TECHNICAL RISK MANAGEMENT OF SYSTEM OF SYSTEMS BASED ON TECHNOLOGY READINESS ASSESSMENT

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Abstract

With the development of system of systems (SoS) in defense aera, risk issues in high-tech weapon system development become more and more important. The relationship between technical risk management and technology readiness assessment (TRA) was analyzed and common XRL maturity models widely used in system engineering process were compared and discussed. The difference between system and SoS, system engineering (SE) and system of systems engineering (SoSE) were discussed according to the definitions and characteristics in this paper. The technical risk management model for SoS has been established based on the TRA model for single system, including framework, object, criteria, process, etc. Future Combat Systems were chosen as the case study. Finally, some suggestions were given for the identification and evaluate for technical risk of SoS.

Keywords: technical risk management, technology readiness assessment, system of systems.

1. General Introduction

With the development of Future Operating Concepts such as Penetrating Counter Air, Multi-Domain Operation Concept, Agile Operation, distributed air warfare, and manned unmanned collaborative operations, the confrontation of future wars has gradually become from single weapon system capabilities to SoS confrontation. Forming a SoS level operation capability through multiple single weapon system integration is an important trend in future defense system. And defense SE is gradually shifting towards SoSE. The demand for technical risk management in SoS has become more urgent, requiring a comprehensive and systematic identification of the technical risk sources of the project, and adopting a continuous structured approach for risk assessment and management [1].

At present, TRA methodology for defense system has become international standards and tools for science and technology management and defense weapon system acquisition. However, the TRA methodology for SoS faces with severe challenges: in terms of evaluation objective, SoS is more complex and comprehensive and the interaction is exceptionally complex; In terms of evaluation criteria, the SoS involves a series of unsynchronized total lifecycle SE models in terms of time and technological maturity, and coordinating performance, schedule, and funding consistency to ensure system development success is very difficult for program managers. The current TRA guidelines for individual defense system are difficult to meet the evaluation requirements of the SoS [2-3]. The technology maturity evaluation methodology for SoS has been discussed in this paper based on the

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existing methodology, which can be used in future technology readiness assessment for complex defense systems.

2. Maturity Models for Technical Risk Management for Defense System

2.1 Relationship between technical risk management and technology readiness assessment

The TRA method fully implements the ideas and concepts of technical risk management, and forms more specific standards in various stages, such as risk identification, risk analysis and assessment, risk mitigation and monitoring, as shown in Figure 1.

