Systems Engineering for Military Ground Vehicle Systems

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Abstract

Systems engineering is a key discipline for the development, deployment, and sustainment of military systems. The wide variety of product types and tendency to leverage emerging technologies require that disciplined technical planning and the management processes be used by engineers and program managers in all phases of a product's life cycle. This chapter will explore some fundamentals for a variety of topics in military systems engineering and acquisition. Focused on systems engineering, a couple of Army vehicle applications are also presented.

Introduction

Systems engineering is commonly defined as (a) *disciplined technical planning and management* or (b) *the process by which a stated user desire is transformed into a tangible product that is optimized in terms of affordable operational effectiveness*. Systems engineering is a key discipline for the development, deployment, and the sustainment of military systems. The wide variety of Army product types and the tendency to leverage emerging technologies require that disciplined technical planning and management processes be used by engineers and program managers in all the phases of a product's life cycle.

Setting the Context

The Defense Acquisition System, as defined in the Department of Defense (DoD) Directive 5000.01 and DoD Instruction 5000.02, provides a high level framework within which the military's official Programs of Record must be used to develop, field, and sustain their systems. Acquisition Programs of Record are directed, funded efforts that provide new, improved, or continuing materiel, weapon or information system, or service capability in response to an approved need. The Defense Acquisition System is most commonly communicated through the use of the "wall chart" (Figure 1) which depicts the Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System. This "wall chart" is published by the Defense Acquisition University (DAU) and can be downloaded free of cost from https://acc.dau.mil/ifc/download_pdf.htm .

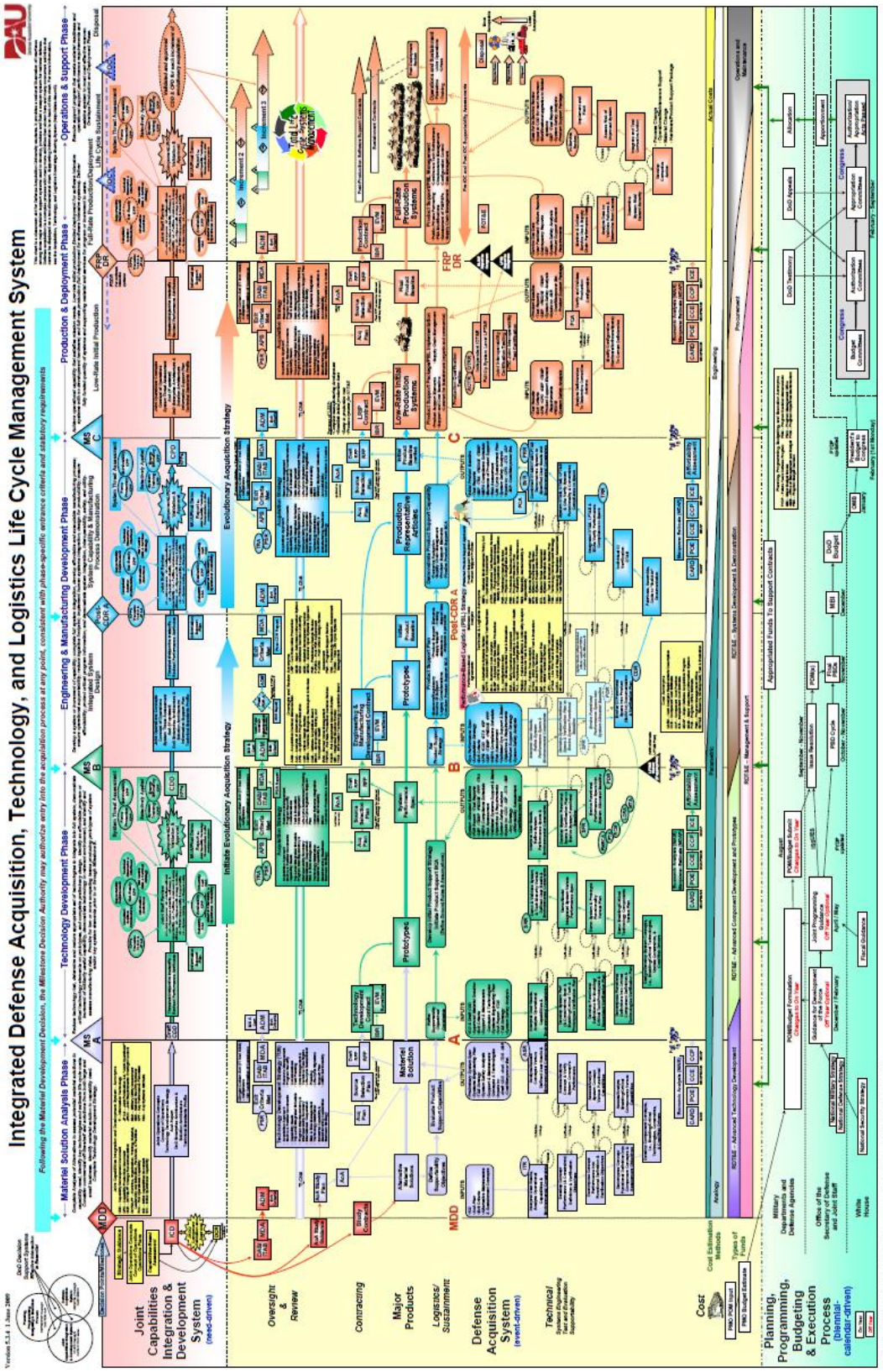

Figure 1: The Integrated Defense Acquisition, Technology, and Logistics Life Cycle Management System, also commonly known as the "Wall Chart"

The “wall chart” for systems acquisition and engineering in the Department of Defense (DoD) depicts a flowchart occurring through a series of rows and columns. The columns divide a given system’s lifecycle into the following major phases: Materiel Solution Analysis, Technology Development, Engineering & Manufacturing Development, Production & Deployment, and Operations & Support. Each of the above phases are divided by decision points. There are three major rows shown on the chart. The Defense Acquisition System is the most detailed row which is in the middle of the chart. In the chart, it becomes obvious that each of the major lifecycle phases contain their own tailored “systems vee” that defines the overall phase-specific systems engineering process to be followed. Referring back to the second definition of systems engineering provided in the section titled “Introduction”, the columns in the “wall chart” depict how a required operational capability is transformed from a stated user desire to an affordable, operationally effective, tangible, fielded and sustainable product or capability.

