BUILDING ON A LEGACY: RENEWED FOCUS ON SYSTEMS ENGINEERING IN DEFENSE ACQUISITION

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This article examines the evolving model used to describe the systems engineering process in Defense Acquisition University (DAU) courses. As implied in the title, discussion topics reflect both the legacy and current focus of systems engineering within the Department of Defense (DoD). The first two sections provide a historical context of the systems engineering discipline and outline the evolution of process models and terminologies used to describe process activities within DoD. The last two discussion sections describe interactions among the technical processes and technical management processes, and analyze the implications of systems engineering terminology changes introduced with updates in defense acquisition guidance released in June of 2009.

Keywords: *Defense Acquisition, Systems Engineering, Technical Process, Technical Management, Process Model*

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In 2004, Department of Defense (DoD) officials initiated efforts to revitalize systems engineering practices in defense acquisition programs. Acting in his role as the Defense Acquisition Executive, Michael Wynne (2004) issued a policy memorandum that stressed the need "to drive good systems engineering practices back into the way we do business" (p. 2). That statement highlighted an assessment that revitalization efforts would build on a legacy of proven processes and practices first formalized to support defense acquisition programs in the past. Terminologies and models describing the systems engineering process continue to evolve. However, fundamental aspects of the discipline have not changed since DoD released the first systems engineering standard (DoD, 1969).

The continuing need for systems engineering is driven by the increasing technical complexity and development costs of defense acquisition programs. Programs developing complex systems exhibit the same features that led to the need to formalize the systems engineering process in the first place, as noted in an early text published by the Defense Systems Management College (DSMC, 1986). Many acquisition programs involve large, geographically dispersed design teams, numerous subsystems under concurrent development, severely constrained development time, and incorporation of advanced technologies.

Purpose

This article examines the evolving systems engineering process model taught as part of Defense Acquisition University (DAU) courses. One can gain new perspectives on systems engineering process interactions by tracing the model's evolution over time. This article will provide a historical context of the systems engineering discipline in DoD, outline the evolution of process models and terminologies used in DSMC and DAU courses, and analyze the implications of terminology changes introduced in the *Interim Defense Acquisition Guidebook* (Interim DAG) released by the Office of the Secretary of Defense (OSD) in 2009.

Historical Context

According to the International Council on Systems Engineering (INCOSE, n.d.), the term *systems engineering* was first used at Bell Telephone Laboratories in the early 1940s. Interest in the systems engineering discipline grew during World War II when project managers and engineers oversaw the development of capital ships, aircraft, and weapons systems (National Research Council, 2008). Use of systems engineering practices increased following World War II as government programs leveraged an array of new technologies in developing computer

systems, command and control centers, telecommunications, ballistic missiles, missile defense systems, and spacecraft. The coordination of development teams employing thousands of engineers integrating multiple subsystems drove the need to formalize the methods for delivering useful, reliable systems (DSMC, 1986; National Research Council, 2008).

FORMALIZING THE DISCIPLINE

Because of the department's role in acquiring and developing large-scale, complex systems, defense acquisition managers led the way in codifying the systems engineering process—beginning with the publication of Military Standard 499 (MIL-STD-499). The baseline version of MIL-STD-499 was approved for trial use by U.S. Air Force developmental agencies and "for possible conversion to a fully coordinated document mandatory for use by all Department of Defense Agencies" (DoD, 1969, cover). The baseline MIL-STD-499 documented the first formal consensus standard governing the systems engineering community of practice. Department officials approved a subsequent revision of the military standard (MIL-STD-499A) for Air Force use only (DoD, 1974). However, MIL-STD-499A quickly became the de facto systems engineering standard for many defense acquisition programs.

During the early 1990s, DoD's systems engineering standard underwent another review cycle. Two parallel (but opposing) actions impacted what was then the only documented standard for systems engineering. Both actions unfolded under the banners of defense acquisition reform.