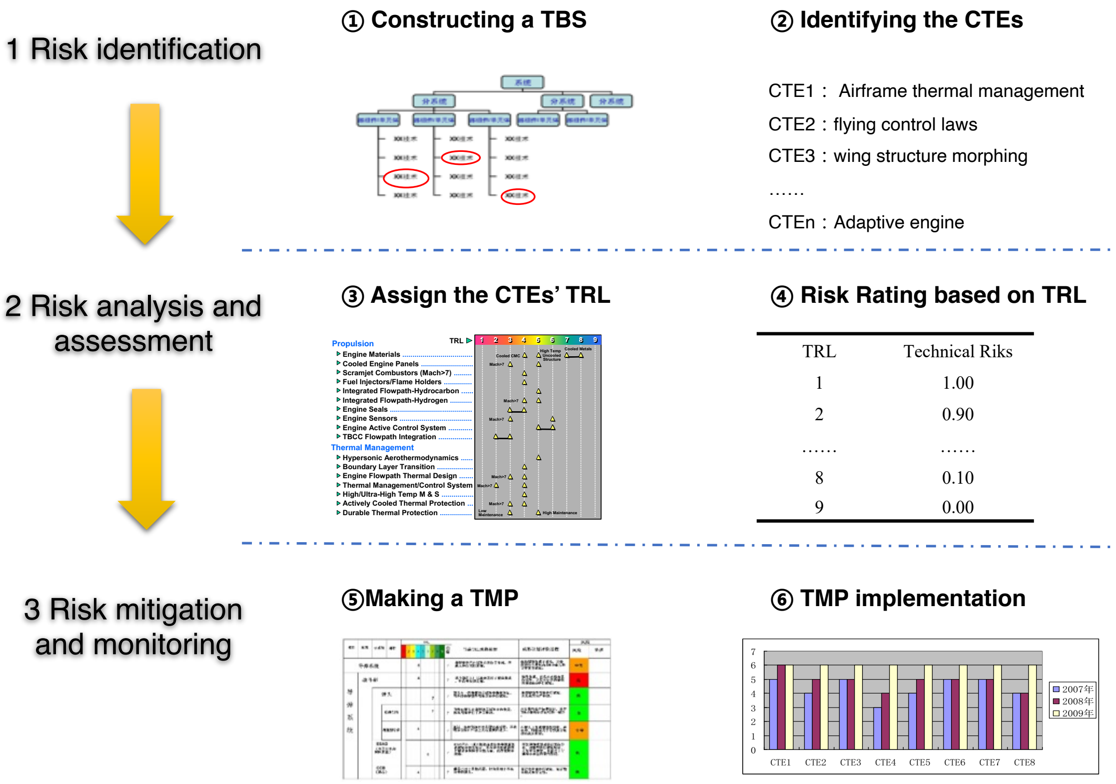

Figure 1 – The relationship between TRA and technical risk management.

In risk identification stage, the Technology Breakdown Structure (TBS) is constructed according to risk occur probability and consequence, the Critical Technology Elements (CTEs) list is identified and determined; In the risk analysis and assessment stage, the risk of identified CTEs is analyzed and rated according to the 9-level TRL definition and evaluation rules; In the risk mitigation and monitoring stage, technology maturity plan is established for immature technologies (high-risk technologies), and implemented, which form a closed loop to achieve risk mitigation or reduction.

2.2 Maturity Models in System Engineering Management

In recent years, several maturity evaluation methodologies represented by technology maturity, integration maturity, and system maturity has rapidly developed and been applied in practice. The three models are closely related and complementary to each other, playing an important role in risk management of defense weapon system development.

The systems engineering and technology maturity evaluation reflects a common development pattern, as shown in Figure 2[4]. Generally, system engineering process describes a "V" model, which involves the decomposition of system design requirement with “downstroke” activities and the verification of system implementation with “upstroke” activities. System engineering includes basic research, technology development, subsystem and system integration, system manufacturing and production, deployment and operation support, etc. and technology maturity models is one of maturity models needed to manage the technologies quantitatively during system development. In the same time, the technology maturity process also contains system engineering processes. A "downward" process of decomposing and defining user requirements implied in the left side (TRL1~TRL3) and an "upward" process of integrating and validating clearly decomposed system modules implied in the right side (TRL4~TRL9).

