Chapter 1 – Introduction to System Engineering

1. A "system" may be considered as constituting a nucleus of elements (i.e., materials, equipment, software, people, facilities, data, information, services, and money) combined in such a manner as to accomplish a function in response to an identified need. A system may vary in form, fit, and structure; must have a *functional* purpose; is contained within some form of *hierarchy*; and may be broken down into *subsystems* and related components. As a point of emphasis, a system must respond to an identified functional need. Thus, the elements of a system must include not only those items that relate directly to the accomplishment of a given mission scenario or operational profile, but must also include those elements of logistics and maintenance and support that must be available and in place should a failure of a prime mission related element occur. If one is to ensure the successful completion of a mission, all of the support elements must be available, in place, and ready to respond to a given need. The issue here is to address ALL of the elements of a system as an integrated "whole" from the beginning and not some "after-the-fact" as has been the case in the past. Refer to Section 1.1.1, pages 2-5.

   Referring to Section 1.1.2 (pages 5-8), there are different categories of systems. Of particular interest in this text are systems that are *human-made*, *physical* by nature, *dynamic* in operation, and of an *open-loop* variety. Some examples are identified in Figure 1.1. You may wish to have the student describe a "system" with which he/she is familiar.

2. This is basically a student exercise. A "flow diagram" in this instance may constitute an illustration such as in Figure 1.11 (page 17), perhaps expanded to some extent to include a breakout of what might be included within "system operations." The objective is to get the student to start thinking in terms of the "life cycle" and the major activities contained within! While not shown in Figure 1.11, it would be appropriate to include a "feedback" loop such as illustrated in Figure 1.10.

3. A "system-of-systems (SOS)" refers to a system within, and as an integral part of, a larger group of systems located in the same overall structure. It refers to a collection of systems, tied together in some manner, to provide a functional capability beyond that of any single individual system in the structure. The system in question is often contained within some form of hierarchy. An example is an airplane, within an

airline, in a specified geographical area, which is within an overall worldwide transportation capability. Within the overall transportation capability itself, in addition to the airplane there may also be rail, automotive, and/or sea vehicles. The airplane, rail, automotive, and sea systems must all be addressed in terms of their respective interfaces and within the context of the higher-level structure. Refer to Section 1.1.3 (pages 8-9).

4. All of those elements required to successfully accomplish (complete) a designated system "mission;" i.e., hardware, equipment, software, people, facilities, data/information, and supporting resources. This includes not only those items required and are directly associated with the completion of a specific mission scenario (or a series of scenarios), but the maintenance and support infrastructure as well. So often, this maintenance and support infrastructure is not considered; however, without such there is no guarantee that the system will successfully complete its mission requirement. Refer to Section 1.1.1 (pages 2-5).

5. "System engineering" may be defined as the "application of scientific and engineering efforts to (l) transform an operational need into a description of system performance parameters and a system configuration through the iterative process of requirements analysis, functional analysis and allocation, synthesis, trade-offs and design optimization test and evaluation, and validation; (2) integrate related technical parameters and ensure compatibility of all physical, functional, and program interfaces in a manner that optimizes the total definition and design; and (3) integrate reliability, maintainability, usability (human factors), safety, producibility, supportability serviceability), disposability, economic feasibility, and other factors into the total engineering effort to meet cost, s9hedule, and technical performance objectives." System engineering may be defined somewhat differently (depending on the source) as indicated in Section 1.3.2 (pages 18-25).
System engineering includes a top-down approach viewing the system as a *whole*; providing a *life-cycle* orientation commencing with the initial identification of a "need" and extending through design and development, production and/or construction., system utilization and sustaining support, and system retirement and material recycling/disposal; and promotes an *interdisciplinary* and *iterative* approach throughout the design and development process to ensure that all design objectives are met in an effective and efficient manner. Basically, it constitutes a highly-disciplined *process* for not only bringing a new system into being but in the re-engineering of existing systems for the purposes of improvement and/or upgrading.

