadvantages*:~~

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~~(a) Each project organization operates independently. In an attempt to maintain identity, separate operating procedures are developed, separate personnel requirements are identified, and so on. Extreme care must be taken to guard against the possible duplication of effort.~~

~~(b) From an overall company perspective, the matrix structure may be more costly in terms of administrative requirements. Both the project and the functional areas of activity require similar administrative controls.~~

~~(c) The balance of power between the project and the functional organizations must be clearly defined initially and closely monitored thereafter. Depending on the strengths (and weaknesses) of the individual managers, the power and influence can shift to the detriment of the overall company organization.~~

~~(d) From the perspective of the individual worker, there is often a split in the chain of command for reporting purposes. The individual is sometimes "pulled" between the project boss and the functional boss.~~

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~~13) Student exercise. Reference: Section 18.3 (pages 658-670) and Figures 18.14-18.20 (pages 662-668).~~

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~~14) The requirements for staffing an organization initially stem from the results of the systems engineering planning activity described in Sections 18.1 (page 641) and 18.2 (page 643). Tasks are identified, combined into work packages and a work breakdown structure (WBS), and the work packages are grouped into specific position requirements. These positions are then arranged within the applicable organizational structure considered to be the most appropriate for the need (i.e., functional, project, product line, matrix, of combination thereof). With regard to specific position requirements, an entry–level *systems engineer* should have the following qualifications:~~

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~~(a) A basic formal education in some recognized branch of engineering; i.e., at least a baccalaureate degree in engineering or equivalent.~~

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~~(b) A high level of general technical competence in the engineering fields being pursued by the organization, project, and so on; i.e., those disciplines required for system design and development.~~

~~(c) Relevant design experience in the appropriate areas of activity. For example, if a company is involved in the design and development of electrical/electronic systems, then it is desirable for the candidate to have had some prior design experience in electrical/electronic systems. A different type of experience would be required for aeronautical systems, for civil systems, for hydraulic systems, and so on.~~

~~(d) A basic understanding of the design requirements pertaining to all phases of the system life cycle; i.e., the design for reliability, maintainability, human factors, producibility, safety and security, supportability, disposability, sustainability, quality, and economic feasibility (life–cycle cost).~~

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~~(e) An understanding of the systems engineering process and the methods/tools that can be effectively employed in bring a system into being, commencing with the definition of system requirements, functional analysis and allocation, and so on.~~

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~~(f) An understanding of the relationships among functions to include marketing, contract management, purchasing, integrated logistic support, configuration management, data management, production (manufacturing), quality control, customer and supplier operations, and so on.~~

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~~(g) A basic understanding of the relationships among the varies elements that may exist in a system-of-systems (SOS) configuration; i.e., work-related approach relative to the definition and integration of requirements, accomplishing various design-related activities, review and evaluation of sub-contractors and suppliers both nationally and internationally, and so on.~~

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~~As the specific definition of a *systems engineer* will often vary from one organization to the next, individual perceptions as to the requisites will differ. Based on experience, it is believed that a good solid technical engineering education is a necessary foundation, some design experience is essential, a thorough understanding of the system life cycle and its elements is required, and knowledge of the many design interfaces that occur is highly beneficial. The individual(s) selected must be technically competent, self motivated, and flexible; creative and demonstrate initiative; objective and possess good communication skills; be effective at interpersonal skills in management; and must promote a democratic/participative style of leadership. Reference: Section 18.3.4, page 669 ("Staffing the Systems Engineering Organization").~~

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~~15) The nature of systems engineering activities requires consideration of the following characteristics when developing an organizational structure:~~

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~~(a) The personnel selected for the systems engineering group are, in general, highly professional senior-level individuals with varied backgrounds and having a wide breadth of knowledge; i.e., an understanding of research, design, manufacturing, and system maintenance and support applications. The emphasis is on overall system-level design and technology applications, with knowledge of user operations and sustaining life-cycle support in mind.~~

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~~(b) The systems engineering group must incorporate "vision" and be "creative" in the selection of technologies for design, manufacturing, and support applications. Group personnel are constantly searching for new opportunities, must be innovative, and applied research is often required in order to solve specific technical problems.~~

