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THE SYSTEMS ENGINEERING OVERVIEW AND PROCESS
(FROM THE SYSTEMS ENGINEERING MANAGEMENT GUIDE [1990])

Defense Systems Management College

The past several decades have seen the rise of large, highly interactive systems that are on the forward edge of technology. As a result of this growth and the increased usage of digital systems (computers and software), the concept of systems engineering has gained increasing attention. Some of this attention is no doubt due to large program failures which possibly could have been avoided, or at least mitigated, through the use of systems engineering principles. The complexity of modern day weapon systems requires conscious application of systems engineering concepts to ensure producible, operable and supportable systems that satisfy mission requirements.

Although many authors have traced the roots of systems engineering to earlier dates, the initial *formalization* of the systems engineering process for military development began to surface in the mid-1950s on the ballistic missile programs. These early ballistic missile development programs marked the emergence of engineering discipline "specialists" which has since continued to grow. Each of these specialties not only has a need to take data from the overall development process, but also to supply data, in the form of requirements and analysis results, to the process.

A number of technical instructions, military standards and specifications, and manuals were developed as a result of these development programs. In particular, MIL-STD-499 was issued in 1969 to assist both government and contractor personnel in defining the systems engineering effort in support of defense acquisition programs. This standard was updated to MIL-STD-499A in 1974, and formed the foundation for current application of systems engineering principles to military development programs.

In its simplest terms, systems engineering is both a technical process and a management process. To successfully complete the development of a system, both aspects must be applied throughout the system life cycle. From a government's program management point of view, the Defense Systems Management College favors the management approach and defines systems engineering as follows:

> Systems engineering is the management function which controls the total system development effort for the purpose of achieving an *optimum balance of all system elements*. It is a process which transforms an operational need into a description of system parameters and integrates those parameters to *optimize the overall system effectiveness*.

A system life cycle begins with the user's needs, expressed as constraints, and the capability requirements needed to satisfy mission objectives. Systems engineering is essential in the earliest planning period, in conceiving the system concept and defining system requirements.

As the detailed design is being done, systems engineers: 1) assure balanced influence of all required design specialties, 2) resolve interface problems, 3) conduct design reviews, 4) perform trade-off analyses, and 5) assist in verifying system performance.

During the production phase, systems engineering is concerned with: 1) verifying system capability, 2) maintaining the system baseline, and 3) forming an analytical framework for producibility analysis.

During the operation and support (O/S) phase, systems engineering: 1) evaluates proposed changes to the systems, 2) establishes their effectiveness, and 3) facilitates the effective incorporation of changes, modifications and updates.
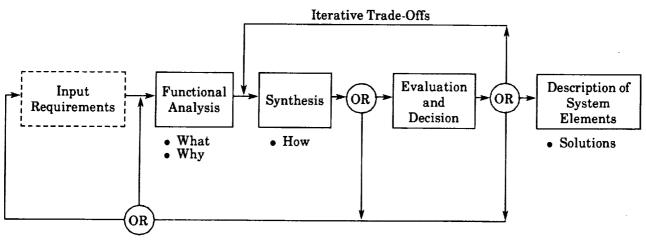
Figure 1   The Systems Engineering Process

THE SYSTEMS ENGINEERING PROCESS

Although programs differ in underlying requirements, there is a consistent, logical process for best accomplishing system design tasks. Figure 1 illustrates the activities of the basic systems engineering process.

The systems engineering process is iteratively applied. It consists primarily of four activities: functional analysis, synthesis, evaluation and decision, and a description of systems elements. The product element descriptions become more detailed with each application and support the subsequent systems engineering design cycle. The final product is production-ready documentation of all system elements.

Since the requirement to implement a systems engineering process may cause major budgetary commitments and impact upfront development schedules, it is important to understand the inherent objectives:

- Ensure that system definition and design reflect requirements for *all* system elements: equipment, software, personnel, facilities and data.
- Integrate technical efforts of the design team specialists to produce an *optimally balanced design.*
- Provide a comprehensive indentured framework of system requirements for

use as performance, design, interface, support, production and test criteria.

- Provide source data for development of technical plans and contract work statements.
- Provide a systems framework for logistic analysis, integrated logistic support (ILS), trade studies and logistic documentation.
- Provide a systems framework for production engineering analysis, producibility trade studies, and production and manufacturing documentation.
- Ensure that life cycle cost considerations and requirements are fully considered in all phases of the design process.

Successful application of systems engineering requires mutual understanding and support between the military and contractor program managers. They must be willing to make the systems engineering process the backbone of the overall development program. They must understand the need to define and communicate among the engineering specialty programs. They must recognize the role of formal technical reviews and audits, including the value, objectives and uniqueness of each formal review and audit. They must also know the objectives of the program and possess a thorough interpretation of the user's requirements.