The top row on the chart depicts the Joint Capabilities Integration and Development System (JCIDS). The JCIDS is the process by which validated operational requirements are generated. These requirements serve as the official “voice of the customer” that must be transformed into tangible systems by the acquisition community. As part of the JCIDS process, a Capability Based Analysis (CBA) is periodically conducted to identify weaknesses or gaps in the military’s existing or planned capability, or to identify opportunities to enhance capability based on developments using emerging technology. If the CBA results in required new capabilities that cannot be solved through changes to force training, policy, or other conventional factors then an Initial Capabilities Document (ICD) is developed to document the high level operational requirements for a new capability. An ICD essentially serves as the first and highest level configuration baseline for a yet to be developed system or a series of systems. During the Materiel Solution Analysis phase of the lifecycle management framework, a Capabilities Development Document (CDD) is then collaboratively developed between the requirements generation and the acquisition communities. More details on the operational requirements are detailed in the CDD based on the current state of technology and a variety of trade off analyses that seek to balance the correct degree of capability which is focused on maximizing the affordable operational effectiveness of a system. The CDD is refined during the Technology Development phase prior to Milestone B. At Milestone B, the CDD is locked and serves as a more detailed configuration baseline of the operational capability to be delivered. During the Engineering & Manufacturing Development phase of a program, a Capability Production Document (CPD) is crafted prior to Milestone C. A CPD is written at the same level of detail as the CDD, but reflects any operational trade-offs or changes that may have occurred between Milestones B and C. In many cases, a program may progress directly to Milestone C after the ICD has been generated if the Material Solution Analysis phase may have suggested that integration of the technology is expected to be low risk or if a Commercial-Off-The-Shelf (COTS) system exists to meet the operational requirements with minor modification. The JCIDS process also includes a very specific approval process to validate requirements. This usually includes oversight by leaders from the joint services representing the Army, Navy, and Air Force to enhance the joint integration of systems.

The lower row of the "wall chart" depicts the Planning, Programming, Budgeting and Execution (PPBE) process. This is the process by which funds are planned for, allocated, and managed at a high level. While the JCIDS row and Defense Acquisition System row are synchronized with each other in time on the chart, the PPBE row is independent of the other two rows and is synchronized with the biennial calendar followed by the government branches. In practice, executing major programs that take many years to develop and field can be challenging considering that the funding is being provided based on the biennial PPBE process (in which priorities may shift as the composition of the government branches change and their respective priorities evolve with time). Interaction between the PPBE process, the JCIDS process, and the Defense Acquisition System is shown in Figure 2.

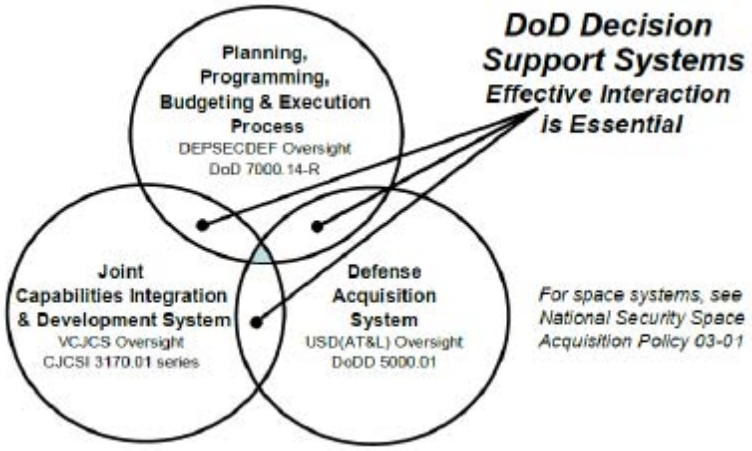

Figure 2: Interaction of the Three Decision Support Systems Depicted within the "Wall Chart"

It should be noted that while the Defense Acquisition System defines the framework within which systems that are intended to be fielded will operate, it does not address how Research & Development (R&D) activities are to take place. The defense R&D community uses many of the same systems engineering framework tools, although it has more freedom for how each individual R&D program is managed. The tools described in this chapter will focus on systems engineering elements used in both acquisition and R&D.

Systems Engineering Relation to Program Management

There are a number of similarities between the disciplines of systems engineering and program management, depicted in the Venn diagram (Figure 3). Systems engineering can essentially be thought to represent a major subset of program management. Program design, risk management, work breakdown structures, earned value management, and schedule management through the use of integrated master plans and schedules are all aspects that ride a fine line between systems engineering and program management.

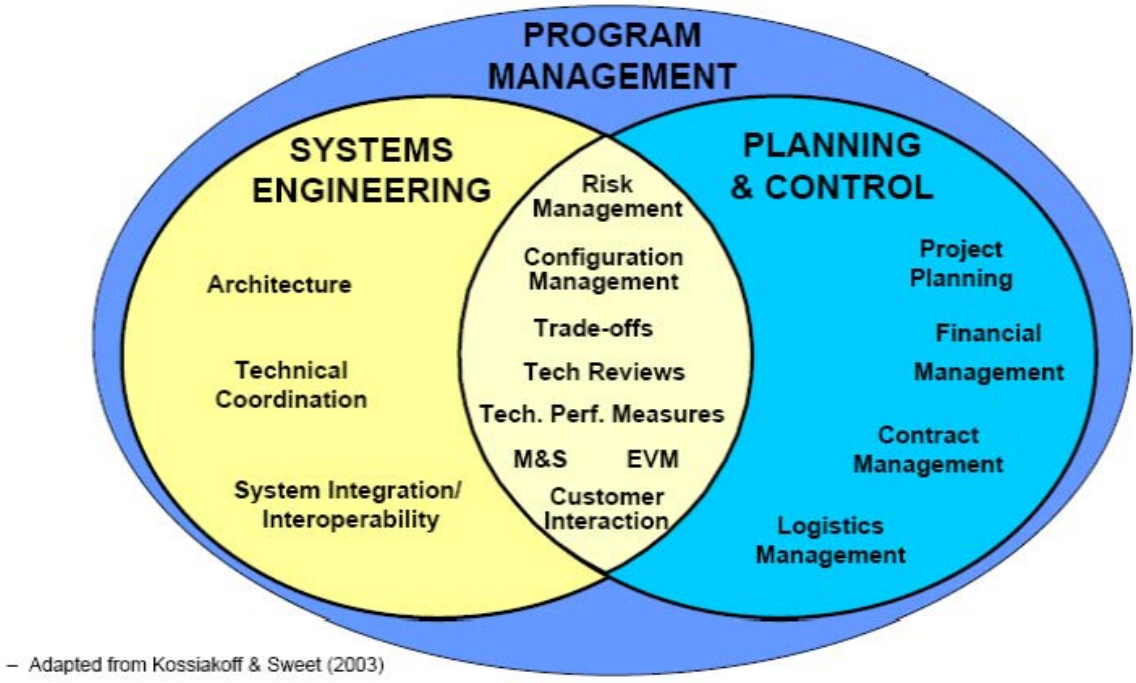

Figure 3: Interaction between Program Management and Systems Engineering (1)

Therefore, it is paramount that an understanding of systems engineering processes and techniques reside not only with the engineers supporting acquisition programs and executing R&D programs, but also with the system acquisition managers, product managers and program managers who lead the programs. Many individuals in the DoD's Program Management career field have areas of background and expertise in contracting, logistics, and business management. Hence, it is important that the engineers with backgrounds in systems engineering communicate with their Program Management career field counterparts and help to integrate disciplined technical planning and management into the broader community.

