RESEARCH ON TECHNOLOGY READINESS ASSESSMENT MODEL FOR SYSTEM OF SYSTEMS

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Abstract

The difference between System and Larger Complex System, and, System of Systems (SoS) and System of Systems Engineering (SoSE) in defense materiel development are discussed according to the definition and characteristic in this paper. Based on analyzing the Technology Readiness Assessment (TRA) Model in System Engineering, the TRA model of SoS is discussed about the assessment model, assessment criteria and assessment process, and some suggestion is given. Finally, the technology maturity assessment for the Future Combat System (FCS) is discussed as an illustration.

Generally, TRA model for system technology includes the identification and assessment of Critical Technology Element (CTE). However, the TRA model for System of System (SoS) faces with many challenges. Firstly, the change of assessment subject make the evaluation becomes more complex. Secondly, the assessment criterion needs to be improved to suitable. The main problems in SoS TRA are discussed in this paper.

1 Definition of System of Systems (SoS)

With the development of Science and Technology (S&T), the topic of defense weapon system engineering has extended to multiple integrated complex system from single complex system. The complex systems include: Family of System (FoS), SoS, Enterprise System (ES), Network Centric System (NCS).

SoS is defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (Defense Acquisition Guidebook) [1]. When integrated, the independent systems can become interdependent, which is a relationship of mutual dependence and benefit between the integrated systems. Both systems and SoS conform to the accepted definition of a system in that each consists of parts, relationships, and a whole that is greater than the sum of the parts; however, although an SoS is a system, not all systems are SoS.

2 System of System Engineering (SoSE) in Defense Weapon System Development

2.1 The Definition of Defense Weapon System Engineering

The defense weapon system engineering aims to manage and control the technology process, activities, and element to ensure the goal realization by using configuration management, technology interface management, technology data management, technology risk management and technology assessment management. The system engineering include: life cycle model, system engineering process and goal-oriented knowledge set (Fig. 1.).

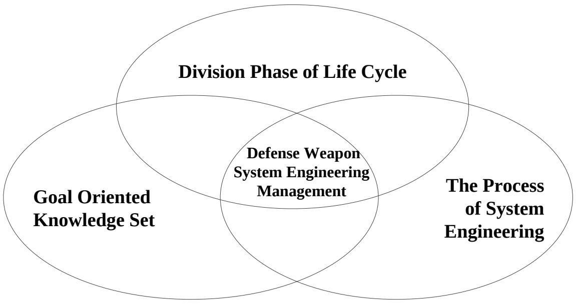

Fig. 1. The Management Frame of Defense Weapon System Engineering

2.1.1 Division of Materiel Life Cycle

ISO/IEC 15288 states: “6.2 - A life cycle model that is composed of stages shall be established. The life cycle model comprises one or more stage models, as needed. It is assembled as a sequence of stages that may overlap and/or iterate, as appropriate for the scope, magnitude, and complexity, changing needs and opportunities.”

The materiel Life Cycle model include: Materiel solution analysis, technology development, engineering and manufacturing development, production and deployment, operation and support, and retire. In these phases, system concept, function baseline, allocation baseline, production baseline is used to describe the status of technology and system respectively, which can ensure the success of materiel development. The system concept is generated and described after translation of system requirement from user need. Function baseline is description for system performance according to system concept. Allocation baseline is description for subsystem or component performance, and is the basis of detail design. Production baseline describes product characteristic according to the description for subsystem or component performance.

The life cycle model deals with the time dimension in Hall system engineering model, divides materiel life cycle into five stages and defines the purpose and entry and exit criteria in each stage. Its’ goal is to assess and control critical events in all life cycle by establishing various baseline.

2.1.2 System Engineering Process

The system engineering process [2] depicts one approach that translates operation needs or requirements to system design through a series of activities. It portrays how requirements analysis, functional analysis, and design take place iteratively and recursively. Each element influences and is influenced by the others as tradeoffs are made to discover the best system solution. System operational requirements, operational effectiveness/utility, and cost are all considered. The functional analysis describes and evaluates the system in qualitative and quantitative terms for the functions that must be achieved to meet the required performance characteristics. Functional analysis forms the bridge between requirements and system design where selections are made among alternative designs—allocating scarce resources (such as cost, weight, power, and space) and guiding the choice of optimal design points.