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~~(c) A "teamwork" approach must be initiated within the systems engineering group. The personnel assigned must be committed to the objectives of the organization, there is a certain degree of independence required, and there must be mutual respect and trust throughout.~~

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~~(d) A high degree of communications must prevail, both within the systems engineering group and with the many other related functions associated with a given project (refer to Figure 18.18, page 665). Communications is a two-way process and may be accomplished via written, verbal, and/or non-verbal means. Good communications must first exist within the systems engineering group. With that established, it is then necessary to develop two-way communications externally (and nationally and internationally as required), utilizing both vertical and horizontal channels as required.~~

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~~Given the objectives described throughout the text, and with the above considerations in mind, the appropriate *environment* must be created to allow for the accomplishment of systems engineering tasks in an effective manner. "Environment" in this instance refers to both (a) the working environment external to the systems engineering function, and (b) the working environment within the systems engineering group itself.~~

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~~The creation of a favorable "environment" within an organization must start from the *top*. The President, or General Manager, must initially "believe in" and subsequently "support" the concepts, objectives, and principles of systems engineering. On numerous occasions, power struggles may occur, conflicting goals and objectives will develop, and there may be a lack of communications between key organizational entities within an overall organizational entity. A mechanism must be established for quick conflict resolution, and all project personnel must know that the systems engineering philosophy WILL prevail. Top management must create this understanding from the beginning.~~

~~Additionally, an effective *managerial style* must be in place. Given the above requirements for a systems engineering group (one that must be knowledgeable, creative and innovative, flexible, have vision, include highly-motivated personnel, operate as a "team," and foster good communications throughout), it is believed that a "democratic" and participative-type managerial approach is preferred over a highly "autocratic" and dictatorial style of management. The objective is to solicit new and good ideas, from both within and externally, and to create a non-threatening group environment that is highly productive, yet flexible.~~

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~~As for any type of organizational entity, the proper level of *responsibility* and corresponding *authority* must be delegated to the systems engineering group manager. It is not uncommon for a higher level manager to delegate "responsibility" but not the "authority" to make it happen. The "leader" of a Systems Engineering Group must have the flexibility, freedom, and authority to carry out the systems engineering goals and objectives described through out this text.~~

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~~As a final point, it should be noted that there are many different organizations throughout industry and in government agencies and institutions that are identified with the title of "Systems Engineering" (and responsible for accomplishing functions and tasks similar to what is described in this text). Some are very effective in implementing the principles and concepts of systems engineering, while many others are not so successful. "Success" is dependent on creating the appropriate environment from within, gaining the proper~~

~~"respect" from the perspective of the outside organizations where major interfaces exist, and providing the right leadership by the systems engineering manager.~~

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~~16) Referring to Section 18.3 (Figure 18.20, page 668), the *Integrated Product and Process Development (IPPD)* concept was initiated by the Department of Defense in the early 1990s. IPPD can be defined as a *management technique that simultaneously integrates all essential acquisition activities through the use of multidisciplinary teams to optimize design, manufacturing, and support processes.* The concept promotes the communications and integration of key functional areas, as they apply to various phases of program activity. IPPD is essentially the application of a "team" approach, as shown in Figure 18.20 (page 668), to solve a wide variety of problems. In this regard, each of the Integrated Process Teams (IPTs) shown in Figure 18.20 is responsible for solving a specific problem related to configuration management, integrated data, cost of ownership, and in the area of performance (respectively). The concept of IPPD is directly in line with the objectives of systems engineering.~~

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~~At a more specific and detailed level, an *Integrated Product Team (IPT)*, or *Integrated Process Team (IPT)*, may be established to address some well-defined problem. An IPT, constituting a team of individuals representing the needed disciplines required for support, may be established to solve a particular problem (e.g., investigating the cause of a performance deficiency, accomplishing a special life-cycle cost analysis, solving a data integration problem). There may be any number of IPTs, each addressing a different problem and coordinated through the IPPD. As the problems are solved, the IPT may be dissolved. Referring to Figure 18.20 (page 668), there are four different IPTs shown. Reference: Section 18.3 (page 658).~~