Systems Engineering Focus Areas and Skills

The purpose of good systems engineering practice should be to enable a given project's team to early on answer crucial questions such as the following during the planning phases of the project:

- What are the key technical reviews that will be used to establish critical technical baselines such as locked operational level, configurations at system , sub-system, and product levels to ensure that the program is ready for the subsequent activity?
- Who will have control over the different levels of technical baselines?
- What is the Integrated Product Team (IPT) structure, and how does the program ensure that it takes into account the advice of subject-matter experts (SMEs) in all applicable areas?
- What processes will be used to oversee key activities, such as requirements management, configuration management, risk management, obsolescence management and data management?

• What are the highest technical risks, and how will the program act to mitigate them?
• How, specifically, will the program manage technology transition to exploit opportunities?

Systems engineering's objective is to answer these questions early in the acquisition process so that they can be answered, agreed upon, and understood by all IPT members prior to executing a program's subsequent phase.

Some of the most common focus areas and/or skills desired for systems engineers in a military environment are as follows:

- design and support of configuration management processes;
- design of technical schedules, design and conduct of technical reviews;
- coordination of technology assessments;
- composition of IPTs;
- market research;
- requirements development;
- requirements management;
- requirements decomposition and design of functionality;
- comparison of market research with operational and performance requirements;
- risk analysis;
- development of mitigation strategies to technical risks;
- development of modeling and simulation strategy;
- development of test strategy;
- alignment/synchronization of technical efforts;
- developing and performing trade studies;
- system of systems (SoS) engineering;
- contract design (integration of technical risk reduction strategies into contracts);
- collection and analysis of field data;
- integration of new technologies and subsystems;
- interoperability management;
- obsolescence management;
- technical baseline management;
- electromagnetic spectrum management;
- compliance with legal and regulatory requirements;
- lifecycle product data management;
- technology readiness assessments;
- technical management;
- communication skills;
- concept development;
- interface management;
- capability gap analysis;
- design of architectures (definition of relationships at different levels);
- decision analysis and

- optimization of design considerations.

Select important topics, relating to the focus areas stated above, are discussed in more detail, throughout the remainder of this chapter.

Requirements Development

It is important to draw the distinction between requirements development and requirements management. *Requirements development* is the process of investigating and capturing the "voice of the customer" in combination with the "voice of the business". *Requirements management* is the process of ensuring adequacy and maintaining the integrity between the different levels of requirements.

As part of the *requirements development* process in a military environment, the voice of the customer primarily is captured from the JCIDS process, described earlier in this chapter. The requirements derive from a combination of different factors, such as the wants and needs of soldiers operating in the field, maintainers of equipment, training facilities, strategic combat operations planners, and more. The "voice of the business" is also incorporated into the JCIDS process and takes into account the more high level strategic direction of the President, the strategic vision of the DoD and the subordinate services, and more. Legal requirements, such as environmental and safety regulations, as well as the voice of the taxpayer are also considered.

The CBA process within the JCIDS process consists of several sub-tasks. A functional area analysis is first conducted where the baseline existing operational capabilities of the armed forces are reviewed. A functional needs analysis is then conducted, when the required operational capabilities for a given mission area are reviewed based on changing threats and tactics of combat and logistics operations. A functional solutions analysis is then conducted where the differences between the existing and the required capabilities are each analyzed in more detail to identify action plans for how to bridge the gaps between them. Solutions may consist of changes to one or more of the domains within what is commonly referred to as Doctrine, Organization, Training, Materiel, Leadership, Personnel, Facilities (DOTMLPF). If a recommended change to the "materiel" domain of DOTMLPF results from the CBA, then an ICD is drafted to establish a new validated operational capability requirement to be fulfilled and thus initiate a new development effort for a particular system.

On validation of the ICD, a more detailed operational requirements document is drafted, outlining the fundamental requirements of the new capability. A draft CDD is prepared before a program enters Milestone A (assuming that the program does not proceed directly to Milestone B or C based on assessed lower risk). After a successful Milestone A decision, the Technology Development (TD) Phase of a program is conducted. The purpose of the TD Phase is to conduct risk mitigation to determine whether or not the requirements listed in the draft CDD are achievable. If the requirements are found to be achievable (through the test of prototypes, modeling and simulation, etc.), then the draft CDD is staffed for approval before Milestone B. If the requirements were found to be

not achievable, then either the draft CDD is refined to a point of low risk, or the program may be terminated or re-scoped.

Within the CDDs and CPDs that eventually define the operational requirements of a system respectively at Milestones B and C, the trade space is established through the use of Key Performance Parameters (KPPs). Each CDD and CPD will list somewhere between two and six KPPs, representing the most critically important operational requirements for the system. Each KPP will also be defined in terms of "threshold" and "objective" goals, to establish a trade space within which one parameter may be adjusted to enable the achievement of another. Some common types of KPPs are "net-centricity", "force protection", "survivability", "energy efficiency", "mobility", and "lethality". The threshold and objective values for each are usually described in one to two sentences. The system performance requirements that describe how to achieve each operational requirement for each will be developed by the acquisition and engineering communities as part of a performance specification. The CDDs and CPDs also use a tiered prioritization system to define which operational requirements are more important than others. This enables the acquisition and engineering community to achieve a better understanding of their customers' priorities to understand any trade-offs that must be made throughout the program.

There are some notable differences between the requirements development processes of the military compared to the commercial sector. In the Army, there is an organization known as the Training and Doctrine Command (TRADOC). One of the core responsibilities of this organization is to generate validated operational requirements (through the JCIDS process described earlier). This organization essentially speaks as the "voice of the customer" to the acquisition and engineering communities. This is different from the profit-motivated commercial industry where there is no single organization representing the official voice of the customer. In most private industry product development processes, companies must find disciplined and innovative ways to understand their current and/or potential customers, target market segments, and more. This includes the use of consumer surveys, market analysis studies, "camping out" with the customer, and even using anthropologists and psychologists in many cases. Of course, the military's more controlled process of requirements development is not perfect. The fact that the end users of military ground systems are often thousands of miles away in restricted access facilities and often in dangerous scenarios implies that the engineers who are developing new systems or technology, often, have much less opportunity to interact with their end users and see their products in real-world use. This also means that it is more difficult for engineers to subject their systems to "use-case scenarios" during the product development process if the requirements are not explicitly stated. Also, the fact that an organization specifically exists to speak as the "voice of the customer" may in some cases lead to the engineers on the product development side to assume that all requirements have already explicitly been defined. This, in turn, may limit their motivation to reach out and understand the end users. As an example, in a war scenario, equipment may be subjected to abuse, which is not explicitly defined.