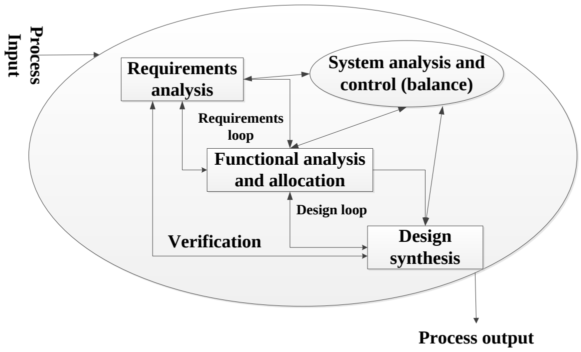

Fig. 2. The Process of System Engineering

The system engineering process deals with the logic dimension in Hall system engineering model. Its’ goal is to achieve the balance between performance, cost, schedule through system analysis and control process.

2.1.3 Goal Oriented Knowledge Set

With the increasing in degree of system complexity and magnitude, at some point, full knowledge is attained about a completed product has become more and more important, because such knowledge is the inverse of risk. The GAO’s knowledge-based process [3] has proved an effective method to get better cost, schedule, and performance outcomes.

This knowledge can be broken down into three junctures refer to as knowledge points: when a match is made between the user’s requirements and the available technology, when the product’s design is determined to be capable of meeting performance requirements, and when the product is determined to be producible within cost, schedule, and quality targets. The knowledge points and their associated metrics are depicted in Fig. 3.

(1) Knowledge Point 1: Requirements and Technology are matched.

Technology development has the ultimate objective of bringing a technology up to the point that it can be readily integrated into a new product and counted on to meet requirements. As a technology is developed, it moves from a concept to a feasible invention to a component that must fit onto a product and function as expected. In between, there are increasing levels of demonstration that can be measured. The technology readiness level (TRL) pioneered by National Aeronautics and Space Administration (NASA) and adapted by the Air Force Research Laboratories (AFRL) has been applied to evaluate whether the knowledge available is match the requirement.

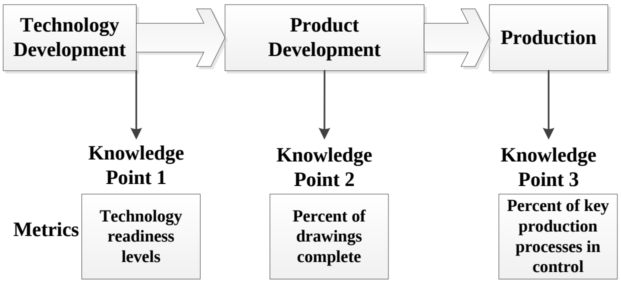

Fig. 3. GAO's Three Knowledge Points Model

(2) Knowledge Point 2: The Design Will Perform as Required

The leading commercial firms achieved near certainty that their product designs would meet user requirements and had gone a long way toward ensuring that the products could be produced by the halfway point of product development. Both Department of Defense (DOD) and the commercial firms hold a critical design review to review engineering drawings, confirm the design is mature, and "freeze" it to minimize changes in the future. The critical documented drawings are not only precision schematics of the entire product and all of its component parts—they also reflect the results of testing and simulation, and they describe the materials and manufacturing processes to be used to make each component.

(3)Knowledge Point 3: Production Units Will Meet Cost, Quality, and Schedule Objectives

This knowledge point means that manufacturing processes would produce a new product conforming to cost, quality, and schedule targets before fabricating production articles. Reaching this point means more than knowing the product could be manufactured; it meant that all key processes were under control, such that the quality, volume, and cost of their output were proven acceptable. The leading commercial firms rely on good supplier relationships, known manufacturing processes, and statistical process control to achieve this knowledge early and, in fact, have all their key processes under statistical process control when production begin. The ability to establish control for key processes before production begin is the culmination of all the practices employed to identify and reduce risk.