Refer to pages 18-20.

System engineering is important for reasons stated in Sections 1.2 and 1.3. Following a bottom-up, "design-it-now-and-fix-it-later," approach will not always produce the desired results from a customer's perspective, and can be very costly in the long term.

System engineering constitutes a *process* for bringing systems into being (refer to Figure 1.13). *System science* deals primarily with the observation, identification~ description, experimental investigation, and theoretical explanation of facts, physical laws, interrelationships, and so on, associated with natural phenomena. Science deals with the basic concepts and principles that help explain how the world behaves; e.g., principles of biology, chemistry, physics (refer to Section 1.3.5). *System analysis* constitutes an on-going, iterative, analytical effort, utilizing various models/tools to help solve a wide variety of problems throughout system design and development, production, operational use and sustaining support (refer to Section 1.3.6, page 27). System analysis is accomplished within and throughout the system engineering process, utilizing scientific principles to help solve problems.

6. System engineering per se is not considered as an engineering discipline in the same context as civil engineering, mechanical engineering, reliability engineering, or any other design specialty (refer to Section 1.3.2, last paragraph, Page 25). It constitutes an over-arching activity that addresses the system as an entity and causes the integration of the various applicable and specialized design disciplines (or "domains"). Whereas, civil engineering, electrical engineering, etc., are considered to be more specialized, concentrated, focused, and limited in terms of breadth of coverage. System design and development usually requires expertise from many different design disciplines, and the role of system engineering is to ensure that these specialty areas work together as a "unified team."

7. Referring to Figure 1.11, Example "A," the three illustrated life cycles (i.e., the top-level dealing with the prime mission-oriented elements of the system, the second-level dealing with the production capability, and the third-level dealing with the system support capability) must be addressed from the beginning and in a concurrent manner. Design and management decisions made during the conceptual design phase and pertaining to the prime elements of the system (e.g., the selection of technologies, the selection of materials, developing system packaging schemes) can have a great impact on the specific requirements for both the production process and

the support capability. At the same time, early decisions pertaining to the production and support processes can have a significant "feedback" effect on the top-level life cycle. These life cycles (along with the system retirement and material recycling/disposal process -a possible fourth life cycle) must be addressed in the context of the *whole* (refer to Section 1.3.1).

8. Referring to Figure 1.14, some key objectives might include: (1) ensuring that a top down process is used leading to the identification of hardware, software, human, facility, data, and other resource requirements as they may evolve from the functional analysis; (2) ensuring that there is a "traceability" of requirements from the initial definition of the need through the identification of resources to include hardware, software, people, etc.; (3) ensuring that the evolution from the "WHATs," from the functional analysis, to the "HOWs" is reflected to the extent possible; (4) ensuring that there are no resource requirements identified that cannot be traced back to some functional requirement; (5) ensuring that the sub functions covering the development of hardware, software, human, and other requirements are completely identified and properly scheduled in terms of the overall life cycle; (6) ensuring that the hardware, software, human, and other development cycles (as applicable) are properly integrated, with the necessary communications, as one proceeds from left to right in the figure; (7) ensuring that the appropriate program/design reviews are included on a progressive basis to allow for periodic validation; and (8) ensuring that a *feedback* loop is included for the purposes of initiating corrective action or for product/process improvement.

   While a review of the figure (as shown) will not ensure that meeting these objectives will be guaranteed, the intent here is to thoroughly understand the process that is illustrated and to evaluate such with the above in mind. Hopefully, the process will allow the above objectives to be met.

9. Referring to Figure 1.15, some key objectives might include: (1) ensuring that design requirements and quantitative and qualitative criteria are specified for the system as an entity; (2) ensuring that the appropriate design criteria are identified and traceable from the system-level to the subsystem, configuration item, and lower indenture - levels of the system - developing a top-down "objectives tree" as appropriate; (3) ensuring that the appropriate analytical tools/methods are identified for application throughout the design and development process; (4) ensuring, to the extent possible, that these tools/methods can be properly applied and integrated throughout -

eliminating unnecessary duplication of effort; and (5) ensuring that the results of the various analysis efforts can be integrated into a centralized shared database structure.