Requirements Management & Architecture

Regarding the *requirements management* processes that are employed in the military ground systems domain, a variety of different tools are used for different programs. There are many low-risk programs that leverage COTS systems in the commercial market place. These low-risk programs tend to focus more on simple requirements management tools. For the low-risk programs, a performance specification is developed based on a CDD or CPD. This performance specification is usually developed by an IPT consisting of acquisition leaders, engineers, logisticians, test specialists, environmental specialists, and safety specialists. The performance specification takes the operational requirements as defined in the CDD or CPD and decomposes them to the next level of detail, to include specific power, weight, overall dimensional envelope, and legal and regulatory requirements such as environmental, safety, and electromagnetic spectrum allocation information for systems that require advanced communication systems. These performance specifications are controlled by the DoD and are usually captured in simple documents or spreadsheets. In many cases, disciplined traceability, between requirements, are not maintained due to the low risk, non-complex nature of the COTS programs. On award of a contract, a detailed product level specification is provided and controlled by the contractor.

An example of a COTS equipment meeting the Army's requirements with minor modifications is the Line of Communication Bridge (LOCB). For civilian applications, the above bridges have been used world-wide in situations of natural calamities. Figure 4 shows the use of a US company manufactured LOCB at ground zero after the 9/11 attack on the twin towers in New York. Figure 5(a) shows the application of LOCB from a UK manufacturer carrying interstate traffic in Baltimore County, Maryland. Figure 5(b) shows the UK company manufactured LOCB in use by the military in Iraq. In this case, from systems engineering perspective, the acquisition process for the Army directly proceeded from the ICD to the CPD, eliminating the need for a CDD.

Hence, acquiring a COTS technology solution for a military application results in a reduced acquisition and fielding period with low risk.

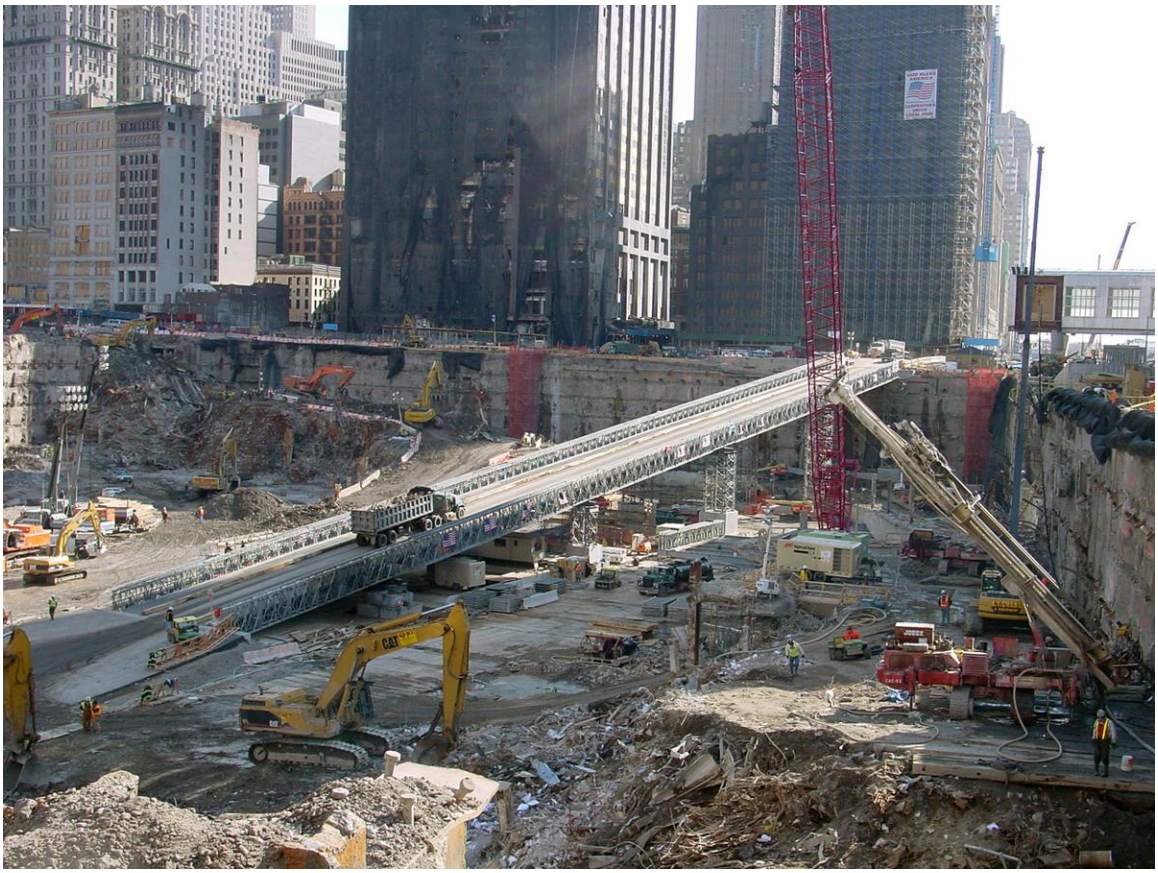

Figure 4: A US Company Manufactured COTS LOCB at Ground Zero after the 9/11 Calamity (2)

Figure 5(a) A UK Company Manufactured COTS LOCB for Interstate Traffic in Maryland (3)

Figure 5(b) A UK Company Manufactured LOCB in Use by the Army at Iraq (3)

For more complex system development efforts, a variety of more disciplined tools are utilized to maintain the consistency and integrity between the different levels of requirements. A common tool for larger acquisition programs or more complex R&D programs is to use a relational database, to create and maintain traceability between the

operational and performance requirements, product specifications, and test methods. These types of tools help organizations keep a variety of requirements up to date, even when modification of one requirement may affect many other requirements. It should be noted that these types of tools may demand a very experienced user to operate the software and can become the sole responsibility of that individual. Hence, programs with very little budget may not be able to afford the investment to use such tools.

For the decomposition of requirements into lower levels, some widely used processes that are common with many "lean" or "design for six sigma" related methods are often used. Often a concurrent approach to decompose operational requirements into both a functional hierarchy and a physical hierarchy is utilized. Figures 6 and 7 below give examples of some initial de-compositions from the DoD's Fuel Efficient Ground Vehicle Demonstrator (FED) program that currently is being executed by the Army's Tank Automotive Research, Development & Engineering Center (TARDEC). The FED program is a vehicle system level demonstrator program that is intended for R&D as opposed to immediate fielding in the military's inventory.