The output of the systems engineering process is documentation. This is the means by which it controls the evolutionary development of the system. Systems engineering prepares a number of technical management and engineering specialty plans that define how each phase of the acquisition cycle will be conducted. Draft plans are usually submitted with the proposal and final plans are delivered in accordance with the Contract Data Requirements List (CDRL). These plans are used by the government to ensure compliance with the contract and used by the contractor to develop detailed schedules and allocation of resources. Specifications are submitted that form the basis for the design and development effort. Top-level specifications are incorporated into the statement of work (SOW) and provided to the developer. The developer will allocate these top-level requirements to lower level system components (hardware and software) and submit the associated specifications and design documents to the government for approval. The status of system development progress is tracked and documented in the form of technical review data packages, technical performance measurement (TPM) reports, analysis and simulation reports and other technical documentation pertinent to the program. In summary, this documentation may include:

- Systems Engineering Management Plan (SEMP)
- Specifications (system, segment, development, product, process, material)
- Design Documentation
- Interface Control Documents (ICDs)
- Risk Analysis Management Plan
- Survivability/Vulnerability (S/V) Hardness Plan
- Mission Analysis Report
- Reliability Plan
- Maintainability Plan
- Integrated Logistics Support Plan (ILSP)
- Software Development Plan (SDP)
- Test and Evaluation Master Plan (TEMP)

- Producibility Plan
- Functional Flow Block Diagrams (FFBD)
- Requirements Allocation Sheets (RAS)
- Audit Reports
- EMI/EMC Control Plan
- Human Engineering Plan
- Trade Study Reports

The systems engineering process is an iterative process applied throughout the acquisition life cycle. The process itself leads to a well defined, completely documented and optimally balanced system. It does not produce the actual system itself, but rather, it produces the complete set of documentation, tailored to the needs of a specific program, which fully describes the system to be developed and produced. Each program's systems engineering process, developed through tailoring and/or adding supplemental requirements, must meet certain general criteria. Although not complete, the following guidelines should be considered in approaching the basic process:

- System and subsystem (configuration item) requirements shall be consistent, correlatable, and traceable both within data produced as basic documentation (e.g., Functional Flow Block Diagram, Requirements Allocation Sheet, and Time Line Sheet) and as related documentation (e.g., work breakdown structure and Logistic Support Analysis Record).
- The concept of minimum documentation shall be evident.
- Acquisition and ownership cost shall be an integral part of the evaluation and decision process.
- Baselines shall be established progressively as an integral part of the systems engineering process.
- The systems engineering process shall result in a design that is complete, at a given level of detail, from a total system element viewpoint.

- The process shall provide for the timely and appropriate integration of mainstream engineering with engineering specialties such as reliability, maintainability, human factors engineering, safety, integrated logistic support, environmental assessments and producibility to ensure their influence on system design.
- The process shall provide for continuing prediction and demonstration of the anticipated or actual achievement of the primary technical objectives of the system. Problems and risk areas shall be identified in a timely manner.
- Formal technical reviews and audits shall be an integral part of the systems engineering process.
- The systems engineering process shall be responsive to change. The impact of changes to system and/or program requirements must be traceable to the lowest level of related documentation in a timely manner.

- Significant engineering decisions shall be traceable to the systems engineering activities and associated documentation upon which they were based.

Figure 2 is an overview of the four basic steps of the systems engineering process.

FUNCTIONAL ANALYSIS

Every engineering effort must begin with a statement of a perceived need. At the beginning of a DOD acquisition effort, this statement will be in the form of a system requirement document, usually developed through a Mission Area Analysis of anticipated threats.

Once the purpose of the system is known, the functional analysis activity identifies what essential functions the system must perform. In order to accomplish this, functional analysis is composed of two primary process segments: functional identification and requirements identification and
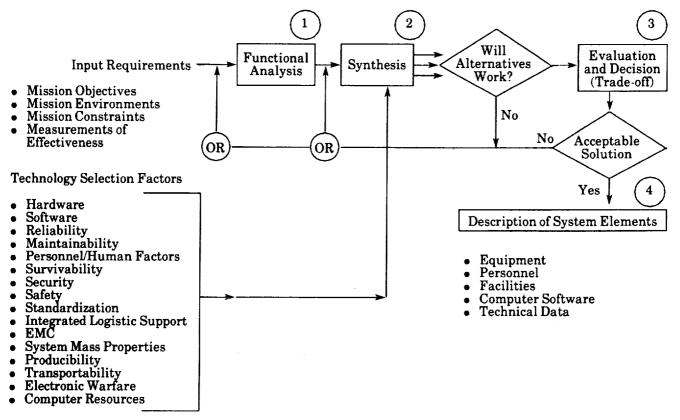
Figure 2 The Systems Engineering Process

allocation (functional performance requirements analysis). It answers the "what" and "why" questions relative to system design.