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~~17) Refer to Figures 18.18 (page 665) and 18.19 (page 666). The appropriate organizational structure and associated communication requirements should initially be defined in the Systems Engineering Management Plan (SEMP). As "Manager" of a Systems Engineering organization, I would initiate a series of individual meetings with the manager(s) of each of the other closely related and supporting organizations; I would conduct a series of briefings and training programs throughout the company (or equivalent parent organization); and I would prepare some educational material for general distribution. As the design progresses, I would "chair" the formal design review meetings, using this medium to promote the necessary communications across the board. I would "go out of my way" to aid others in the performance and enhancement of their activities, using whatever interpersonal skills necessary to gain full cooperation. It should be noted that success in the implementation of systems engineering requirements is dependent on the accomplishments of "others!" The Systems Engineering Manager must depend on the efforts of outside organizations in order to accomplish the objectives described throughout this text, and without "owning" and "controlling" all of the resources necessary for this to happen. A "teaming" effort is essential. Reference: Sections 18.3 (page 658) and 18.4 (page 671).~~

~~18) As a manager of a newly established Systems Engineering Organization, I would need to assume a leadership role in: (a) the early definition of requirements for the system(s) being developed (refer to Sections 3.4 and 3.5, pages 61 and 76 respectively); (b) the early stages of advanced planning (Sections 3.2 and 18.1, pages 58 and 641 respectively) and in the~~

~~development of the System Engineering Management Plan (SEMP - Section 18.2, page 643); (c) the preparation of the System Specification (Type A), and (d) the various stages of system design (e.g., feasibility analysis, functional analysis and allocation, definition of system architecture, design integration, design review and evaluation, and so on). As part of the early planning process and in the development of the SEMP and the System Specification (Type A), I would need to include such requirements that would cover the advent that the design and developing of the new system in question may require the participation of many different external national and international organizations in the future. Given the possibility, it is important that the early planning process accept such from the beginning.~~

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~~As the programs develops, I would need to be involved in establishing an organizational structure similar to that illustrated in Figure 18.18 (page 665), with good interface relationships and the appropriate communications processes firmly established. Further, I would want to assume a leadership role in the evaluation and selection of all external suppliers. Considerations in the selection of external suppliers include a thorough understanding of the environment in which each supplier operates, language and cultural issues, international customs requirements, organizational structures, unique practices and procedures, and all other aspects that could have an significant impact on the supply chain(s) and, ultimately, on the overall ability relative to meeting the requirements of the customer. I would need to have a complete understanding on just how the various outside contractors and suppliers operate relative to dependability, quality of product, meeting on-time delivery requirements within cost, and so on.~~

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~~As the program evolves through the various stages of system design and development, I would continue to implement the approach as initially planned in the SEMP, using the appropriate program management methods/tools (e.g., CWBS, PERT/CPM/COST), conducting periodic program reviews and evaluation, maintaining and ensuring good communications throughout, and so on. The challenges associated with a large program, with many different participating contractors and/or suppliers, may be numerous, especially when involved with a SOS configuration. Hopefully, as an effective Systems Engineering Manager, I would be able to accomplish the required functions in a timely and efficient manner. Reference: Chapter 18 (pages 640-672).~~

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~~CHAPTER 19~~

~~PROGRAM MANAGEMENT, CONTROL, AND EVALUATION~~

~~1) In addressing the subject of *goals* and *objectives* for a systems engineering organization, one needs to deal with two levels of activity to include: (a) the goals specified by the customer and defined through the development of Technical Performance Measures (TPMs) as specific requirements for each of the in-house programs (refer to Section 3.6, page 82), which evolve from the system operational requirements in Section 3.4 (page 61) and the system maintenance and support requirements in Section 3.5 (page 76); and (b) the goals of the company in accomplishing the necessary activities to ensure that the first objective is attained for all in-house programs. The first is customer and program related and the second is internal company related. In some instances, one will find that organizational goals, which are usually in line with company goals, are in conflict with the goals for a specific system development effort or program. Sometimes, while project/program goals will often change with time, organizational goals will remain unchanged (or perhaps stagnant). Care must be taken to ensure that the organizational (and company goals) are directly supportive of the specific goals and objectives for each of the projects/programs being addressed.~~