THE LOSS OF A STANDARD

The Air Force Materiel Command sponsored a joint working group comprised of representatives from OSD, the Services, and industry organizations. The working group formed to review and revise MIL-STD-499A for use by all DoD components, federal agencies, and commercial organizations. Members of the joint committee actively solicited inputs from a wide array of organizations and circulated a coordination draft of the revised standard (MIL STD 499B) to reviewers in government, industry, and academia in 1992. The foreword of the final coordination draft of MIL-STD-499B (DoD, 1994) outlined the focus of the revised standard. The purpose of the new standard was to define a comprehensive, executable process that would result in optimal system solutions while meeting cost, schedule, and performance objectives. According to its drafters, the standard process would be applicable in all phases of system development and could be tailored to the size and complexity of any effort. The drafters also claimed that the revised standard would achieve key DoD acquisition reform efforts to encourage innovation in products and practices; to

better integrate requirements through multi-disciplinary teamwork; to increase teamwork and cooperation within the government and industry; and to reduce the time needed to acquire products and services (DoD, 1994). Stakeholders who participated in the development and review of MIL-STD-499B hailed the document as a true consensus standard.

However, the revised standard was never approved by DoD officials due to another acquisition reform initiative that emphasized use of commercial standards over government standards. Defense Secretary William Perry (1994) issued a policy memorandum barring the use of military specifications and standards on DoD acquisition programs. Exceptions to the new policy required a written waiver from the program's milestone decision authority. As a result, the final draft of MIL-STD-499B was never approved for DoD use, and MIL-STD-499A was cancelled without replacement in 1995.

A PROLIFERATION OF STANDARDS

Because no commercial systems engineering standards existed, two U.S. standards bodies used MIL-STD-499B as the starting point for developing and releasing their own standards in 1994. The Electronic Industries Association (EIA, 1994) issued an interim standard (EIA/IS-632) developed by a working group of participants from industry associations, INCOSE, and DoD. The new standard outlined a consensus process intended for use by commercial enterprises, government agencies, and defense contractors. Similarly, the Institute of Electrical and Electronics Engineers (IEEE, 1994) released a systems engineering standard (IEEE 1220-1994) for trial use by industry organizations. In turn, these standards underwent subsequent diverging revisions that formed the basis for a proliferation of organizational process guides. Arguably, and as a direct result of Perry's (1994) memorandum barring use of military standards, the practice of systems engineering (and the related field of software engineering) became increasingly fragmented within DoD and across departments and agencies due to the use of proliferating industry standards, process improvement frameworks, and organization-specific guides and handbooks. The organization that first codified the discipline now found itself without a standard governing its systems engineering practices.

DoD'S STANDARDIZED TERMINOLOGY

Subsequent to the 2003 release of major revisions to policy documents governing defense acquisition management, OSD (2004) released the first (baseline) version of the *Defense Acquisition Guidebook* (DAG). The DAG outlined discretionary best practices for the acquisition workforce—including a chapter devoted to systems engineering. Overtly recognizing

that "many systems and software engineering process models and standards use different terms to describe the processes, activities, and tasks within the systems engineering and other life cycle processes" (OSD, 2004, ¶ 4.2.2.2), the DAG outlined eight *technical management processes* and eight *technical processes* to be applied throughout the life cycle of DoD acquisition programs.

Presumably in an attempt not to endorse or specify a particular industry standard, the authors of the baseline DAG chose not to represent the 16 generic systems engineering processes in a model. Instead, the DAG described typical phase-specific activities, with a different graphical depiction accompanying the descriptions for each phase of the life cycle. The same phase-specific graphical depictions also appeared in the *technical* portion of the 2004 (and subsequent) versions of the *Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management Framework*—commonly referred to as the *Wall Chart* (DAU, 2004). The technical portion of the *Wall Chart* included activities related to systems engineering, test and evaluation, and supportability—with no correlation to the 16 systems engineering processes described in the DAG.

Following a 2008 revision to DoD Instruction 5000.02 governing the *Operation of the Defense Acquisition System* (DoD, 2008), the revised Interim DAG (OSD, 2009) was posted to DAU's Acquisition Community Connection Web site the following year. The number of generic systems engineering processes described in the new Interim DAG remained the same: eight technical management processes and eight technical processes. However, three of the technical process names changed—indicating that DoD's "standardized process terminology" (OSD, 2009, ¶ 4.2.3) had evolved in alignment with revisions to the international standard issued jointly by the International Organization for Standardization and the International Electrotechnical Commission (ISO/IEC 15288:2008).