The goal oriented knowledge set deals with the knowledge dimension in Hall system engineering model. Its' goal is to attain the enough knowledge before technology development, system design, production.

2.2 The Definition of System of System Engineering

System of systems engineering (SoSE) "deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a SoS capability greater than the sum of the capabilities of the constituent parts". Consistent with the DoD transformation vision and enabling Net-Centric Operations, SoS may deliver capabilities by combining multiple collaborative, autonomous, yet interacting systems. The mix of constituent systems may include existing, partially developed, and yet-to-be-designed independent systems [1].

SoSE should foster the definition, coordinate development, and interface management and control of these independent systems while providing controls to ensure that the autonomous systems can function within one or more SoS. SoSE has characteristic of autonomy, belonging, connectivity, diversity, and emergence.

2.3 The Difference between SE and SoSE

The difference between System Engineering and SoSE [4] includes: focus, boundaries, approach, Goals, etc, as shown in Table 1. The boundary of SoSE is dynamic while the SE is static, SoSE focus on methodology while SE focus on process, and there are multiple parallel system engineering processes with non-synchrony in time and technology maturity while SE needs just one system acquisition process. In addition, the emergency is a hot issue in SoSE.

Table 1 Comparative Analysis of System Engineering and SoSE

No	Factors	SE	SoSE
1	Focus	Single Complex System	Multiple Integrated Complex System
2	Objective	Optimization	Satisficing
3	Boundaries	Static	Dynamic
4	Problem	Defined	Emergent
5	Structure	Hierarchy	Network
6	Goals	Unitary	Pluralistic
7	Approach	Process	Methodology
8	Timeframe	System Life Cycle	Continuous
9	Centricity	Platform	Network
10	Tools	Many	Few
11	Management Framework	Established	None
12	Standards	Few	None

In Comparison with System Engineering, SoSE [5] is the combination of much System Engineering ("Vee" Model). There are a series of life cycles and multiple "Vee" Models in embedded architecture as in Fig. 4.

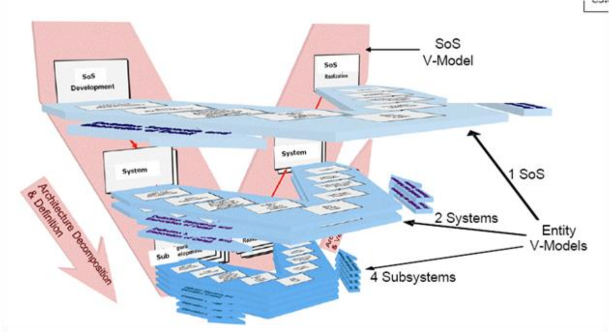

Fig. 4. "Vee" Model in SoSE

3 Technology Maturity Model in Defense Weapon System Engineering

3.1 Definition of Technology Readiness Level Model

The technology issue is the core in defense weapon system engineering. Because its goal oriented characteristic, the ultimate goal of technology development is applied in the production.

This may need a very long course, includes: discovery of theory, assumption of application, the concept formation and validation, design, integration, manufacture, test, production, operation, support, etc. In another perspective, it constitute of knowledge perspective, knowledge theory, knowledge practice.

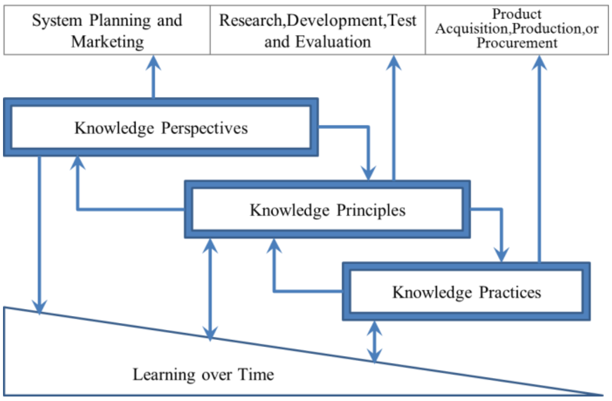

Fig. 5. The Learning process in System Engineering

How to evaluate technology status in a specified point, and its maturity to the production, are the main topic between the technology developer and manager. TRL model invented by Sadin from NASA provide a tool for evaluating the technology development status, which divides the whole process into 9 segments from birth to death of the technology. The role of TRL [6] includes: making the information become visible, making the knowledge structural, making the process flowable, and making the evaluation quantitative.