~~In any event, one can begin with the definition of goals and objectives for the system as specified by the customer (Sections 3.6, page 82 and 3.9, page 95); identify the tasks that need to be accomplished in the implementation of a systems engineering program (Section 18.2.2, page 646); develop specific organizational goals and objectives for accomplishing these tasks; compare these with organizational and company wide goals; review the differences and possible areas of conflict (if any); and incorporate the necessary modifications (as required) to ensure that the internal company wide goals will indeed support those of the customer for the applicable in-house programs. Relative to company organizational goals and objectives, the process of *benchmarking* can be introduced and employed to aid in the growth of the organization and its competitiveness relative to other comparable organizations in a same field of activity. The systems engineering organization, in particular, needs to develop and implement an Organizational Growth Plan. Reference: Section: 19.1 (page 675).~~

~~2) The term *benchmarking* may be defined somewhat differently depending on one's background and experience. Webster defines it as a point of reference from which measurements may be made; something that serves as a standard by which others may be measured. According to R.C. Camp, *The Search For Industry Best Practices That Lead To Superior Performance* (refer to Appendix G, G.11, item 2, page 763), benchmarking can be defined as the continuous process of measuring products, services, and practices against the toughest competitors or those companies recognized as industry leaders. The questions are as follows: Where are we today? How do we compare with others relative to both product and organizational capability (i.e., the competition)? Where would we like to be in the future?~~

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~~Relative to application, one should define the goals and objectives for the organization (assuming that they are directly supportive of system-level goals for all in-house projects); define the tasks to be accomplished in meeting these goals and objectives; identify the metrics associated with each of the tasks being performed (based on current in-house experience); identify the metrics for similar tasks being performed by an outside organization (i.e., those being accomplished by the *best in the field*, or by a competing organization); and develop a plan for product/process improvement (to the extent necessary to be competitive in the future). In attempting to measure the current status (level of maturity) of an organization, one may wish to utilize one of the available "models" for evaluation; i.e., Capability Maturity Model (CMM), Systems Engineering Capability Maturity Model (SE-CMM), Capability Maturity Model Integration (CMMI), or equivalent capability maturity model). For example, it may be feasible and desirable to improve the systems engineering organization by moving from Level 3 to Level 4, which may be the desired benchmark to attain, in Figure 19.9 (page 688). Reference: Sections 19.1 (page 675) and 19.4 (page 681).~~

~~3) Having identified the specific areas of "deficiency" from an organizational perspective, the Systems Engineering Manager can develop an *Organizational Growth Plan* or a *Plan for Improvement*, set some specific "benchmark" target objectives, determine an allowable time period for meeting these objectives, propose alternative approaches and the resources required for the accomplishment of such, and select a preferred approach. On one end of the spectrum, it may be preferable to initiate some training (internal, external, or a combination of each) for existing personnel to fill the gap. On the other hand, it may be more feasible to go outside and "hire" some new people with the appropriate expertise, skills, and experience. From a long-term perspective, either of these alternatives (or a combination of such) would be feasible. For the short term, and if the requirement is to fill a void without the intent of acquiring a permanent capability in the specific area of deficiency, then it may be more feasible to "outsource" and contract with an outside supplier. In any event, the Systems Engineering Manager should have a written plan for organizational assessment, evaluation, and development. Reference: Section 19.4 (page 681).~~

~~4) The manager of an organization needs direct access to a *management information system (MIS)* that will provide the right information, at the right time, in the right format, to the right location(s), with the right degree of reliability, and at the right cost. Further, he/she must be able to initiate the appropriate feedback that is responsive and in a timely manner. The supporting data system must address a number of factors, both of a "technical" and of a program "administrative" nature.~~