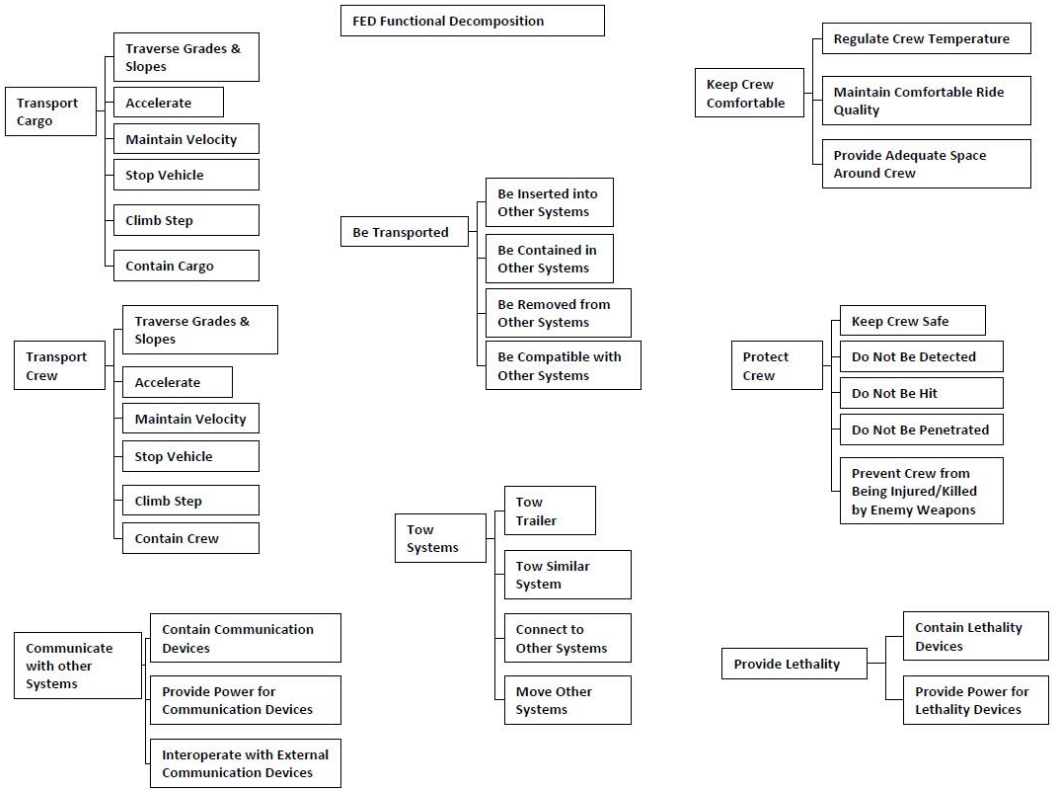

Figure 6: Example of a Preliminary Draft Functional Decomposition from the FED R&D Program

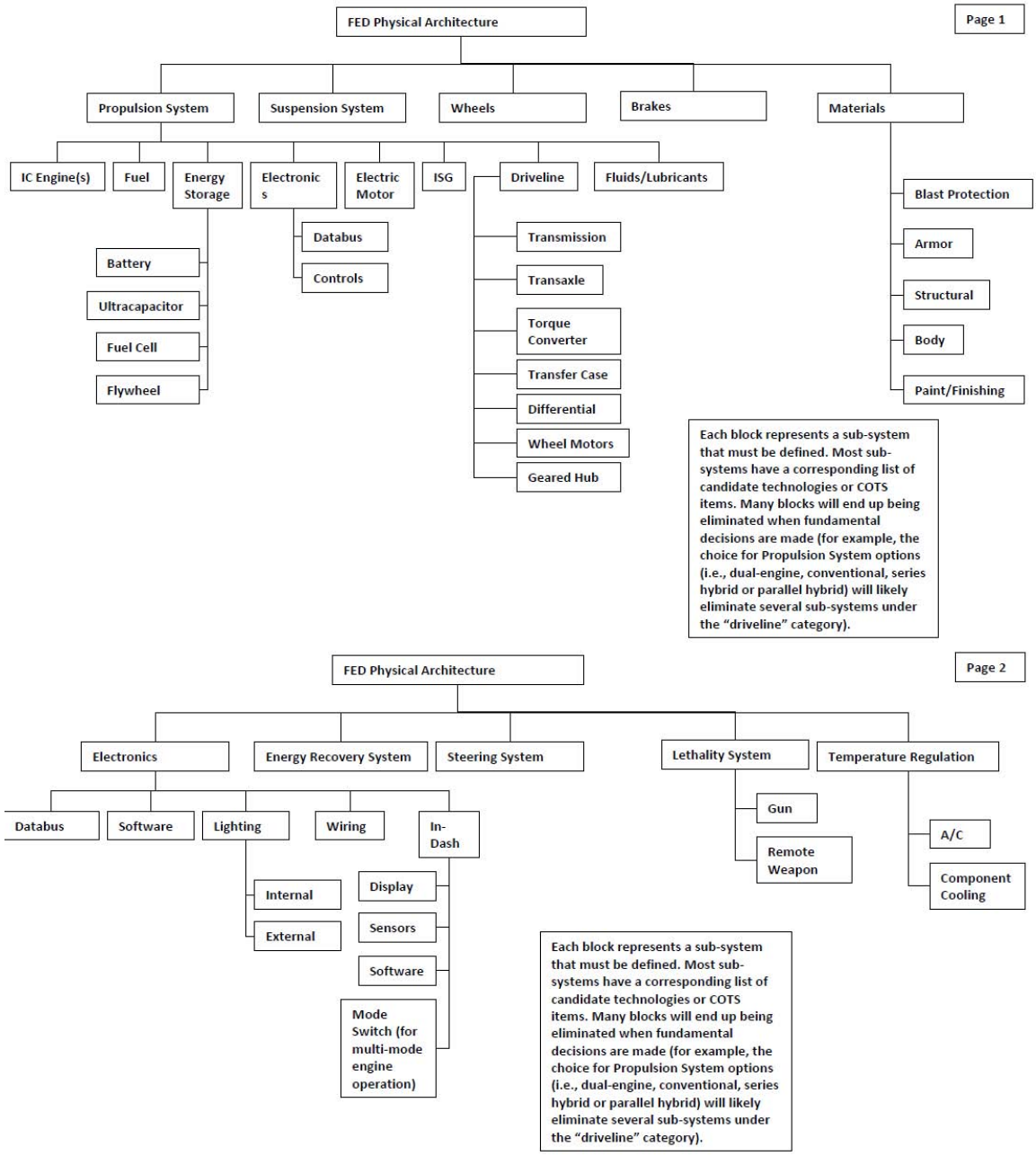

Figure 7: Example of Draft Physical Decomposition from the FED R&D program

The intention to simultaneously produce both functional and physical decompositions is to map the functions to physical hierarchies to support planning as a program progresses through its development phase. The idea is that as a system's architecture progressively evolves from a foggy set of requirements to a concept, a design, and finally a product. Decompositions help to manage requirements, specifications and interfaces. As decisions are periodically made on the various sub-systems of the system, the hierarchies are updated and expanded upon.