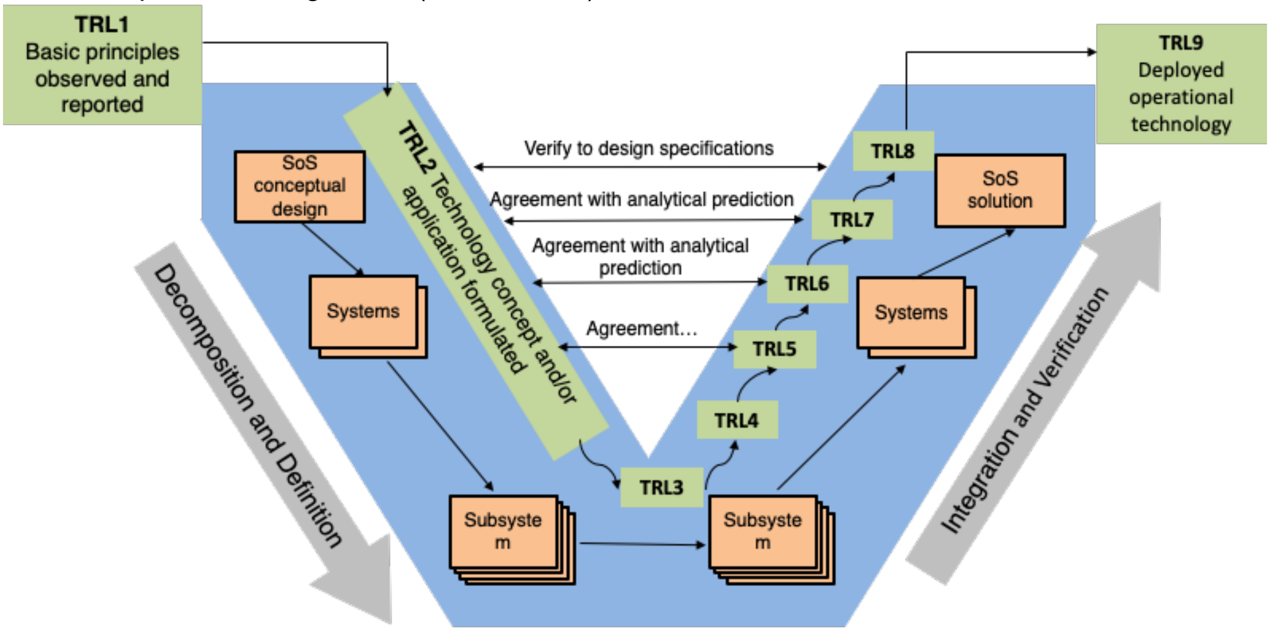

Figure 1 – The relationship between TRA and SE process

TRL1 and TRL2 indicate that technology is in the stage of theoretical research and application conjecture, and the integration relationship between technologies is not obvious. Starting from TRL3, technology began to conduct experiments in the laboratory with basic components, and integration relationships gradually began to emerge between technologies. The detailed explanation of fidelity, verification platform, and environment in the definition and evaluation rules from TRL3 to TRL9 provided in Table 1 [4]. Technology form and validation environment are becoming closer to the final system/product and actual operating environment as the level of technology maturity increased.

Table 1 – TRL representation with constituent sub-attributes

Components Integration		Fidelity	Demonstrator	Environment
TRL3	Basic components not yet integrated	Low	N/A	Laboratory
TRL4	Basic technology components into Breadboard	Low	Breadboard	Laboratory
TRL5	Brassboard with realistic supporting elements, one-to-several technologies	Mid	Brassboard	Relevant
TRL6	Prototype with supporting elements, several-to-many technologies	High	Prototype	Relevant
TRL7	Engineering unit with subsystems and technologies, on vehicle system	High	Engineering unit	Operating
TRL8	Technology with subsystems and technologies, on vehicle system	Actual technology	Flight qualified	Operating
TRL9	Technology with subsystems and technologies, on vehicle system	Actual technology	Flight qualified	Mission/operating

The system maturity process based on Technology readiness level (TRL) and Integration readiness level (IRL) is shown in Figure 3, which includes:

1) Understand the system comprehensively and accurately, including system design, system development plan, etc.

2) Construct the system architecture, draw a system functional structure diagram, and decompose all "hardware technology" and "software technology" from the system to form a list of CTEs.

3) Define network correlation diagrams for key technologies of the system, with a focus on determining whether the integration between technologies is appropriately demonstrated, which directly affects the accuracy of subsequent assignments.

4) According to the TRL and IRL level standards, assign values to the maturity of each technology and the integration between technologies.

5) Input the initial values of TRL and IRL into the algorithm model, and use the SRL matrix formula to calculate the system maturity of individual technologies and the system integration of complex systems.

6) Visualize the detailed development status of complex system in the form of charts, especially the current level of development and the performance changes over time.