~~One might begin with the identification and prioritization of the design goals and objectives as they relate to the systems/products being developed. What are the critical TPMs that are significant, require visibility, and need to be "tracked" on a continuing basis? Refer to Figures 3.17 (page 83), 5.9 (page 143), 19.6 (page 684), and 19.7 (page 685). What are the metrics, what type of information needs to be made visible, in what format, and at what frequency? For example, if life-cycle cost in Figure 5.9 (page 143) is a critical TPM, then the LCC metric and those factors that are required to compile LCC must~~

~~be highlighted through the MIS capability. It is important that the projected or predicted LCC be "tracked" and evaluated, in terms of the specified requirements, on a monthly basis (refer to Figure 19.6, page 684). On the other hand, a less important TPM may not receive the same level of attention.~~

~~Next, one needs to identify the project/program organizational tasks that are required in order to support the goals and objectives associated with the systems/products being developed. This facet of the MIS includes the more traditional cost and schedule reporting structure that is inherent within the program management requirements for most projects (refer to Figure 19.5, page 683, for a typical PERT/CPM report). The important issue here is to ensure that this second area of reporting is directly tied to the first; i.e., the required "tracking" of the critical TPMs **AND** the tasks that need to be accomplished in order that these TPM requirements be met in an effective and expeditious manner. In other words, the organizational goals and objectives must support those design goals/objectives for the system being developed, and the MIS must provide the necessary visibility across the board. Reference: Section 19.4 (page 681).~~

~~5) Decisions as to whether an item should be developed and/or produced *in-house*(internally) or considered for *outsourcing* are based on a number of factors; i.e., internal versus external technical capabilities and capacity, schedule and timing factors, proprietary/warranty rights and ownership factors, economic factors, political factors, and so on. From a pure economic perspective, "make-or-buy" decisions can be based on such criteria as discussed in Chapters 8 and 17. Within the spectrum of cost, however, one needs to ensure that such costs are life cycle oriented. Factors such as warranty/guarantee provisions, access to product data rights, the availability of a supplier life cycle maintenance and support capability, etc., need to be considered. Further, there are non-economic factors such as the protection of proprietary rights which may dictate an internal (in-house) capability, a political decision which dictates that a product should be purchased from Supplier "X" or from Country "Y," and so on. In essence, there are a number of factors involved in the process. Reference: Section 19.2 (page 676).~~

~~6) A *Request for Proposal* (*RFP*) sent out to potential suppliers for bid should include a **Specification** (i.e., *Development, Product, Process,* and/or *Material Specification* – refer to Section 4.2 (page 102) and Figure 4.1 (page 103) for specification types, and an associated **Statement of Work (SOW)**. The specification should include all of the technical design-related requirements and a description of product/process characteristics, and the SOW should specify the tasks that need to be accomplished by the supplier in order to fulfill the requirements of the applicable specification. Relative to the requirements for systems engineering, the tasks specified in the SOW for the supplier should be an extension of those included in the SEMP for the system (refer to the SEMP in Section 18.2, page 643), and must support and complement those tasks conducted at a higher level in the system hierarchical structure. The particular specification type may vary depending on the nature of the work to be accomplished, whether it pertains to the development of a new item or the procurement of a commercial off-the-shelf (COTS) item.~~

~~In any event, the supplier will need to know how the product/component is to be utilized, what functions it must perform and for how long, how it is to be maintained and in what environment (from a system's perspective), what TPMs are applicable and their criticality relative to accomplishing a mission, etc. Thus, the supplier specification must include a brief description of system operational requirements, the maintenance and support concept, the functional analysis leading down to the product/component in question, and the allocated "design-to" requirements (i.e., design criteria). To provide an idea of what should be covered in a RFP, refer to the "Supplier Review Checklist" in Appendix B, Figure B.3 (page 714). The RFP should provide enough guidance such that the supplier, in responding, can adequately cover the topics listed. Reference: Section 19.2 (page 676).~~

~~7) The basic *requirements* for a system are established at the top, and must be "traceable" down to the various individual elements and components of that system. At the same time, the need for a given component and its requirements must be justified upward in response to some identified need. A system may be broken down into elements as shown in Figure 3.25 (page 92), and the requirements must be allocated downward as shown in Figure 4.6 (page 109). There must be a downward-upward *traceability* of requirements maintained throughout, including those requirements for system maintenance and support which evolve from system operational requirements.~~