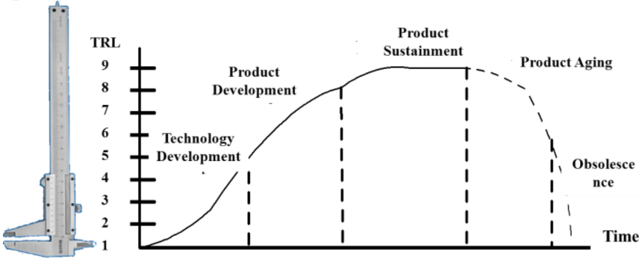

Fig. 6. The TRL model in single production life cycle

3.2 The Technology Readiness Assessment Model

The TRA model include: the assessment organization, the assessment subject, the assessment criterion, the assessment method and the assessment output.

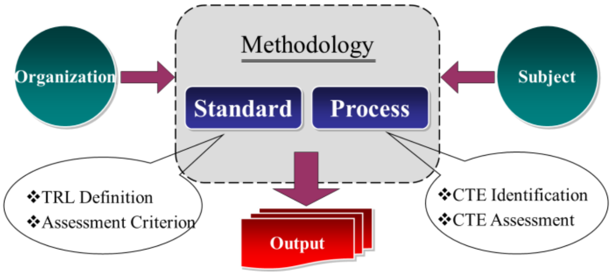

Fig. 7. Technology Readiness Assessment Model

3.3 The System Engineering and Technology Readiness Level

The system engineering process includes science research, technology development, system integration, manufacture/production, operation, etc., which need a series of quantitative assessment model to evaluate and manage. The TRL model has proved to be feasibility to deal with the technology maturity assessment. In fact, in TRL model, there is a system engineering process to describe the technology development process (as shown in Fig. 8). It contains a top-down process to break down and define the user requirement and a bottom-up process to synthesize/integrate and validate the "technology" [7].

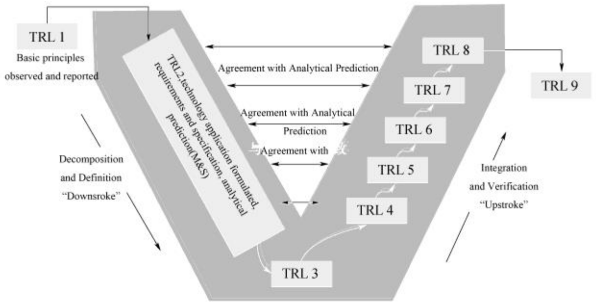

Fig. 8. The "Vee" model in technology readiness levels

Therefore, the TRL model is one SE process in form of "Vee" model. TRL definitions readily indicate progressive levels of technology integration and verification, starting with TRL 3 where low-fidelity components of the technology elements are built and demonstrated separately, through TRL 8 where the actual technology is fully integrated onto the system and flight-demonstrated. At each TRL level demonstration outcomes are compared against analytical predictions, and in TRL 8, verified against design specifications.

The role and characterization of modeling and simulation to procure analytical predictions for technology development are understated in TRL definitions, particularly when considering that analytical results are explicitly called to conduct validation/verification at each readiness level.

4 Technology Readiness Assessments for System of System

The TRA method has proved an effective tool for assessing the technology progress of one single system. However, the system of systems engineering is distinct from system engineering. Thus, the assessment model, assessment criteria, assessment method need to be discussed during assessing system of systems' maturity.

4.1 The Assessment Model Framework

In assessment methodology and management's view, if the system of systems could be regard as a "large, complex" system, the assessment opportunity, organization, process could be designed successfully based on TRA model. The emergence of SoS results in the variation in assessment criteria and assessment process as the assessment subject changes from system to SoS. In the assessment criteria, assessment for integration and logic relationship between the component systems/subsystems in SoS should be emphasized particularly.