Another commonly used tool to develop and manage requirements and system architecture is the DoD Architecture Framework (DoDAF). DoDAF is a framework that is extensively used to develop net-centric, remote communications, or information technology intensive equipment. Based on the concept of "enterprise architecture", the DoDAF is intended to define a set of documents that act as communication tools to visualize, understand, and assimilate the complexities of an architecture description through graphic, tabular, or textual means. Use of the DoDAF forces discipline into the architecture development process by requiring the creation of Operational Views (OVs), System Views (SVs), and Technical Views (TVs) of a system during the requirements development and decomposition phases. OVs define how a system will operate on a macro scale, including what it must communicate with or interface with, and who will be using it (which military services or which nations). The SVs are used to define and document how the major components of the system will interface with the different users or devices (for example, which components of a system will use satellite communications and which will use radio communications), as well as how the major components within a system will interface with each other. TVs are used to define specific open-systems standards to ensure interoperability with other systems and to leverage commercial standards (for example, which internet protocol?). A list of approved standards is maintained by the DoD and the TVs must ensure that they comply with the list to maximize interoperability in the future. Some example formats for DoDAF integrated architectures are presented in Figure 8.

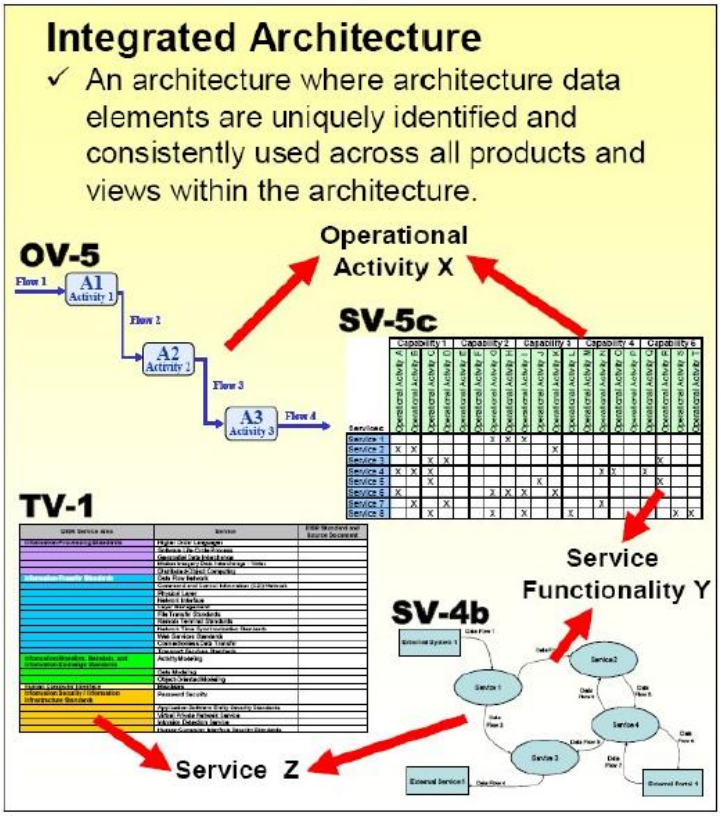

Figure 8: Illustration of DoDAF Integrated Architecture Products (4)

Configuration Management

Configuration management is the process to maintain a consistent and an up to date set of definitions of what a system is as it evolves and is sustained throughout its lifecycle. There are a variety of levels of configurations, at various requirements levels, to meet the actual physical and/or software configurations of a system. In many ways, the set of operational requirements, which are developed through the JCIDS process into an ICD, CDD, or CPD, defines the highest level of a system's configuration. Performance requirements are developed based on the operational requirements. These performance requirements represent a more defined level of a system's configuration or architecture. As detailed product level requirements or descriptions are evolved, they represent a more detailed system configuration. A bill of materials is an example of a level of configuration that must be maintained. Another example is a set of drawings or a Technical Data Package (TDP). The ultimate level of a system configuration is the physical makeup of an actual piece of hardware. Configuration management shares many processes with requirements management, as it aims to ensure consistency among all different levels of configurations. All quantities of a given component within the product variants should be the same throughout their fleet and the drawings, models and requirements defining that the product should be accurate and up to date, even after a change is made in a fleet after decades of being fielded.

The terms *configuration baseline* or *technical baselines* refer to "locked" configuration levels. For example, an approved set of operational requirements, such as a CDD, would constitute a locked "operational baseline". The approval of a set of performance specifications would constitute a "functional baseline" being established. The performance specifications for the lower level configuration items within a system would constitute an "allocated baseline". The detailed drawings, models, and bills of materials defining the exact physical attributes of a system would constitute a "product baseline". Technical baselines are established or "locked" at key points during a program. For example, "technical reviews" such as a Preliminary Design Review (PDR) or Critical Design Review (CDR) are respectively used to establish the allocated and product baselines.

A very useful tool used for the technical planning of a program is a specification tree. A specification tree essentially is a communication tool to convey a large amount of information related to a program's planned configuration management approach. In Figure 9, an example specification tree is shown from TARDEC's FED program. In this specification tree, the top area graphically depicts the operational baseline, and clarifies that since it is an R&D program (as opposed to a Program of Record to be fielded), the operational requirements for the FED program were defined based on a combination of the High Mobility Multipurpose Wheeled Vehicle (HMMWV) Operational Requirements Document (ORD) and the Joint Light Tactical Vehicle (JLTV) Draft CDD. CPD is the revised term for ORD. The arrow on the left of the graphic indicates that the FED operational requirements will be developed during the concept phase of the program. The blue bubble on the right indicates that the FED operational baseline will be locked during an event called the Executive Steering Group Review. The next level down shows that a

FED system specification will be developed to define the functional baseline at the beginning of the development phase. The functional baseline will be established on conducting a PDR. The arrow on the right also indicates that the DoD will control the operational and functional baselines, but that the contractor will be given the latitude to control the more detailed technical baselines to be established after the PDR. Similar logic is used to define both how and when the allocated and product level baselines will be established during the program.