~~As these requirements are developed at each level in the overall hierarchical structure and for each component of the system, they must be described through some form of a *specification*. Referring to Figure 19.3 (page 678), the various applicable specifications must be presented in some form of structure in order in order to show this traceability. The *specification tree* presented in the figure may include any combination of specifications covering developmental items, commercial specifications covering COTS items, process specifications, design standards, and so on. Of course, extreme care must be taken to ensure that there is no unnecessary redundancy incorporated, and that (in the event of conflict) an order of *precedence* has been established. In the past, there has been a tendency to prepare one overall specification and then attach a list of many lower-level specifications without indicating the degree of importance or which document takes precedence in the event of conflict. Past practices in this area have often been quite costly overall. In any event, the development of a good *specification tree* is intended to help provide a clear picture of requirements and their application, and to preclude some of the conflicts experienced in the past. Reference: Sections 3.9 (page 95), 4.2 (page 102), 19.2 (page 676), and Figure 19.3 (page 678).~~

~~8) Referring to Figure 19.3 (page 678), the applicable TPMs that should be included in each of the specifications indicated are derived initially through the TPM identification and prioritization process described in Section 3.6 (page 82). Top-level metrics are first identified based on the system mission and functions to be performed; these are broken down into lower level (but supporting) metrics in a hierarchical manner; the system is then defined in terms of a functional packaging scheme (similar to that illustrated in Figure 3.25 (page 92); the allocation process is then accomplished as described in Section 4.3 (page 104) and Figure 4.6 (page 109); the applicable lower-level metrics are assigned to different elements of the system (Figure 4.6); trade-off studies are conducted to determine whether~~

~~or not an item should be constructed "in-house" or "outsourced;" specifications are developed to cover each element of the system (Figure 19.3, page 678); and the appropriate metrics for each of these elements must be included in the applicable specification. Reference: Section 19.2 (page 676).~~

~~9) As a start, refer to the "Supplier Evaluation Checklist" in Figure 19.4 (page 679) and the "Supplier Review Checklist" presented in Figure B.3, Appendix B (page 714). Further, there is a more comprehensive "Supplier Evaluation Checklist" in Appendix C of *Logistics Engineering and Management*, 6th Edition, Pearson Prentice Hall, NJ, 2004. Referring to the latter, the categories of interest in conducting a supplier evaluation include: (a) General Criteria; (b) Product Design Characteristics TPMs, technology applications, physical characteristics, effectiveness factors, producibility factors, disposability factors, environmental and sustainability factors, and economic factors); (c) Product Maintenance and Support Infrastructure (maintenance support requirements, data/documentation, warranty/guarantee provisions, and customer service capability); and (d) Supplier Qualifications (planning/ procedures, organizational factors, available personnel and resources, design approach, manufacturing capability, test and evaluation approach, management controls, experience factors, past performance, maturity, and economic factors).~~

~~These factors (which are not necessarily listed in order of importance) provide an indication of what should be considered in the evaluation of different supplier proposals, leading to the selection of one. The specific "order" may vary somewhat depending on the type of system element being solicited (complex new design or source of manufacturing for known entity), the nature of the program and applicable phase, the item(s) being sub-contracted; and so on. The recommended approach is to develop one's own list and prepare a number of probing questions in support of each item, such as shown in Figure B.3 (page 714). Reference: Section 19.2 (page 676).~~

~~10) Student exercise. Referring to Figure 19.4 (page 679), I would develop a detailed checklist (similar to the one in Figure B.3, page 714) with a series of questions pertaining to "supplier organization." An example of some questions: (a) Has the supplier's organization been adequately defined in terms of activities, responsibilities, interface requirements, and so on? (b) Does the supplier's organizational structure support the overall program objectives for the system? (c) Is it compatible with the producer's organizational structure? (d) Has the supplier identified the organizational element responsible for accomplishing systems engineering requirements? Etc.~~