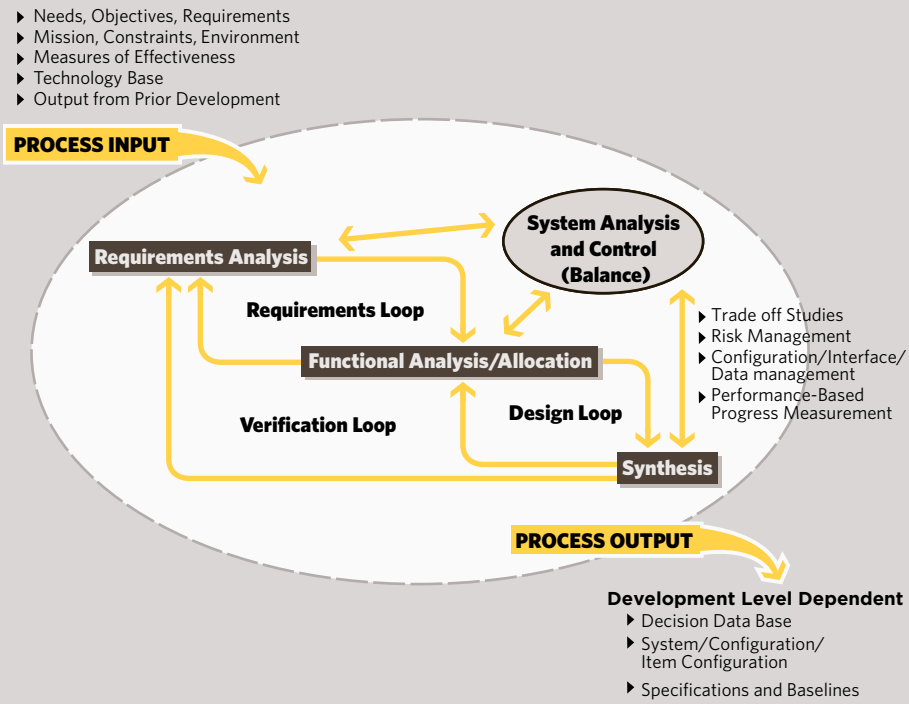
An Evolving Systems Engineering Process Model for DoD

Instructors at DSMC (and later at DAU) had used variations of the MIL-STD-499 systems engineering process model to teach systems engineering principles and practices to members of the acquisition workforce since 1974 (Schmidt & Crisp, 2006). The university's courses still included the legacy systems engineering process model when OSD officials released the baseline DAG in 2004. The model used by DAU faculty members to support discussion of the systems engineering process evolved in recent years with changes introduced in the baseline DAG (OSD, 2004) and subsequent updates in the Interim DAG (OSD, 2009).

LEGACY MODEL

A depiction of the legacy systems engineering process model appears in Figure 1. The legacy model has several advantages. One advantage is an elegant simplicity that lends itself to describing—and understanding—essential elements of the systems engineering process. That simplicity facilitated instruction and learning while conveying some of the complexities of the systems engineering problem-solving methodology. The legacy model depicts three primary, sequential design process steps: *requirements analysis, functional analysis and allocation, and synthesis.* Additionally, the model portrays an oval shape entitled *systems analysis and control* that represents technical management activities and tools that support all three primary design process steps. At a high level, the model captures the top-down application of the design steps, their interfaces with technical management activities, and iterative, recursive loops between process pairs that ensure all system requirements are completely defined, traced, and verified.

FIGURE 1. LEGACY (MIL-STD-499B) PROCESS MODEL



However, the legacy model also has disadvantages. One disadvantage is the failure to elaborate the *systems analysis and control* portion of the model. Another disadvantage is that the *verification loop* does not highlight the importance of test planning, testing, and evaluation of results as integral parts of the product development process. Perhaps the latter

disadvantage is one of the reasons why variations of V-shaped models that explicitly show test-related activities have become prevalent depictions of the systems engineering process. The "V" form (or *Vee*) "most accurately represents system evolution from the perspective of decomposition and integration activities" (Forsberg, Mooz, & Cotterman, 2005, p. 109). Of particular note, the first international systems engineering standard (ISO/IEC 15288:2002) employed a V-shaped process model.