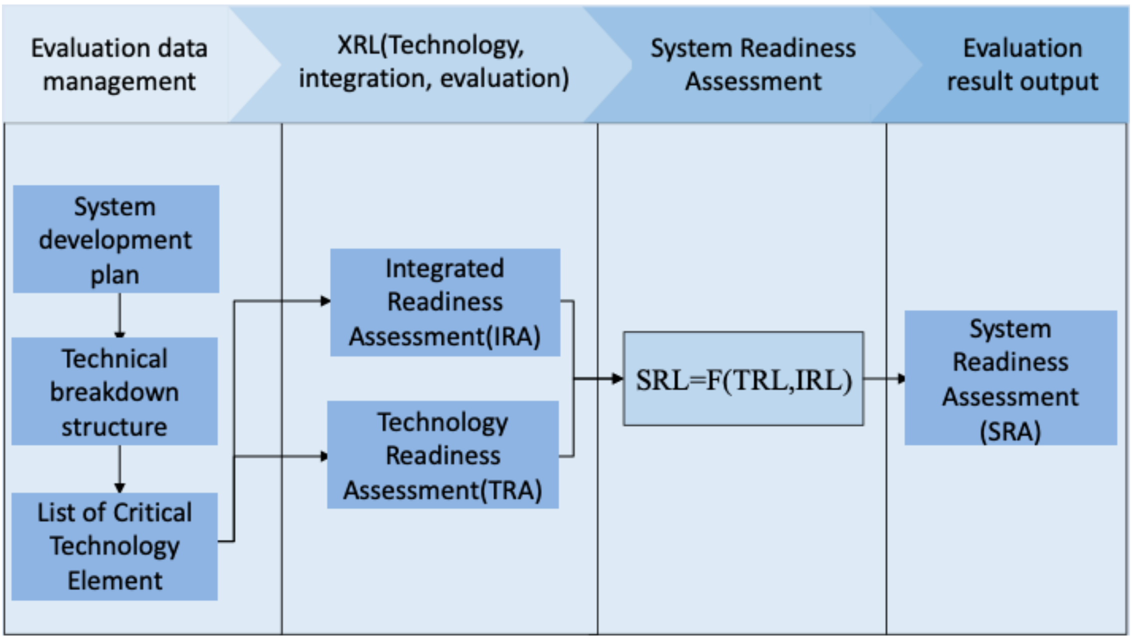

Figure 2 – The system readiness assessment process

3. System Engineering and System of Systems Engineering

3.1 Attribution for System of Systems

The Defense SoS mainly includes five main characteristics, as show in Figure 4[5]. Autonomy refers to the ability of a system as part of SoS to make independent choices; Belonging refers to constituent systems have the right and ability to choose to belong to SoS; Connectivity refers to the ability to stay connected to other constituent systems; Diversity refers to evidence of visible heterogeneity; Emergence refers to formation of new properties as a result of developmental or evolutionary process.

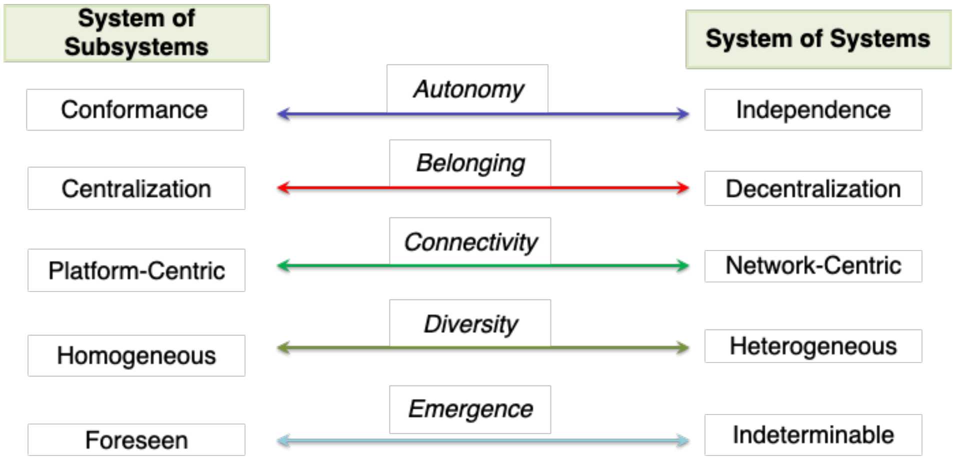

Figure 4 – Distinguishing characteristics of system and SoS

The above five features are not independent, but interdependent with each other. For example, the level of autonomy can determine the degree of belonging, which in turn affects the degree of connectivity, and may limit the diversity of units and the emergent properties of systems. The transformation of diversity may also affect attribution, leading to an increase in autonomy and a corresponding impact on emergence.

3.2 System of Systems Engineering

SoSE deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new system into an SoS capability greater than the sum of the capabilities of the constituent parts. SoSE provides 7 core elements for the application of system engineering processes [6]:

- Translating the capability objective into high-level system requirements that change over time.
- Understanding the composition of the system and its relationships.
- Assessing the degree to which the system performance meets its capability objectives over time.
- Developing and evolving a SoS.
- Monitoring and assessing the potential impact of changes in system performance.
- Addressing system requirements and solution options.
- Orchestrating system upgrades.