While the illustration in Figure 1.14 conveys an "integrated" approach, progressing from left to right, the intent of Figure 1.15 is to convey an integrated approach from the top down. The objective is to show a "traceability" of requirements from the top, and to show an efficient approach in the day-to-day design process through the utilization of an integrated design workstation (or equivalent). There could be a considerable duplication of effort unless care is taken to first be familiar with and understand the available tools and their applications, understand the applicable inputs and outputs, and understand how some of these tools CWI be integrated and utilized in an effective manner. For instance, a FMECA may be required in response to a reliability program requirement, a maintainability program requirement, and a logistics program requirement. A single unified analysis should be responsive to all needs.

10. 10. The *feedback* loop in Figure 1.16 provides a mechanism to enable that very necessary communication that is required for (1) an assessment of the consequences from those design and management decisions made earlier, and (2) for enabling the iterative and continuous capability pertaining to product/process improvement. One thing that has been missing in the design and development of new systems is the appropriate "feedback" of data from the field describing customer/consumer experiences associated with systems that either are presently or have been in use in the past. Thus, we often accomplish our tasks in ignorance, are not aware of our past mistakes, and continue to repeat the same things over and over again. The feedback loop is an essential element in systems which, in tum, constitutes an iterative process (refer to Figures 1.12, 1.13, 1.14, and 1.28).

11. In conceptual design, major system engineering functions may include: (1) a description of the problem and an identification of the customer/consumer need; (2) the accomplishment of a feasibility analysis; (3) definition of system operational requirements; (4) development of the maintenance concept; (5) identification and prioritization of technical performance measures (TPMs); (6) design integration at the system level; (7) preparation of the System Specification Type "A," (8) preparation of the Test and Evaluation Master Plan (TEMP); (9) preparation of the System Engineering Management Plan (SEMP); and (10) Chairing the conceptual design review. While it certainly is not expected that the system engineer, or the

system engineering organization, will do all of this, it IS expected that system engineering will assume a major leadership role in the completion of these activities. Establishing a good "baseline" design at the system-level, which is accomplished as part of the conceptual design phase, is essential for the successful completion of all follow-on activities. System engineering emphasis must be provided in the "front-end" of a program.

During the preliminary design phase, system engineering activities may include (1) the development and refinement of the functional analysis; i.e., a description of the system in *functional* terms; (2) partitioning of the system into its major subsystems and components; (3) allocation, or apportionment, of system-level design requirements to the various lower-level elements of the system; (4) assisting in the preparation of lower-level specifications (Types B, C, D, and E) to ensure a "traceability" of requirements from the System Specification Type "A;" (5) ensure that all design related activities are being properly coordinated and integrated; and (6) Chairing the formal design review meetings. Again, the system engineering organization is expected to assume a leadership role in the completion of these activities.

During the detail design and development phase, system engineering activities may include (1) providing a leadership role in the on-going coordination and integration of all design-related activities; i.e., customer, contractor in-house, and supplier activities; (2) monitoring test and evaluation activities and providing as assessment of the system design configuration in terms of the initially specified requirements; (3) monitoring all proposed engineering change proposals; i.e., Chairing the CCB and providing a leadership role in configuration management; and (4) Chairing the formal design review meetings. The "baselines" shown in Figures 1.13 and 1.14 must be maintained.

During the production/construction, system operational use and support, and the retirement and material disposal phases, system engineering primarily focuses on those activities associated with system *assessment* and the *validation* of the system configuration in terms of fulfilling the ultimate need(s) of the customer/consumer. Accomplishing such requires a good data collection, analysis, and management information system (MIS) structure, a good "feedback" capability, and the monitoring of proposed changes and modifications for corrective-action or for the purposes of continuous product/process improvement. Again, the emphasis here is on the "system" and how well it is doing in terms of the initially-specified requirements, as well as the "capturing" of good field experience that can be effectively applied in the design and development of future new systems.