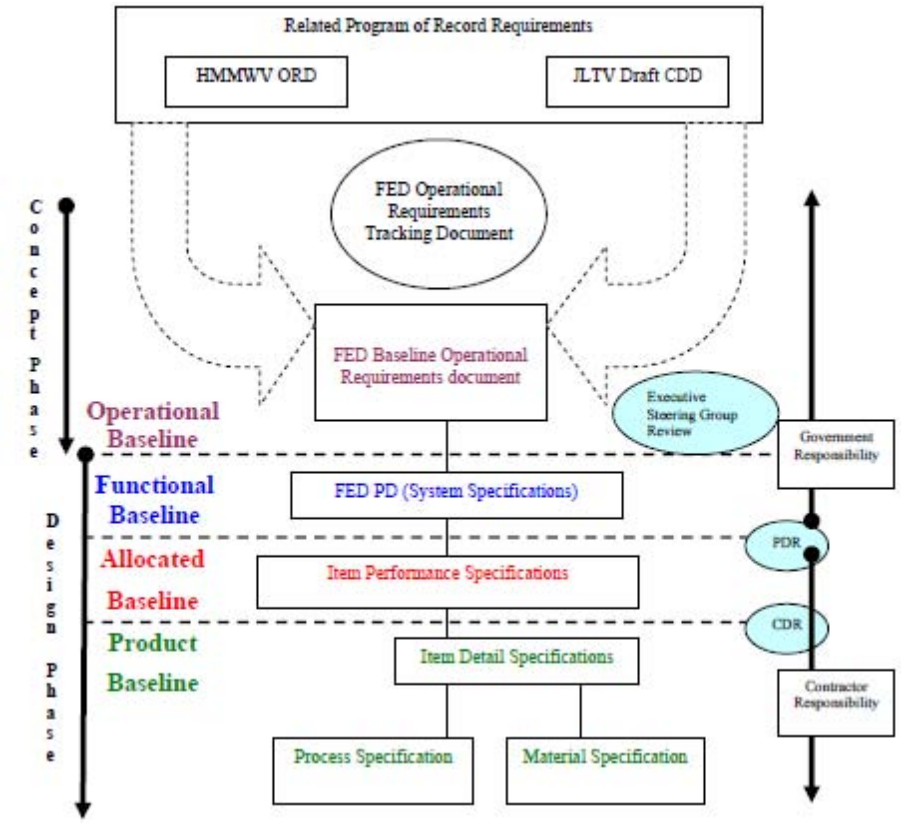

Figure 9: Example of a Specification Tree from the FED Program

An example of a common tool used to bring structure and discipline to a configuration management process is an integrated data environment. This is usually a secure database where program team members can "check out" and "check in" documents to ensure that a single version of a document or drawing is being worked on and is kept up to date. Often there is some kind of workflow and approval process to manage changes to technical baselines to ensure that changes to one baseline maintains consistency with other technical baseline levels or related program documentation. Numbering conventions for version control are often utilized to communicate to team members what level of approval a given version of a document has been subjected to.

Technical Reviews

Technical reviews are events conducted during a program's lifecycle to address risk mitigation, establish configuration baselines, and maximize a program's overall probability of success. Common technical reviews used during the design phase of a program are the PDR and CDR. Contrary to the way that many programs are planned, technical reviews are intended to be "event-driven" as opposed to "calendar driven". The basic concept is that the program's leadership must define the activities and artifacts to be completed prior to each technical review (entrance criteria). Then the technical reviews are conducted after each of the entrance criteria activities are completed. This essentially serves as a way to ensure that a program does not progress into the next phase till its overall risk is reduced to a defined level, making it manageable. On completion of each technical review, a set of "exit criteria" is implemented. An example is the locking in of an established product baseline. The technical reviews are not intended to be forums for heated discussions. They are intended to review and validate that a program is mature and healthy enough to progress into the next planned phase.

Risk Management

Risk management is a common practice used by many industries to increase the probability of success of a given event or outcome. Although risk management fits within the overall direct responsibility of program management; it is also commonly associated with systems engineering. The DoD's approach to risk management is not unique. Similar to the approaches adopted in the commercial industry, risks are identified and characterized based on an assumed probability of occurrence and severity of the potential consequence. Risks are prioritized into high risk, medium risk, and low risk, or some other prioritization system. Figure 10 shows a typical "risk matrix" that is used to communicate the severity of risks. Once risks are identified and characterized in terms of severity, a path forward is defined to handle the same. In the DoD, typical choices to handle a given risk are to avoid the risk, control the risk, transfer the risk, or accept the risk. In some cases, a 90% solution to a problem that can be implemented in a matter of weeks is preferred over a 100% solution that would take many months to implement.

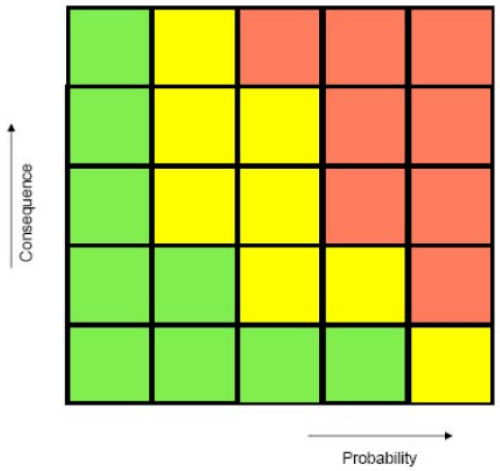

Figure 10: Risk Matrix

Details of risk management are well understood by different industries, and therefore will not be discussed in this chapter. However, the key to effective risk management is to determine as to how to integrate it into a given program's "battle rhythm". Differently stated, each project team should establish some regular, recurring process to identify new risks, track existing risks, characterize risks, develop action plans to execute risk mitigation strategies, and assign ownership for executing the action plans.

Technology Maturity

Managing the maturity of technology is an important practice in the military. The fact that the military often requires capabilities that are unique from commercial capabilities implies that emerging technologies often become important. Additionally, the military's objective of maintaining a strategic advantage over its adversaries implies that the use of new commercial technologies can be leveraged to create a strategic disadvantage for adversarial countries or organizations.

The most common tools used to manage technological maturity are Technology Readiness Levels (TRLs). The TRLs, used by the DoD, are based on definitions by the National Aeronautics and Space Administration (NASA). A summary of the TRLs used by the DoD is included in Table 1.

There is often a debate and discussion regarding what constitutes one TRL level versus another. The TRL levels often become a very useful tool to plan a program, manage risk, and determine the cost and schedule trade-offs between potential future systems that would utilize different levels of technological maturity. Figure 11 shows a common planning methodology for what levels of TRLs are appropriate for which stages in a program's lifecycle. The most critical element to discern from Figure 11 is that technologies of TRL 6 or higher must be attained by Milestone B.

Since the function of maturing technology is handled by a one DoD organization (the R&D centers such as TARDEC) while the function of developing and fielding full systems is handled by the Program Managers (PMs), it is important that the organizations maintain coordination as to their plans and progress with reference to the program. A commonly used tool to facilitate this is a Technology Transition Agreement (TTA). A TTA is a document that is signed by officials from both the R&D and the PM organizations (and any other relevant stakeholders) who define the criteria by which the PM will decide on whether to utilize the technology. Typically the R&D organizations prepare the TTA and obtain written statements from the PM defining whether they show "interest", "intent" or "commitment" to use the technology.