Table 2 – Technical &technical management processes application in SoSE

	Technical Processes								Technical Management Processes							
	Rqtsdevl	Logical analysis	Dsgign solution	Implement	Integrate	Verify	Validation	Transition	Decision analysis	Tech planning	Tech asses	Rqtsmgmt	Riskmgmt	Config mgmt	Data mgmt	Interface mgmt
Translating capability objective	X											X	X	X	X	
Understanding systems and		X											X	X	X	X

relationships																
Assessing performance to capability objective							X		X		X		X		X	
Developing and Evolving a SoS architecture	X	X	X						X	X		X	X	X	X	X
Monitoring and assessing changes									X				X	X	X	X
Addressing requirements and solution options	X		X						X	X		X	X	X	X	X
Orchestrating upgrades to SoS				X	X	X	X	X	X		X	X	X		X	X

The 16 technical and technical management processes defined in Defense Acquisition Guidebook is related to the above 7 core elements of SoSE. The SoSE applies some activities as shown in Table 2. The matrix of SE processes related to the SoSE core elements and suggests places where the SE team needs to plan for SE support to the SoS.

3.3 Comparison between SE and SoSE

Compared with system engineering, SoSE has significant differences in the following aspects, as shown in Table 3, mainly reflected in 12 aspects such as focus, purpose, boundary, problem, and structure [5,7].

Table 3 – Comparative analysis between SE and SoSE

No.	Factor	SE	SoSE
1	Focus	Single complex system	Multiple integrated complex systems
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	--
12	Standards	Few	--

Overall, the characteristics such as autonomy, belonging, and emergence make the SoSE significantly different from system engineering. SE considers processes, focuses on platforms, and only requires once acquisition. However, SoSE considers methodology, network-centricity, and requires multiple parallel system engineering with asynchronous time and technological maturity. In addition, emergence is also a characteristic that system engineering does not possess.

4. Technology Readiness Assessment Model for System of Systems

4.1 The Technology Assessment Framework

The technology readiness assessment model has been developed with fully considering the differences between systems and SoS (interoperability, emergence, relevant environment, etc.) that may bring changes to evaluation standards and methods. And the framework for evaluating systems is proposed, as shown in Table 4.

Table 4 – Comparison in TRA for system and SoS

No.	Factor	Systems	System of Systems
1	Objective	Single system	Multiple systems
2	Organization	3 layers and 2 lines	3 layers and 2 lines (More sub-lines)
3	Standards	TRL definitions and criteria	SoS TRL definitions and criteria
4	Process	CTE identification and evaluation	CTE identification and evaluation
5	Output	TRA report for system	1+N TRA reports

In this framework, the evaluation object has changed from single system to complex system, also from single system engineering to multiple system engineering. The evaluation process includes technology maturity evaluation both at system level and the top SoS level. As for evaluation subject, it involves multiple asynchronous system engineering processes, which managed by deferent organization. The evaluation organization should establish communication mechanisms between two different levels of systems on the basis of the commonly used evaluation organizations of "decision-making layer -management layer - implementation layer" and "project line - evaluation line", in order to coordinate the evaluation related work between multiple systems that require interoperability, as well as the evaluation work between the two levels of SoS and systems.

4.2 The Assessment Criteria

The assessment criteria are divided into two levels: system level and system of systems level. The system level TRL definition follows the commonly used technology readiness level definition, focusing on the evaluation of CTEs for independent systems. The technology form and environment still focus on individual system. However, SoS TRL definition refers to the commonly used system TRL definition and is mainly used to evaluate SoS level critical technologies. The technology form focuses on SoS level critical technologies and verifies the testing environment required for interconnection and interoperability between independent systems in the system of systems.