The basic analytical tool for functional identification is the Functional Flow Block Diagram (FFBD), showing logical sequences and relationships of operational and support functions at the system level. Specific functions will vary from system to system and will be traceable to mission requirements and objectives. Maintenance flow diagrams depicting general maintenance and support concepts will lead to analysis of requirements on an end item/equipment basis. At this level, since functions are more standardized, functional identification is often accomplished using the End Item Maintenance Sheet (EIMS) or Logistic Support Analysis Record (LSAR). Similarly, detailed test requirements are identified using the Test Requirements Sheet (TRS), and productivity requirements are identified using the Production Sheet (PS).

It should be kept in mind that the systems engineering process is always iterative. Each acquisition phase will involve functional analysis to progressively more detail. For example, during the Concept Exploration/Definition (C/E) phase, analysis of support functions will concentrate on Maintenance FFBDs, which will support the establishment of gross maintenance concepts. During Full Scale Development (FSD), emphasis will shift to detailed analysis of the maintenance requirements of specific equipment using the EIMS or LSAR.

The Requirements Allocation Sheet (RAS) is used as the primary analytical tool for requirements identification and allocation, or functional performance requirements analysis as it often is referred to, in conjunction with FFBDs and special purpose documents such as EIMSs, TRSs, and PSs. The RAS serves three purposes in documenting the systems engineering process: 1) initially, it is used to record the performance requirements established for each function; 2) during synthesis, it is used to show the

allocation of the functional performance requirements to individual system elements or a combination of elements; and 3) following evaluation and decision, the RAS provides the functionally oriented data required in the description of the system elements.

The Time Line Sheet (TLS) is used to perform and record the analysis of time-critical functions and functional sequences. In performing time requirements analysis for complex functional sequences, additional tools, such as mathematical models or computer simulations, may be needed. Time requirements analysis is performed in any or all of the functional cycles of the process to determine whether time is a critical factor. The TLS complements the FFBD in its ability to show a lower level of detail, as well as to illustrate the impact of concurrent functions within a given sequence. TLSs are used to support the development of design requirements for the operation, test and maintenance functions. They identify time-critical functions and depict the concurrency, overlap and sequential relationship of functions and related tasks. Time-critical functions are those that affect reaction time, downtime or availability.

SYNTHESIS

Synthesis supplies the "how" answers to the "what" outputs of functional analysis.

Two documentation tools accomplish and record the synthesis of design approaches or alternative approaches. The Concept Description Sheet (CDS) is used to collect the performance requirements and constraints, as delineated by functional analysis, that apply to an individual subsystem or end item. The CDS also describes at the gross level a design approach for meeting the requirements. The Schematic Block Diagram (SBD) is used to develop and portray the conceptual schematic arrangement of system elements to meet system and/or subsystem requirements. The CDS and SBD

are both applicable to all acquisition phases and provide the basis for development of the descriptions of system elements.

EVALUATION AND DECISION

Since program risk and cost are dependent on practical trade-offs between stated operating requirements and engineering design, continual evaluations and decisions must be made not only at the beginning of the program but throughout the design and development activity.

The Trade Study Report (TSR) is used to summarize and correlate characteristics of alternative solutions to the requirements and constraints that establish the selection criteria for a specific trade study area. The report also documents the rationale used in the decision process and should present risk assessment and risk avoidance considerations. Other tools, such as analytical or mathematical models or computer simulations, may be needed and used in accomplishing the evaluation and decision process.

DESCRIPTION OF SYSTEM ELEMENTS

All systems can be defined by a set of interacting system elements which fall into five categories: equipment (hardware), software, facilities, personnel, and procedural data.
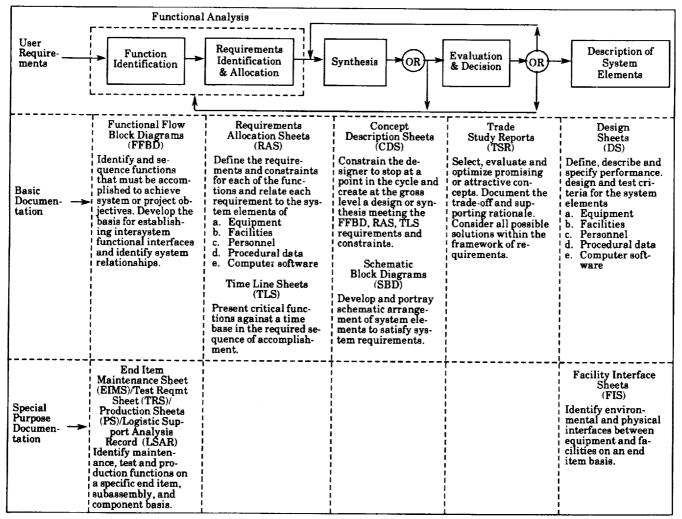