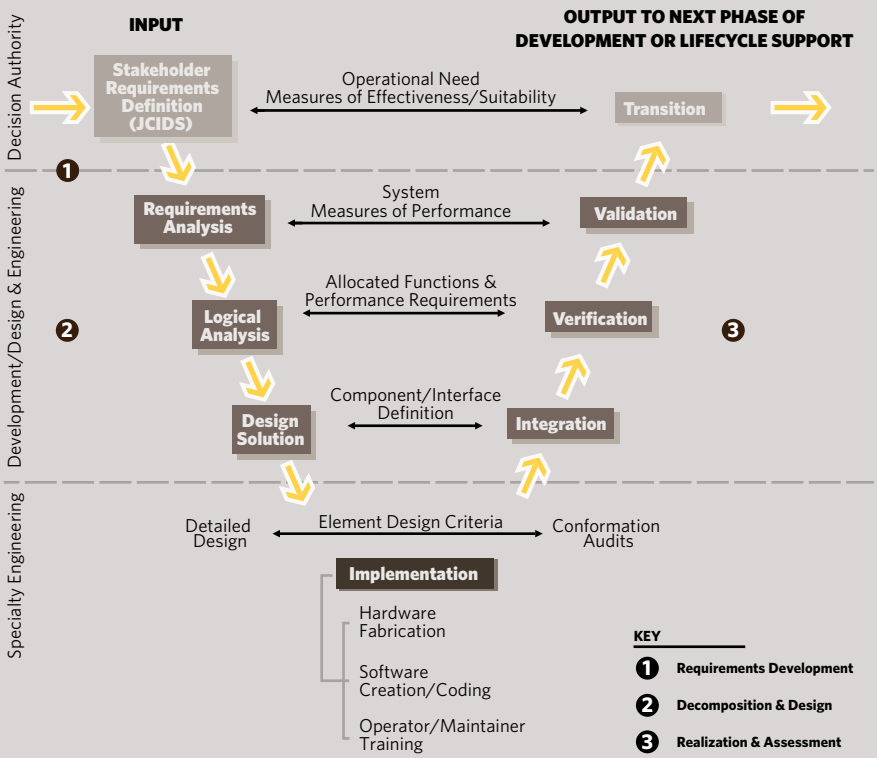
With the introduction of the new process terminologies in the baseline DAG and a revised *Wall Chart* in 2004, instructors teaching systems engineering principles in DAU courses faced a quandary. Lesson materials contained the legacy systems engineering model, but that model did not match the descriptions of the standardized technical management processes and technical processes endorsed by OSD or the depictions of the phase-specific technical activities in the DAG and the *Wall Chart*. Under normal circumstances, the courses in DAU's career field curricula are updated to reflect changes in policy as soon as possible after those changes occur. In this case, however, course developers at DAU planned extensive changes to selected courses as part of a *systems engineering revitalization* initiative sponsored by the Systems and Software Engineering Directorate within OSD. The Defense Acquisition Executive (Wynne, 2004) challenged educational leaders at DAU to "reinvigorate" (p. 2) systems engineering training. In response, the university's administrators initiated a complete makeover of the systems engineering curriculum.

As part of the effort to revise the *Systems Planning, Research, Development, and Engineering* (SPRDE) curriculum, one of DAU's course managers submitted a white paper (Redshaw, 2004) to the SPRDE performance learning director at the university's headquarters. Redshaw's white paper outlined a proposed unified approach to developing the replacement for the course that she managed. The white paper included descriptions and graphics of two models Redshaw proposed to use in the new course to portray the eight *technical processes* and eight *technical management processes* described in the DAG.

THE HIERARCHICAL VEE MODEL

One of the models in Redshaw's white paper (2004) appears in Figure 2. The model portrays the technical management processes in a V-shaped pattern (or *Vee*) superimposed on a notional organizational hierarchy. The Vee shape was adapted from the international systems engineering standard (ISO/IEC, 2002). The organizational hierarchy was adapted from a framework developed by Kossiakoff and Sweet (2003). The white paper explicitly correlated the left-hand and right-hand activities in the Vee to the three primary processes and the verification loop in the legacy process model. The left-hand side of the Vee captured the top-down design process; the right-hand side reflected the design *implementation,*

FIGURE 2. HIERARCHICAL VEE MODEL



integration, verification, validation, and *transition* activities described in the DAG. Redshaw's hierarchical depiction of the systems engineering technical processes was included in subsequent updates of the *DAU Program Managers Tool Kit*, with the graphic's last appearance in the 14th edition (DAU, 2008).