4.2 The TRL Definition and Assessment Criterion

Based on the efforts of many researchers and experience from various systems' assessment practices, the TRL definition and assessment criteria can be discussed.

The SoS TRL has been defined by replacing the "system" with "SoS" in the description of TRL definition.

When establishing the assessment criteria for SoS, the architecture should include checklist related integration other than technology, manufacture, programmatic based on the TRL checklist developed by Air force Research Laboratory (AFRL). The operation related to Key Performance Parameter (KPP), system architecture related to the boundary for KPP, function architecture related to the degree of integration, technology architecture related to standard and protocol are the important consideration factors.

4.3 The Relevant Environment

The relevant environment may not be fully understood and be difficult to defined because other systems [8]: Modeling and simulation may be inadequate, test and evaluation environments may not be fully misunderstood, system performance and the relationships among systems change over time, or testing all permutations is impossible.

Hence, when identifying the SoS environment(s) and interfaces, it's necessarily to focus on what makes the SoS environment unique, such as, considering execution time or data throughput and information exchange requirements to/from other systems, including information assurance considerations, identifying functional dependencies and the technologies that enable these functions.

4.4 Identification and Assessment of CTE

The SoS CTEs are identified based on the Work Break Structure (WBS) or Technical Work Break Structure (TWBS) thoroughly by using the expanded identification questions [8], such as:

- Is the technology contributing to a more effective performance of the SoS in development?
- Is this technology creating new relationships between systems?
- Are technologies fielded on the associated systems being modified to meet new requirements of the SoS?

There are little difference between component system and SoS's TRA. When conducting a TRA for a system that is part of the SoS, many lessons need to learn, such as, including all system specific technologies that meet the CTE criteria, assessing SoS CTEs that are in the system undergoing the TRA even if they are not system specific CTEs.

Compared with component system TRA, when conducting a TRA for the SoS, the flowing lessons need to know, such as, including all CTEs required to meet SoS operational requirements, including SoS unique CTEs and system unique CTEs required for a system to participate in the SoS regardless of who is responsible for funding or development, internal and external dependencies should be treated equally and all associated CTEs should be formally assessed in the SoS TRA against the SoS requirements.

In either case, situations where a capability in one system is dependent on a technology in another system for its functionality should be taken into account. And any TRA completed or being conducted on a system within the SoS for identification of relevant CTEs should be considered.

5 Case Studies for Future Combat System

The Army's Future Combat Systems (FCS) [9] that includes 14 elements plus the network and the solider is selected as case study. And the interoperability, CTE identification and assessment are discussed respectively.

5.1 Background

This program consists of an integrated family of advanced, networked combat and sustainment systems; unmanned ground and air vehicles; and unattended sensors and munitions intended to equip the Army's new transformational modular combat brigades, within a SoS architecture.

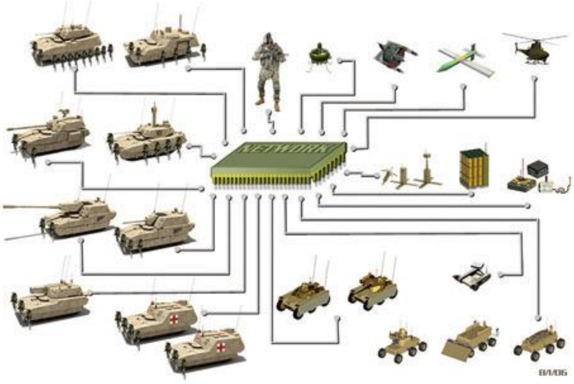

Fig. 9 The Army's Future Combat System (FCS)

The DoD and GAO have evaluate the FCS program several times since it started in May 2005. The Government has identified and evaluated the immature technologies in FCS, and advanced the technology to mature by making technology maturity plan for those high risk technologies.

5.2 Interoperability for FCS

The definition and taxonomy of degree of interoperability are useful in identifying critical functions and technologies in FCS, which are pertinent to the definition of relevant environment and type of systems. The FCS operates with other systems via contribution, coordination and cooperation. The most important interoperability attributes for FCS are described in the flowing 6 aspects [10], as shown in Table 2.