	Functional Analysis				
Basic Documentation	**Functional Flow Block Diagrams (FFBD)** Identify and sequence functions that must be accomplished to achieve system or project objectives. Develop the basis for establishing intersystem functional interfaces and identify system relationships.	**Requirements Allocation Sheets (RAS)** Define the requirements and constraints for each of the functions and relate each requirement to the system elements of a. Equipment b. Facilities c. Personnel d. Procedural data e. Computer software **Time Line Sheets (TLS)** Present critical functions against a time base in the required sequence of accomplishment.	**Concept Description Sheets (CDS)** Constrain the designer to stop at a point in the cycle and create at the gross level a design or synthesis meeting the FFBD, RAS, TLS requirements and constraints. **Schematic Block Diagrams (SBD)** Develop and portray schematic arrangement of system elements to satisfy system requirements.	**Trade Study Reports (TSR)** Select, evaluate and optimize promising or attractive concepts. Document the trade-off and supporting rationale. Consider all possible solutions within the framework of requirements.	**Design Sheets (DS)** Define, describe and specify performance. design and test criteria for the system elements a. Equipment b. Facilities c. Personnel d. Procedural data e. Computer software
Special Purpose Documentation	**End Item Maintenance Sheet (EIMS)/Test Reqmt Sheet (TRS)/ Production Sheets (PS)/Logistic Support Analysis Record (LSAR)** Identify maintenance, test and production functions on a specific end item, subassembly, and component basis.				**Facility Interface Sheets (FIS)** Identify environmental and physical interfaces between equipment and facilities on an end item basis.

Indenture is carried to the level required for the selected level of engineering to identify, describe and specify.

Figure 3 Basic and Special Purpose Documentation for Systems Engineering

Two documentation forms are used to describe these system elements: the Design Sheet (DS) and the Facility Interface Sheet (FIS). The DS is used to establish and describe the performance, design and test requirements for equipment end items, critical components and computer software programs. The FIS is used to identify the environmental requirements and interface design requirements imposed upon facilities by the functional and design characteristics of equipment end items. The DS and FIS provide the basis for the formal identification required for configuration management.

The systems engineering process produces the basic and special purpose documentation that controls the evolutionary development of the system. Figure 3 correlates the particular documentation associated with each step of the systems engineering process.

The systems engineering process itself does not actually produce the system, but produces the documentation necessary to define, design, develop and test the system. As such, a variety of engineering and planning documentation is required throughout the acquisition cycle, and systems engineering is the vehicle used to produce that documentation.

Numerous plans are prepared to define which technical activities will be conducted. They address the integration of engineering specialties requirements, "design-for" requirements and organizational resource requirements, and discuss how progress toward system-level goals will be measured. The Systems Engineering Management Plan is the key planning document that reflects these requirements. Contractor compliance with these plans is monitored by government organizations to ensure that standard policies and procedures in the area of systems engineering are employed. Additionally,

specifications are prepared as part of the systems engineering process to form the basis for the design and development effort. The top-level specification (system or segment) is normally approved and draft lower level specifications (configuration items) are developed reflecting allocated system requirements to lower level components or subsystems, which designers and subcontractors translate into hardware and software production plans.

In order to provide a continuing assessment of the system's capability to meet performance requirements, the systems engineering organization prepares technical review data packages, technical performance measurement (TPM) reports, analysis and simulation reports, and other documentation.

The systems engineering process is one approach to providing disciplined engineering during all acquisition phases. Although current application of the process has focused on C/E, D/V, and FSD, systems engineering process techniques and principles are equally applicable to the analysis and definition of production requirements.

The systems engineering process also provides the logic and timing for a disciplined approach, with certain internal assurances of technical integrity such as traceability. Technical integrity ensures that the design requirements for the system elements reflect the functional performance requirements, that all functional performance requirements are satisfied by the combined system elements, and that such requirements are optimized with respect to system performance requirements and constraints.

The DSMC Systems Engineering Management Guide may be purchased from the U.S. Government Printing Office (1991-306-417-QL 3).