The hierarchical Vee depiction provides a powerful visualization of interfaces among key stakeholders and domains of responsibility in the acquisition process as well as "process linkages" (DAU, 2008, p. 78) between the steps on the left-hand and right-hand sides of the Vee. The top portion highlights process and organizational interfaces between decision authorities and the project team developing the system. Depending on the project or the area of the system hierarchy under consideration, the primary stakeholders may include the users, project sponsors, senior decision makers, project or engineering managers at a higher level in the system hierarchy, or the acquiring organization in an acquirer-supplier contract agreement.

The first technical process described in the baseline DAG (OSD, 2004) was *requirements development*. At the system level, Redshaw's (2004,

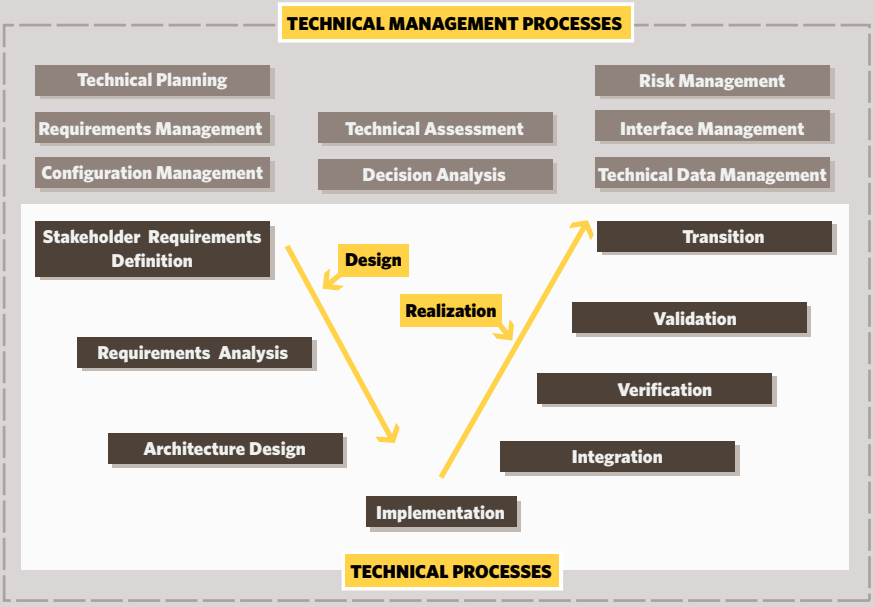
2006) hierarchical Vee model portrayed requirements development as two subordinate processes occurring at the organizational intersection of the project's development team with the Acquisition Management System and the Joint Capabilities Integration and Development System (JCIDS).

The outputs of the first subordinate process—*stakeholder requirements definition*—include the capabilities documents that govern technology development, system development, and production as well as baseline agreements between decision authorities and the development team that establish project scope and deliverables. The concept of organizational interfaces is particularly important in a system-of-systems or net-centric context. The systems engineer responsible for developing a system or subsystem must view it *from the outside*, or within the framework of the larger architecture in which the system is intended to operate. "To achieve good results, systems engineers involve themselves in nearly every aspect of a project, pay close attention to interfaces where two or more systems or system elements work together, and establish an interaction network with stakeholders and other organizational units of the enterprise" (Haskins, Forsberg, & Krueger, 2007, p. 41). In addition to the interface between the JCIDS and acquisition domains, translating users' needs into technical requirements involves interfaces between the acquiring agency and the supplier's organization, and between the systems engineer and other engineering managers at various levels in the system hierarchy.

The second subordinate process is *requirements analysis*—a direct and deliberate correlation to the first process step in the legacy systems engineering process model. Anyone familiar with the legacy model readily can see the correlation of its remaining two design process steps (*functional analysis & allocation* and *synthesis*) with two technical processes described in the baseline DAG (*logical analysis* and *design solution*, respectively).

The component level of design occurs at the interface of the systems engineering and specialty engineering domains in the system hierarchy. As the detailed design is finalized for *implementation*, the systems engineer and component design specialists identify and resolve technical issues and select workable, producible solutions that will not jeopardize the overall system design, capabilities, performance, or suitability (Kossiakoff & Sweet, 2003). Implementation of system elements occurs within specialty domains (Schmidt & Crisp, 2006). However, the systems engineer monitors the outcomes because they affect the overall design, performance, cost, and schedule. Similarly, the systems engineer monitors the outcomes of integration, verification, and validation with an eye to potential discrepancies requiring design modifications. At the end of each development phase, project managers and decision authorities review systems engineering outputs during the *transition* process to determine if results warrant further development, production, or deployment to operational use.