Table 2 The interoperability attributes for FCS

Factors	FCS
Completeness	all relevant items available, such as entities, their attributes, and relationships between them
Correctness	all items in the system faithful representations of the realities they describe
Accuracy or Level of Precision	dependent on the purpose
Consistency	across different systems and applications (tailored)
Connectivity	specified integration of nodes, type of connections, syntactic compatibility, quality of service and bandwidth/data rate requirements
Capacity	databases, scalability, number and type of applications, processor requirements
COTS	use of and consideration of obsolescence, instability in standards or availability, security, and reliability

5.3 CTE Identification for FCS

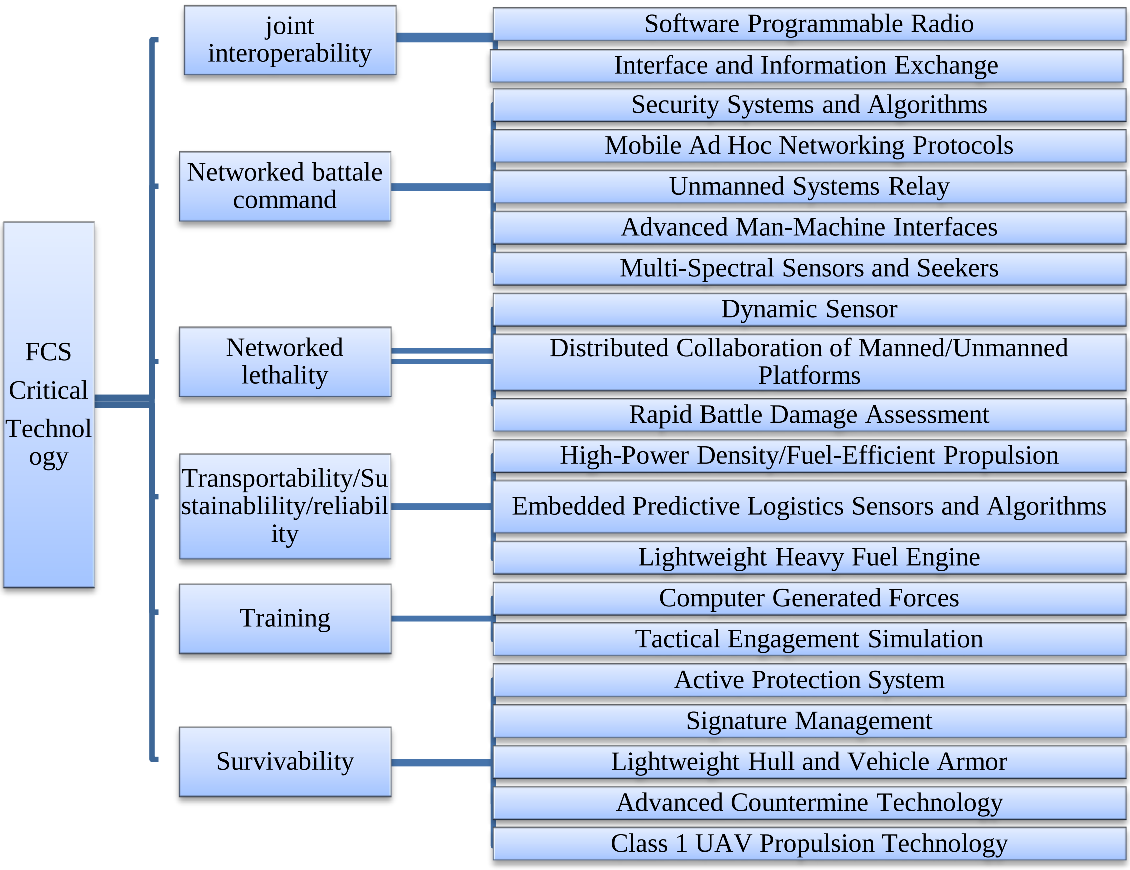

Fig. 10. The FCS critical technology and technology break structure

The FCS has 54 critical technologies [11] identified based on the WBS, including joint interoperability, networked battle command, networked lethality, transportability, sustainability, reliability, training, and survivability related technology, as shown in Fig. 10. These technology selections may change because the requirements and the architecture definition were not stable.

