INSTRUCTOR'S GUIDE

TO PROBLEM SOLUTIONS

For

SYSTEMS ENGINEERING AND ANALYSIS

Fifth Edition

By

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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.

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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

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**.