FIGURE 3. UPDATED CSEP MODEL



A COMPREHENSIVE SYSTEMS ENGINEERING PROCESS (CSEP) MODEL

Redshaw's white paper (2004) also proposed a *comprehensive systems engineering process* (CSEP) model. The CSEP model depicted the eight *technical processes* operating within a framework governed by the eight *technical management processes*. The author refined the CSEP framework over time, culminating in an article that proposed it as a new model for DoD systems engineering (Redshaw, 2006). Faculty members across DAU adopted variations of the CSEP model as a visual aid to explaining the systems engineering process to practitioners in various acquisition career fields. An updated CSEP model appears in Figure 3.

Process Interactions

The updated CSEP model in Figure 3 incorporates the standardized terminology in the Interim DAG that OSD released in 2009. The latest revision (as this article goes to press) of the *Program Managers Tool Kit* (DAU, 2009) included a similar depiction of the comprehensive systems engineering process. While terminologies and process depictions have evolved over time, the process interactions depicted in the CSEP model have remained essentially the same as those implied in the legacy systems engineering model.

TECHNICAL PROCESS INTERACTIONS

Members of the development team apply the *technical processes* at all stages of development to elaborate the system, generate information for decision makers, and provide starting points or inputs for the next level of development. The technical processes are used to (a) develop and define the requirements for the system and lower-level configuration items; (b) transform requirements into technical product, process, and material descriptions; (c) fabricate system elements; (d) assemble system elements into higher-level assemblies and end products; and (e) verify and validate system products, capabilities, and services against requirements established at each level in the system hierarchy.

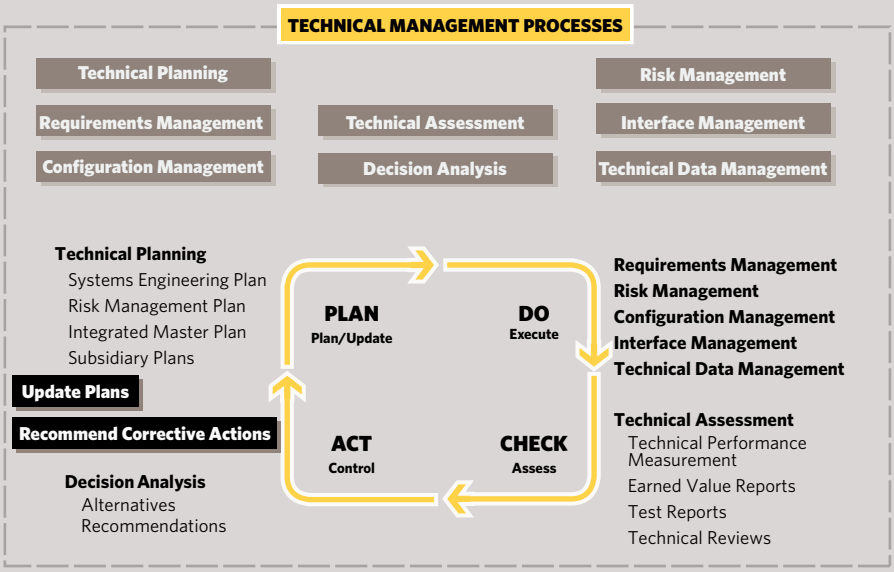
The V-shaped model highlights some of the important characteristics of the technical processes, including the sequential order of process completion. The left-hand side of the Vee portrays the top-down design that occurs as requirements are allocated progressively from the system level to lower-level elements in the architecture in a manner consistent with the arrangement of the design process steps in the legacy model. However, the V-shaped model explicitly illustrates the bottom-up design implementation from lowest level components to higher assemblies in order to integrate the complete system, verify and validate that all requirements are met, and transition to the next level of the system structure or to the next life cycle phase.