Among all these technologies, the majority is relevant to the KPPs/operation, such as, lightweight heavy fuel engine, signature management, etc.; others are related to SoS interoperability, such as interface and information exchange. On the other hand, the CTEs include FCS unique CTEs as well as system unique CTEs required for the specific system to participate as a component system of FCS (e.g, Unmanned Systems Relay) regardless of who is the stakeholder or developer.

5.4 FCS system engineering and CTE evaluation

The FCS system engineering [12] described using the popular "Vee" model captures some very important features of the system engineering and architecting process, as shown in Fig. 11. Here, time moves from left to right. The major program reviews that occur as time evolves, such as SRR, PDR, CDR, DRR, etc., are shown on the bottom,

The process unfolds by traversing the "Vee", including the design side by traveling down the left-hand side of the "Vee" and the verification side up the right-hand side, and by so doing its projection on the horizontal axis moves with time from left to right.

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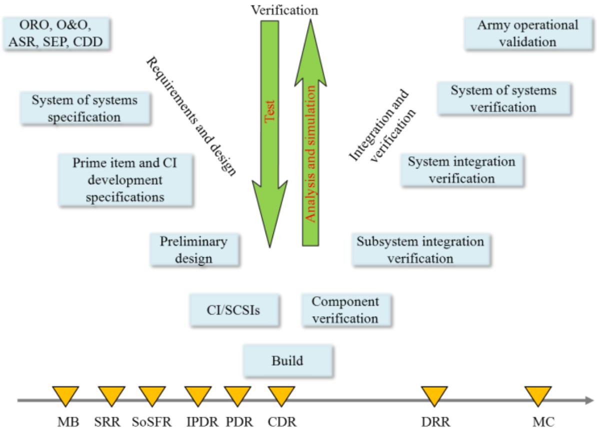

Fig. 11 The FCS System Engineering Framework

In system engineering, there are many decision gates needing the status of CTEs to evaluate the engineering risks. DoD and the Army have evaluated the FCS critical technologies four times during the last ten years, and the changes for some critical technologies' status over time are shown in Table 3.

Table 3 The FCS CTE TRL over time (partially)

	CTE#	CTE Name	2004	2005	2009
1	1A	JTRS-GMR	5	5	5
2	1B	JTRS-HMS	5	5	5
4	2A	Interface & Info Exchange – Army	4	4	6
5	2B	Interface & Info Exchange – Joint and Multi-National	4	4	6
7	3A	Cross Domain Guarding Solutions	3	4	6
10	3B1	Security Systems & Algorithms – Intrusion Detection IP Network	5	4	6
11	3B2	Security Systems & Algorithms – Waveform Protocols	3	3	5
12	6	Unmanned Systems Relay	5	5	X
13	7A	Wideband Networking Waveform	5	5	5
24	12	Rapid Battlespace Deconfliction	4	5	5
32	16A	Aided Target Recognition for RSTA– Ground Only	5	5	5
54	32B	Lightweight Heavy Fuel Engine	3	4	5

In terms of critical technologies, 35 of 54 critical technologies (reduce to 44 for some reasons, and cited by GAO) had become mature, that is, the rated TRL changed at least once, and also 8 critical technologies had not reached to TRL 6 in 2009, which is generally regarded as mature technology. In 2008, several critical technologies' rated TRL even had decrease for some reasons.

All the four TRA relied on the Independent Review Teams (IRT) based on numerous data provided by developer and PM office, rather than rigorous assessment criteria. However, the evaluate results are reliable and used for the program manage until the FCS program terminated in 2009.

6 Conclusions

It has proved that evaluating the SoS technology maturity is necessary and feasible by evolving the TRA model for single system. The definition of SoS, interoperability and relevant environment, and the design for technology locator checklist and assessment checklist, are the main issues in SoS technology readiness assessment. However, in comparison with single system technology readiness assessment, there are many hard works to solve in the future, such as how the logical relationship and interoperability in component systems in SoS influences the identification and assessment criteria for CTE, etc.

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