12. Agile Engineering is a process, primarily applied in the development of software that is similar to the concepts associated with the waterfall model (see page 28.) The emphasis is on small group activities stressing the continuing interaction and feedback among participating individuals, close collaborating with the customer, the utilization of simplified tools and the development of working software versus a lot of documentation, and is readily responsive to design changes. It represents a simplified approach in the development of selected software modules, and should be properly integrated within the overall system engineering process illustrated in Figure 1.13 (refer to Section 1.3.7, page 29).

13. Agile Engineering is a more simplified and informal approach (involving small group activities with close feedback, less documentation, more "working" software that may be receptive to quick changes in design, and so on). Refer to Footnote 22 on page 29.

14. Referring to Section 1.3.7 (Figures 1.17, 1.18, and 1.19), the *Waterfall*, the *Spiral*, and the *Vee* models were developed with the objective of describing and illustrating a <u>process</u> for bringing a system into being! These models were developed in the 1980s when the basic makeup of systems became more *software-intensive*. Each of the models illustrated, when <u>properly implemented</u>, can be effective in accomplishing its objective. Unfortunately, these models are not being properly implemented in many instances, are often categorized as being "deficient," and new models (with new identifiers) are introduced with the objective of “resolving all problems" - instead of making what is already in existence work!

    When comparing the *Waterfall*, *Spiral*, and *Vee* models with the "model" proposed throughout this text, the author feels that the latter is more <u>complete</u> from a life-cycle perspective. All of the phases (and associated activities) identified in Figure 1.9 are not adequately covered in Figures 1.16, 1.17, and 1.18.

15. Referring to 1.5 (Figure 1.26), successful implementation of the principles and concepts of system engineering is dependent both on an understanding of the process illustrated in Figure 1.13 and its implementation (i.e., the technological issues), and

on the organizational environment that needs to be created to allow it to happen (i.e., the management issues). Without top-level management support; and an environment allows for creativity and innovation, the goals and objectives of system engineering will not be accomplished! There have been numerous examples where individuals at the lower levels of an organization believed in and tried to implement system engineering principles, but without success because of highly rigid autocratic and structured pattern at the higher levels where the resistance to change is predominant. On the other hand, there are examples where the upper level of management is willing, but where the individuals at the lower level(s) have not had any experience in this area, do not understand the process, and do not know what to do! Thus, both sides of the spectrum shown in Figure 1.26 are critical to the process. These activities must be addressed from the beginning and throughout the system life cycle.

Referring to Figure 1.21, there is a "forward" flow of activities that are essential and lead to the accomplishment of the mission in fulfilling the requirements of the customer; i.e., those functions represented in blocks 1, 2, 3, 4, 6, and 7. Additionally, there is a "reverse" flow of activities that are essential in providing the required maintenance and support of the system in the event of failure and are necessary in ensuring that the system will be restored to full operational status as required; i.e., those functions represented in blocks 3, 5, 7, and 8 (refer to the dotted line). All of these activities are required for the successful implementation of system engineering objectives, and all of these requirements must be addressed as part of the system requirements definition process during conceptual design. These activities are inherent within the process illustrated in Figure 1.26, where "technology" and "management" are applicable.

16. Referring to Figure 1.22, the logistics and supply chain activities include the initial evaluation and selection of suppliers, the procurement and physical supply of materials from the various sources of supply to the production/manufacturing facility, the flow of materials through the production/manufacturing process, and the physical distribution (transportation and warehousing) of finished products to the appropriate customer sites. These activities are essential not only in providing the necessary support to the design and production processes, but the effectiveness and efficiency in the accomplishment of these activities can affect the overall life-cycle cost and the ultimate cost effectiveness of the system. Thus, the activities reflected in Figure 1.22 must be considered as an inherent part in defining the requirements for the system, and these activities must be addressed from the beginning during

conceptual design.