In addition to their application across the life cycle, the technical processes are applied at different levels in the system hierarchy to elaborate and mature the system. In the top-down application on the left-hand side, measurable criteria are documented at each level of system decomposition and design—forming the basis for test and evaluation during bottom-up system realization on the right-hand side. Using an automotive analogy, the technical processes form a problem-solving *V-8 engine* that is applied throughout the life cycle to ensure complete and balanced coverage of input and derived requirements to lower elements in the system hierarchy. At the end of each development phase, project members review outputs and evaluate test results to determine if all products meet requirements. Decision makers determine if acquirer-supplier agreements are met, if further system development and maturation is warranted, and if the project is ready to *transition* to the next planned effort, phase, or acquisition life cycle function (such as production, deployment, or operation).

TECHNICAL MANAGEMENT PROCESS INTERACTIONS

The *technical management* processes in the CSEP model are equivalent to the *systems analysis and control* portion of the legacy model. Members of the development team apply the technical management processes to establish and evolve project plans, assess actual achievements and

FIGURE 4. OPERATION OF THE TECHNICAL MANAGEMENT PROCESSES

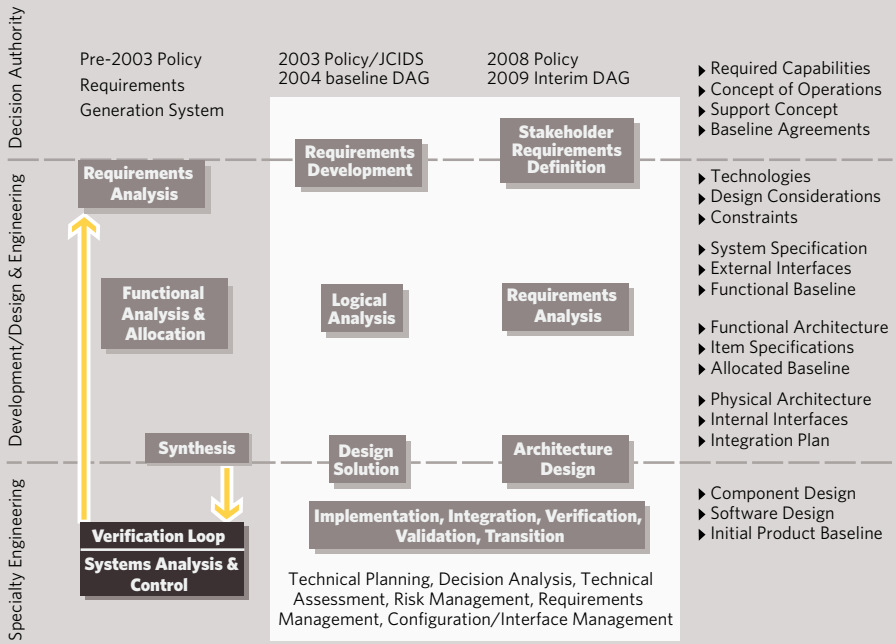


Technical Management Processes are used to manage the technical development of the system, including its supporting or enabling products. They include: Technical Planning, Technical Assessment and Decision Analysis, and a set of processes collectively referred to as Technical Control Processes. These include: Requirements Management, Interface Management, Risk Management, Configuration Management, and Technical Data Management.

progress against those plans, evaluate and select alternatives, and control project execution. Note that in the CSEP model the technical processes always operate within the encompassing framework of the technical management processes. While the technical management processes follow no explicit order, they typically interoperate cyclically as shown in Figure 4. The results of one part of the cycle become the inputs to others.

Collectively, the technical management processes form the executive—or *control logic*—that steers system development to meet project or phase objectives. Using another automotive analogy, the technical management processes operate together as a *rotary engine*. These processes operate continuously in concert with one another to support and control the application of the technical processes, balance technical and business needs of all stakeholders, implement project plans, and respond to unforeseen events. Documented technical project plans form the basis for execution and assessment. Team members continuously assess results to determine progress in meeting project plans and to identify the need for corrective actions or additional planning.

FIGURE 5. EVOLVING TERMINOLOGIES REFLECT EXPANDED FOCUS



New terminologies for an expanded focus. Recall that the baseline DAG (OSD, 2004) introduced eight technical processes and eight technical management processes. Redshaw (2004, 2006) correlated the legacy systems engineering process model to the new terminologies in the DAG through the hierarchical Vee, depicting the technical processes and a comprehensive model that included all 16 processes. Redshaw argued that the three design processes applied by the development project team were the same in both models, although terminologies had changed slightly to reflect that actions associated with the JCIDS process provided inputs to govern system development. Figure 5 shows the evolution in terminologies from the legacy MIL STD 499 systems engineering model (prior to 2003), the baseline DAG (OSD, 2004), and the Interim DAG (OSD, 2009).