In the SoS TRL definition, the verification and validation process for individual technologies has added activities within the system, which require more validation activities for individual technologies (TRL6-9). It is necessary to coordinate all related systems, build a test verification environment, and verify the functionality of the system in the SoS, especially the functionality and performance related to interoperability. The design, manufacture, and validation activities of multiple independent systems are inseparable, and there is a lot of interoperability that needs to be closely linked and verified with each other. Perhaps a certain function of System A depends on a certain technology of System B. Therefore, it is necessary to construct the TRL evaluation rules of the SoS from the perspectives of operational concept, system architecture, functional system (integration level), technical system (standards, protocols), etc. [8].

Table 5 – TRL definition for SoS

TRL	Definition
1	SoS basic principles observed and reported
2	SoS technology concept and/or application formulated
3	Analytical and experimental critical function and/or characteristic proof-of-concept
4	Component and/or breadboard for SoS validation in laboratory environment
5	Component and/or breadboard for SoS validation in relevant environment
6	SoS/system model or prototype demonstration in a relevant environment
7	SoS prototype demonstration in a operational environment
8	Actual SoS completed and “flight qualified” thorough test and demonstration
9	Actual SoS “flight proven” through successful mission operation

4.3 The Assessment processes

4.3.1 Identification for Critical Technology Elements

The main ideas and methods of TRA evaluation for reference systems should also consider the following factors:

- The operational needs/performance requirements of SoS are difficult to allocate to independent systems and their subsystems.
- Certain interactions between systems cannot be predicted in advance, and degradation may occur when independent systems are combined together.
- The allocation of operational needs and performance requirements for SoS may evolve over time.

Usually, program managers at both SoS level and the component system level are required to perform their respective roles, responsible for identifying CTE at the corresponding level, and conducting close communication and collaboration to determine common system level requirements and specific system technologies required. A certain technology of the system may not be the CTE of the system itself, but may become a CTE when the system is incorporated into the SoS. On the contrary, a certain system specific CTE may not be the CTE of the SoS, for example, the advanced armor technology of tank system in Future Combat Systems (FCS) is not the CTE of FCS. The list of CTEs should distinguish between common technologies of SoS and technologies unique to specific systems. If a technology is needed to enable the system to meet the key performance parameters (KPP)/operational requirements of the SoS, it should be included in the SoS CTE list.

Firstly, construct a list of SoS systems and a TBS, providing all components of the SoS, clarifying the scope, functional performance, operational environment, and interrelationships of each system. Based on this, construct the TBS of each system, and synthetize to form the TBS of the SoS as shown in Figure 5.

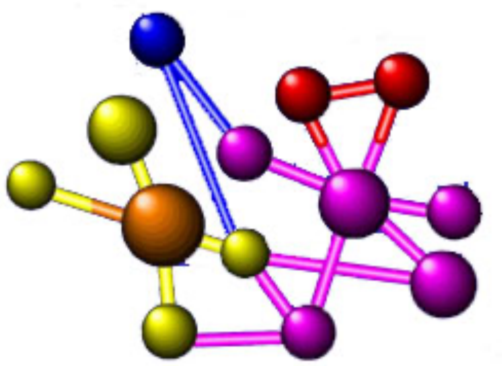

Figure 3 – Technology breakdown structure for SoS

Secondly, the interoperability between systems in SoS is analyzed, which refers to the provision and reception of services from other systems, units, or forces. Through the exchange of these services enable them to operate effectively together. Interoperability is very common in SoS, for example, mission planning systems can be based on external intelligence data, or the air defense missile system will normally rely on radar. Interoperable systems can independently perform functions, while interrupting service flow (workflow) can cause significant loss of functionality.

Thirdly, identify CTEs using the checklist. The CTEs related to systems and SoS should be considered from at least three perspectives: operational view, systems view and technical standards view. Here operational view focus on operation, including KPPs and concept of operation. Systems view focus on system architecture and functional architecture, the system architecture should clarify the boundaries and scope of key performance parameters, while the functional architecture should focus on the comprehensive integration level of functions (systems, subsystems, etc.). The technical architecture mainly considers how to achieve the functional and performance requirements of the system from a technical perspective, involving technical standards and protocols. As shown in Figure 6 [8].