17. Referring to Figure 1.23, the infrastructure and related activities as presented include the sustaining maintenance and support of the system throughout its planned life cycle. If the system is to meet its objective (in response to customer requirements), then this infrastructure must be available, in place, and ready to respond to the need in the event of system failure or if the system is inoperative for any reason. The lack of having such a capability can significantly impact the overall effectiveness and the life-cycle cost of the system. Since an objective of system engineering is to design and develop, produce, and deliver a system that is reliable, effective, efficient, and that will respond to customer needs, it essential that this infrastructure be addressed as a major element of the system and within the context of the system engineering process.

18. Referring to Figure 1.24, the various elements of logistics are identified. These elements pertain to and are integral to both the "forward flow" and "reverse flow" activities illustrated in Figure 1.21. These elements should be considered as "inherent" elements of the system to ensure that the system will be able to fulfill its mission requirements. If a system failure should occur, the appropriate logistics support must be ready and available to restore the system to full operational status in order to complete its planned mission.

19. Referring to Section 1.4.2, each and all of the design disciplines are important and must be addressed, along with possibly some others not mentioned. The degree of emphasis (as to which discipline is more important) depends on the basic characteristics of the system and its mission requirements. For example, in the design of space systems where, in the completion of a given mission there is little to no opportunity for the accomplishment of any maintenance actions, reliability becomes a critical requirement. Thus, the "design for reliability" receives a higher degree of emphasis than perhaps some of the other disciplines. On the other hand, the "design for maintainability" is perhaps not as critical. For systems, where the accomplishment of selected preventive maintenance actions can be realized without negatively impacting system effectiveness and life-cycle cost, the reverse might be true. In such situations, the "design for maintainability" becomes more critical and receives a greater degree of emphasis in the design process. For systems where the accomplishment of many critical functions is dependent on the human operator, then the "design for human factors" receives a greater degree of emphasis than perhaps

some others.

20. Refer to the first paragraph in response to Problem 15. An organization can claim to have the best "technical" approach possible; however, the implementation of such will not be successful unless the appropriate "management" structure is in place and is supportive. Additionally, a supporting management structure can be in place; however, a good "technical" knowledge of the design requirements and the tools and how they can be utilized in an effective and timely manner is essential. Both sides of the spectrum in Figure 1.26 are critical to the process as shown.

21. The System Specification Type “A" constitutes the top-level *technical* document that identifies the requirements for and describes the system in functional terms. It should be "performance-oriented," identifying the "WHATs" in terms of system expectations. It describes the "baseline" from which all subordinate specifications evolve. Without a good baseline, or foundation upon which to build, all subsequent activity may be questionable. Unfortunately, there have been many instances in the past where the system specification has been poorly prepared, including very vague and general statements concerning requirements, and has been difficult to understand. This, in turn, has led to the development of lower-level specifications (written in specific terms) that have not always reflected the truly-intended requirements at the system level. In other words, the "traceability" of requirements downward and upward has not been possible. Specifications are discussed further in Chapter 3, Section 3.2 and a sample outline for the System Specification Type “A” is presented in Table 3.1 (page 134). Nevertheless, it may be worthwhile for the student to develop an outline of a specification at this time.

22. The focus of Product Life-Cycle Management (PLM) is on the technical aspects of system design, development, and system operations. Enterprise Resource Planning (ERP) deals with the execution of all business aspects of manufacturing. Manufacturing Execution System (MES) is utilized to manage a company’s shop floor, controlling the equipment as well as scheduling production runs across different routings within a production fabrication run. These related frameworks (like PDM) deal with different portions of the system development and production life cycle. All must interact as needed with the appropriate systems engineering activities such as requirements and configuration management, trade-off analyses, corporate approved and compliant components, manufacturing constraints and operation, and the like. Refer to Section 1.4.9 (page 46).