Figure 5 also overlays the concept of hierarchical domain responsibilities with notional considerations and outcomes in all three models. Visually, the progression in Figure 5 suggests a key concept about the role of systems engineering in balancing the tension between requirements and the evolving design. "Systems engineering serves as the glue that binds the technical solution to the high-level requirements and maintains the program baseline" (Meier, 2008, p. 67). To achieve successful acquisition outcomes, stakeholders in all domains of responsibility must practice disciplined systems engineering.

By categorizing two sets of processes, the drafters of the baseline DAG (OSD, 2004) and the Interim DAG (OSD, 2009) emphasized

another instructional point. Systems engineering is both a technical and a management discipline, and acquisition practitioners must apply both sets of processes in tandem throughout the system life cycle (DSMC, 1986). Solid technical planning is the starting point to determine how the project team will apply the systems engineering processes in a coordinated fashion in each phase of development. Current acquisition policy prescribes that program managers embed systems engineering in program planning (DoD, 2008).

The legacy model emphasized the importance of three design processes that—despite the changes in terminology—appear among the new technical processes. These three steps are the heart of the technical aspect of systems engineering as "the translation of a user's needs into a definition of the system and its architecture through an iterative process that results in an effective design" (National Research Council, 2008, p. 1). Due diligence in applying these first three process steps assures a robust design with sufficient flexibility and adaptability to facilitate successful completion of the remaining steps and the project (Meredith & Mantel, 2000). In applying the design steps, stakeholders explicitly identify relationships, requirements interdependencies, and assessment criteria tracked throughout system development (Meade & Farrington, 2008). When applied in a disciplined manner in conjunction with the technical management processes, the design steps lay the groundwork for a solid technical solution.

Using the updated terminology in the Interim DAG (OSD, 2009), *stakeholder requirements definition* establishes a firm baseline for system requirements and constraints the development project team must meet, thus defining project scope. During *requirements analysis*, members of the project team examine users' needs against available technologies, design considerations, and external interfaces to begin translating operational requirements into technical specifications. *Architecture design* entails developing a coherent functional architecture to achieve required capabilities across scenarios from the operational concept; developing a physical architecture, internal interfaces, and integration plan; synthesizing alternative combinations of system components; and selecting the optimal design that satisfies and balances all requirements and constraints. The optimal design is one that results in a validated, affordable system that is operationally effective and suitable.

Summary

The legacy model formerly used in DSMC and DAU courses traces its genealogy to MIL-STD-499 (DoD, 1969, 1974, 1994), which was the first—and for 26 years the only—documented consensus standard for the systems engineering discipline. While retaining essentially the same design process

steps and attributes of the legacy systems engineering process model in Figure 1, the hierarchical Vee and CSEP models offer additional valuable insight. The hierarchical model in Figure 2 illustrates interactions among domains of responsibility and relationships among the eight technical processes. The CSEP model in Figure 3 connotes the encompassing and executive nature of the eight technical management processes described in the baseline DAG (OSD, 2004) and the superseding Interim DAG (OSD, 2009). The V-shaped pattern of the technical processes in Figure 2 and Figure 3 illustrates a sequential order of application to achieve top-down design and bottom-up realization of the system. The rotary pattern in Figure 4 depicts a continuing cyclical interaction among the technical management processes. The technical management processes provide the *executive logic* that governs and controls the technical problem-solving methodology in the *V-8 engine*.

The introduction of new process steps in the baseline DAG (OSD, 2004) and the updated Interim DAG (OSD, 2009) highlight the interaction of systems engineering in all aspects of development, while the categorization of two sets of processes emphasizes that systems engineering is both a technical and a management discipline. Figure 5 summarizes the evolution of the terminologies used to denote key design steps in the systems engineering process. Building on the legacy of the standard that first formalized the discipline in 1969, the evolution in terminologies and process models supports the increased emphasis on systems engineering throughout the life cycle and in all domains of responsibility. As emphasized in current defense acquisition policy, achieving successful program outcomes requires effective acquisition management that reflects a disciplined approach to systems engineering.

Author Biography

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