~~11) The proper level of supplier *integration* starts with the initial identification and prioritization of TPMs (Section 3.6, page 82), the allocation process (Section 3.7, page 86, and Section 4.3, page 104), the preparation of the appropriate specifications (Figure 19.3, page 678), and in conducting the trade offs leading to "outsourcing" decisions (Section 19.2, page 676). As Systems Engineering Manager, one would want to be involved in the process which leads to the initial determination of *supplier requirements*. Given this, and with a good understanding of these requirements, I would then want to be involved in the supplier evaluation and selection process to ensure that the best suppliers are selected for~~

~~the job at hand, and that all negotiated contracts/agreements adequately address systems engineering requirements for the program. As the program progresses, I would want to ensure that the proper *communications link* has been established between the various suppliers located around the world, visit each supplier's facility as necessary, and conduct periodic program reviews and the appropriate design reviews (if product design and development activities are involved) at the supplier's facility. Additionally, I would want each supplier to submit some form of an activity or status report, the frequency of which depends on the nature of the supplier's activity (monthly is recommended in most instances). Finally, I would try to reflect the supplier’s activity within the context of the program evaluation factors described in Section 19.4 (page 681). Reference: Sections 19.2 (page 676) and 19.4 (page 681).~~

~~12) Refer to Figure 19.5 (page 683). I would first visit the supplier's facility and determine the “cause(s)” of the schedule slippage. If the cause is the result of some internal supplier problem, I would (in cooperation with supplier management) search for possible solutions and initiate the necessary corrective action. If the cause is the result of some deficiency of a lower level “supplier” of the major supplier, then I would work with the major supplier’s management in initiating the necessary corrective action at the lower level. Such corrective action may include a number of different approaches — by “redesigning” around a given obstacle, by applying more resources to the critical activity/task (through the shifting of resources from a less critical activity/task where there is some schedule flexibility), and/or a combination of these. Given a selected approach, a plan needs to be developed and implemented to correct the situation. Reference: Section 19.4 (page 681).~~

~~13) Refer to Figure 19.6 (page 684). Assuming that the projected LCC results are not favorable at Program Review 3 (independent of what is projected for the long term), one would want to: (a) review the cost breakdown structure (CBS) and identify the “high cost contributors;” (b) determine the “cause and effect” relationships, or the actual causes for the high cost; and (c) initiate the necessary corrective action which will ultimately result in a LCC reduction. Corrective action may include any number or combination of approaches such as redesigning an item of equipment or software to improve reliability, modifying a process to reduce time and increase efficiency, redesigning the maintenance and support infrastructure to reduce resource consumption and cost, and so on. Reference: Section 17.3 (page 574) and Figure 17.5 (page 575), and Section 19.4 (page 681).~~

~~14) Refer to Figure 19.7 (page 685). The three problem areas noted refer to life cycle cost (LCC), availability, and MMH/OH, and all three are interrelated, each having an impact on the others. Given this, I would first determine which of the three is the most critical TPM and proceed to solve it; then, solve the second most critical; and so on. I may wish to review the results of the latest prediction (or projected estimate), identify the major contributors (on the basis of the results), determine the “cause and effect” relationships, and investigate alternative design approaches that would eliminate the “causes” and lead to improvement. Each proposed alternative should be evaluated in terms of its impact on not only LCC (for example) but on availability, MMH/OH, and other factors as well. The three TPMs in Figure 19.7 are all interrelated and a change in any one may have an impact on the others. Also, any single change may have a negative impact on other TPMs not~~

~~previously identified as being a problem. This process can be applied on an iterative and continuous basis, employing a sensitivity analysis as necessary, leading to the elimination of the three problem areas identified in Figure 19.7 and improvement overall. Reference: Section 19.4 (page 681).~~

~~15) I would likely follow the basic steps required in developing a "model" similar to the SE-CMM method illustrated in Figures 19.9 and 19.10 (pages 688 and 689 respectively). This includes identifying the systems engineering tasks that need to be accomplished, "tailored" to my specific organization; determining the desired "metrics" associated with task accomplishment; comparing the results of task accomplishment relative to the principles and practices of *good* systems engineering (through the application of *benchmarking* methods); determining the relative positioning ("level-of-maturity" status) of my organization using a scale similar to that illustrated in Figure 19.9; identifying the weaknesses within my organization; and initiating a *continuous process improvement (CPI)* program leading to organizational enhancement. Reference: Section 19.4.2, page 682 ("Evaluation of the Systems Engineering Organization").~~