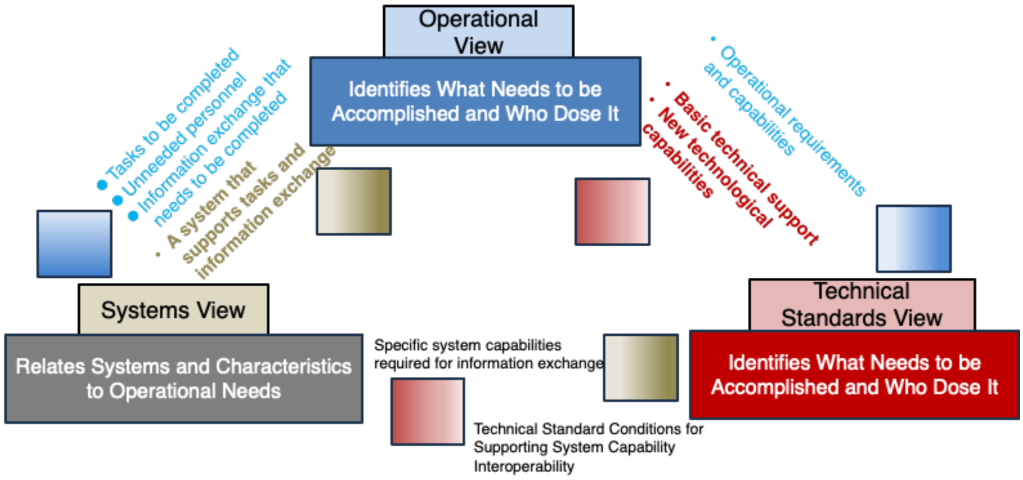

Figure 4 – Application of architecture framework in SoS

Finally, establish a mapping relationship between each CTE and the KPPs of the operational architecture, system architecture, and physical architecture, and then combine interoperability analysis with requirements in physical environment, data environment, logical environment, user environment, etc., carefully examine each item to determine the final list of CTEs.

4.3.2 Evaluation for Critical Technology Elements

The Evaluation for CTEs includes evaluation for CTEs for SoS and systems according to the TRL definition and assessment criteria, which usually divided into two steps. Firstly, decoupling various systems in the SoS, evaluating the unique CTEs of each system according to current methods by an independent expert group. The final TRL for CTEs is scored after initial evaluation by TRL definition and detailed evaluation by TRL assessment criteria and basic data. Secondly, regarding the CTEs at the SoS level, the focus is on interoperability and validation work in the integrated environment. It is recommended to evaluate with a focus on analyzing the technical status and risks of various CTEs in the SoS from two aspects: interoperability analysis, technical challenges and system challenges faced.

The following principles should usually be followed [2-3]:

- In any case, it is necessary to consider that a certain capability in one system depends on a certain technology in another system.
- When selecting CTEs for SoS, all completed and ongoing system TRAs should be considered;
- When the CTEs environment of a certain system is not dependent on any other system in the SoS, it should be evaluated according to the system's TRA method.

5. Case Studies for System of Systems

5.1 Background

The FCS of the US Army was once considered a core project in the modernization transformation of the US Army, and is the largest acquisition program. It includes 14 major systems, other enabling systems, and an upper layer network for providing information advantage and survivability [2-3]. The FCS program initialized in 1999 and was ultimately cancelled in June 2009 due to various reasons and multiple adjustments. The Government Accounting Office (GAO) have conducted evaluation for FCS since 2005, identifying and evaluating immature critical technologies, implementing technology maturity plans to promote their maturity and monitor the program risk.

5.2 CTE Identification

According to its Work Breakdown Structure (WBS), 54 CTEs have been identified in the FCS, including joint interoperability, network combat commands, etc. Due to unstable requirements and architecture definitions, the list of these CTEs has been constantly changing. The number of CTEs increased from 31 when first evaluated in 2003 to 55 in 2004, and to 49 in 2005. Most of these CTEs are related to KPP/operations, such as light and heavy oil engines, signal management, etc., while others are related to SoS interoperability, including joint tactical radio systems, combat personnel information, and interfaces and information exchange [9-12].