TRL	Definition	Description	Supporting Information
1	Basic principles observed and reported.	Lowest level of technology readiness. Scientific research begins to be translated into applied research and development (R&D). Examples might include paper studies of a technology's basic properties.	Published research that identifies the principles that underlie this technology. References to who, where, when.
2	Technology concept and/or application formulated.	Invention begins. Once basic principles are observed, practical applications can be invented. Applications are speculative, and there may be no proof or detailed analysis to support the assumptions. Examples are limited to analytic studies.	Publications or other references that outline the application being considered and that provide analysis to support the concept.
3	Analytical and experimental critical function and/or characteristic proof of concept.	Active R&D is initiated. This includes analytical studies and laboratory studies to physically validate the analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.	Results of laboratory tests performed to measure parameters of interest and comparison to analytical predictions for critical subsystems. References to who, where, and when these tests and comparisons were performed.
4	Component and/or breadboard validation in a laboratory environment.	Basic technological components are integrated to establish that they will work together. This is relatively "low fidelity" compared with the eventual system. Examples include integration of "ad hoc" hardware in the laboratory.	System concepts that have been considered and results from testing laboratory-scale breadboard(s). References to who did this work and when. Provide an estimate of how breadboard hardware and test results differ from the expected system goals.
5	Component and/or breadboard validation in a relevant environment.	Fidelity of breadboard technology increases significantly. The basic technological components are integrated with reasonably realistic supporting elements so they can be tested in a simulated environment. Examples include "high-fidelity" laboratory integration of components.	Results from testing a laboratory breadboard system are integrated with other supporting elements in a simulated operational environment. How does the "relevant environment" differ from the expected operational environment? How do the test results compare with expectations? What problems, if any, were encountered? Was the breadboard system refined to more nearly match the expected system goals?

TRL	Definition	Description	Supporting Information
6	System/subsystem model or prototype demonstration in a relevant environment.	Representative model or prototype system, which is well beyond that of TRL 5, is tested in a relevant environment. Represents a major step up in a technology's demonstrated readiness. Examples include testing a prototype in a high-fidelity laboratory environment or in a simulated operational environment.	Results from laboratory testing of a prototype system that is near the desired configuration in terms of performance, weight, and volume. How did the test environment differ from the operational environment? Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
7	System prototype demonstration in an operational environment.	Prototype near or at planned operational system. Represents a major step up from TRL 6 by requiring demonstration of an actual system prototype in an operational environment (e.g., in an aircraft, in a vehicle, or in space).	Results from testing a prototype system in an operational environment. Who performed the tests? How did the test compare with expectations? What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before moving to the next level?
8	Actual system completed and qualified through test and demonstration.	Technology has been proven to work in its final form and under expected conditions. In almost all cases, this TRL represents the end of true system development. Examples include developmental test and evaluation (DT&E) of the system in its intended weapon system to determine if it meets design specifications.	Results of testing the system in its final configuration under the expected range of environmental conditions in which it will be expected to operate. Assessment of whether it will meet its operational requirements. What problems, if any, were encountered? What are/were the plans, options, or actions to resolve problems before finalizing the design?
9	Actual system proven through successful mission operations.	Actual application of the technology in its final form and under mission conditions, such as those encountered in operational test and evaluation (OT&E). Examples include using the system under operational mission conditions.	OT&E reports.

Table 1: TRL Definitions

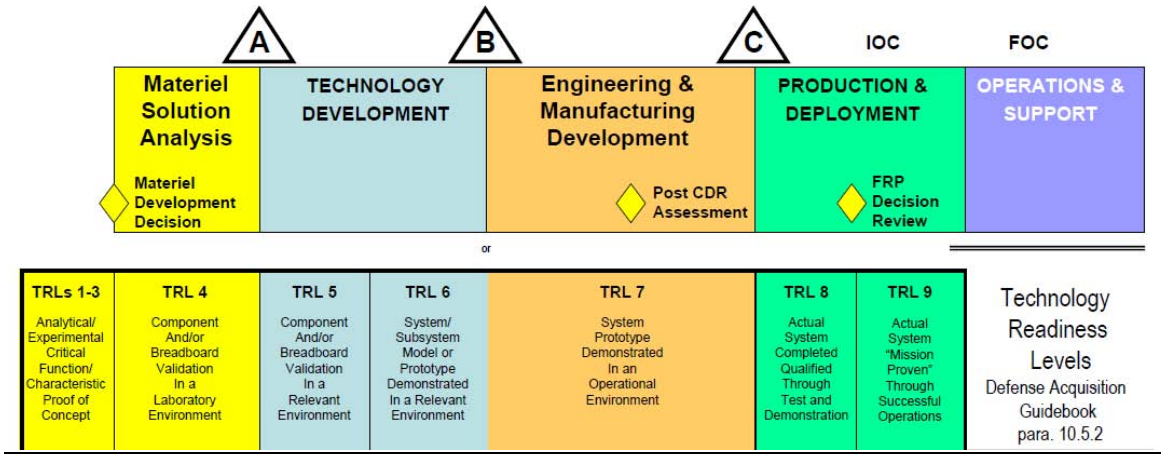

Figure 11: Alignment of TRLs with Acquisition Lifecycle

Systems Engineering Metrics

Systems engineering metrics are used in the DoD for tracking progress toward an objective and for establishing success criteria. Metrics may be defined for a specific program, or for an entire organization.

For program specific metrics, a common practice is to use Technical Performance Measures (TPMs). TPMs are technical metrics that are established based on KPPs and/or the technical requirements that correlate to the most significant program risks. Table 2 displays an example of TPMs for a program. The idea is that the responsible IPTs will track progress toward meeting each of the requirements. Feedback based on tracking the TPMs will influence the program's risk management activities.

KPP	TPMs	Responsible IPT	Conflict / Justification
Mobility	Top Speed	Mobility Sub-IPT	Potentially conflicts with Payload KPP
Mobility	Speed on Grade	Mobility Sub-IPT	Potentially conflicts with Payload KPP (CH-47 internal transport)
Transportability	Weight	Transportability Sub-IPT	Potentially conflicts with Force Protection KPP
Transportability	Size	Transportability Sub-IPT	Multiple Envelopes
Net Ready	Computing Resource Metric, Software Metric, Power	C4ISR IPT	Complex integration
Force Protection	Armor pounds per square foot to meet required protection levels; Armor TRLs	Survivability Sub-IPT	Requirements not demonstrated in relevant environment
Survivability	Weight Supported by Roof	ESOH IPT	Safety is paramount
Payload	Weight Capacity, Volume Capacity	Mobility Sub-IPT	Potentially conflicts with Mobility KPP
Material Availability	Reliability	Reliability Sub-IPT	Reliability requirements never demonstrated on similar systems
Integrated Performance	Rollup of all other TPMs; System Integration Metric	SE IPT	Integrated performance never demonstrated on similar systems

Table 2: Example of TPMs for a Program

Conclusion

There are a variety of common systems engineering practices within the DoD. Through the disciplined application of these tools, better products are delivered to customers faster and at reduced cost. The majority of these tools are readily applicable to products outside of the realm of the defense industry.

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References

1. Interaction between Program Management and Systems Engineering, Adapted from Kossiakoff & Sweet (2003).
2. Written permission to use the picture, at Figure 4, showing the use of a LOCB bridge for 9/11 Ground Zero, NY in this book, from Eugene Sobecki, on 08 September 09.
3. Written permission to use the pictures Figures 5a and 5b showing the use LOCB for both civilian and military applications to be used in this book, from Kevin Traynor on 17 September 09.
4. Illustration of DoDAF integrated architecture products, "Image by an Army soldier/civilian."

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