~~16) Student exercise. Refer to Figures 19.8, 19.9, 19.10, and 19.11 (pages 686-690). The questions generated could be similar in format to the checklist questions presented in Appendix *B*, except that the emphasis should be directed to systems engineering capability. For example: *Does the systems engineering organization actively participate in the definition and allocation of requirements in the design and development of new systems? Does the systems engineering organization assume an active leadership role in the scheduling and conducting of formal design reviews? Does the systems engineering organization serve in a leadership capacity in the integration of all applicable engineering and non-engineering organizations in and throughout the day-to-day design process?* Reference: Section 19.4.2, page 682 ("Evaluation of the Systems Engineering Organization").~~

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~~17) Refer to Figure 19.9 (page 688). First, you will probably need to accomplish some outside research for a greater understanding of the major focus area categories (i.e., *performed, managed, defined*) and the related questions for each of the detailed focus areas (i.e., *focus area 1, focus area 2*, etc.). Having assessed your current organizational capability, you learn that your organization falls within the *managed* area. Further, upon developing a chart similar to that illustrated in Figure 19.10 (page 689), you will note those areas that show some weaknesses and, based on a review of the input evaluation questions, you should be able to identify some of the "causes" for these weaknesses. Then, when reviewing the expectations for being included in the higher level *defined* category, you will be able to identify some of the deltas, or gaps where improvement will be required; i.e., what is required for the organization to grow from the *managed* category to the *defined* category? This should enable you to determine what areas need to be improved within your organizational capability which, in turn, should lead to the development of an *Organizational Growth Plan (OGP)*, or some formal document of an equivalent nature. Organizational improvement may result from the implementation of some formal training involving those currently in the organization, the hiring of some new personnel with the~~

~~capabilities and experience needed, and/or a combination of each. Reference: Section 19.4.2 (page 682).~~

~~18) Risk can be defined as the potential that something will go wrong as a result of one or a series of events. It can include technical risk, cost risk, schedule risk, and program risk (refer to Figure 19.12, page 691). Risk can be measured as the combined effect of the probability of occurrence and the assessed consequences given that occurrence. Risk, as used in this text, refers to the potential of not meeting a specified technical and/or program requirement (i.e., not meeting a specified TPM, a schedule, or cost requirement). While all areas of risk (i.e., technical, schedule, and cost) are of interest to the Systems Engineering Manager, of particular concern for the systems engineer are: (a) not meeting the required TPMs for the system as an entity; and (b) not performing the program tasks that are essential to ensuring that these TPM requirements are met. Reference: Section 19.5 (page 690).~~

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~~19) Student exercise. *Risk management* constitutes an iterative process to include the following steps: risk planning, risk identification, risk monitoring, risk assessment, risk modeling and analysis, risk abatement, risk reduction, and risk handling. These areas should be covered in a *Risk Management Plan.* The Risk Management Plan should be included as a major section of the SEMP (refer to Figure 18.4, page 645), or described in the SEMP with reference to a full-scale plan which may be included elsewhere. Reference: Section 19.5 (page 690).~~

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~~20) The development of a risk management capability is extremely important (i.e., critical) as the potential of introducing program risk becomes greater with system complexities increasing, the introduction of new technologies in system design becoming more of a common practice, the nature of organizational interfaces becoming more complex and demanding with increased outsourcing and a greater number of suppliers in the loop, and so on. From a systems engineering perspective, having an effective risk management capability in place assumes even a greater degree of importance since the Systems Engineering Manager serves in a leadership capacity relative to the initial development of system requirements, the identification of outsourcing requirements and the selection of suppliers, the integration of many different technical and supporting disciplines and related organizations throughout system design and development, etc. There are many challenging decisions that must be made throughout a typical program/project, and the associated risk(s) in the day-to-day decision-making process could be rather extensive. Reference: Section 19.5 (page 690).~~

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