In the process of advancing the FCS project, the continuous changes in CTEs are mainly due to the following reasons:

- The first is the difficulty for technology readiness assessment due to the complexity of FCS, which includes a large scale and highly complex systems and involves 14 types of systems such as multiple manned/unmanned subsystems. Each individual weapon system can be divided into several deferent subsystems, which takes a huge challenge for identifying and evaluating CTEs.
- Secondly, the FCS is formed to a SoS through connecting numerous discrete systems with each other, which is also one of the biggest risk sources for itself. The network system of FCS will ultimately be integrated into the Global Information Grid. Among the 14 systems, the integrated common combat environment, communication and computer systems, combat command software, and ISR system are four key modules. In addition, logistics and training systems will also be embedded, and compared to independent systems, technological uncertainty is greater.
- Thirdly, the operational requirements of FCS are extremely complex, posing great challenges for development risk management. According to the FCS Operations Manual developed by the US Army and major system contractors in 2004, FCS is divided into 7 categories with 544 operational requirements and 11697 specialized requirements, with over 90 thousand specific requirements for each subsystem. The large and complex number of operational requirements, corresponding to different KPPs, also brings difficulties to the risk identification and evaluation of CTEs.

Here, both SoS level CTEs such as joint interoperability and system level CTEs such as high-power density/fuel efficiency thrusters, light and heavy oil engines, as well as computer force generation, tactical combat simulation, and training related technologies were identified.

5.3 CTE Evaluation

Between 2004 and 2010, the FCS conducted four technology readiness assessment [9-12], and the changes in the technology maturity of some CTEs over time are shown in Table 6

Table 6 – Technology readiness level over time for FCS CTEs (partially)

No.	CTEs	2004	2005	2009
1	JTS-GMR	5	5	5
2	WIN-T Software Radio	5	5	6
3	Cross Domain Guarding Solutions	3	4	6
4	MANET Protocols	5	5	5
5	Decision Aids/Intelligent Agents	6	6	6
6	Dynamic Sensor-Shooter pairing Algos and Fire Control	5.5	5.5	6
7	Precision Munition Guidance--PGMM	5	5	X
8	Distributive Collaboration of UGVs	5	5	6
9	High Power Density Engine	5	4.5	6
10	Fuel-Efficient hybrid Electric Propulsion	6	6	6

Among the 55 Critical Technology Elements (later reduced to 44), 35 CTEs are gradually maturing, reaching at least TRL6. The other CTEs were not yet mature as of 2009, and even 7 CTEs experienced a decrease in TRL in 2008.

6. Conclusions

For the technology readiness assessment for System of Systems, a comprehensive analysis is conducted with technology risk identification and evaluation, and some suggestions are given in this paper:

(1) The technology risk evaluation usually takes into account both individual system and SoS. it is recommended to adopt the traditional process of four steps: technology risk identification, technology risk analysis, technology risk evaluation, and technology risk mitigation. The main difference between methodology in system and SoS lies in the specific evaluation methods. The evaluation methods for individual system are relatively mature, and the commonly used method is the technology readiness assessment based on TRL; The evaluation method of SoS can refer to the technology risk assessment method of individual system, fully considering the identification of new technology risk sources brought about by the integration of various systems in the SoS, as well as the validation environment and validation activities of these risk sources.

(2) Using technology readiness assessment methods as the main tool to carry out technology risk assessment of weapon systems. The various stages in the technology maturity evaluation method also correspond to the universal process of risk assessment. According to the risk assessment process, different methods are selected in each stage. In the risk identification stage, the CTE method is proposed in the technology maturity evaluation. Firstly, a technology breakdown structure is constructed, and then CTEs are identified and a list of CTEs is determined by analyzing each technology elements; Risk analysis and grading process, using technology maturity evaluation to provide the technology readiness level of CTEs, and converting the level of technical risk; In the risk mitigation phase, a technology mature plan method is adopted to develop a risk mitigation plan.

(3) The methodology for evaluating the technology maturity of SoS has currently formed a basic framework and has been validated through examples of weapon systems represented by Future Combat Systems. However, there are still many areas worth further deepening research in order to improve the methodology. Firstly, further considering the differences between SE and SoSE, designing a more complete evaluation model and overall framework; Secondly, fully considering the characteristics of the SoS, improve evaluation standards and processes; Finally, improving the evaluation method of SoS technology maturity through continuous practices continuously.

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8. Copyright Statement

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