SoS Systems Engineering (SE) and Test & Evaluation (T&E)

Final Report of the NDIA SE Division SoS SE and T&E Committees

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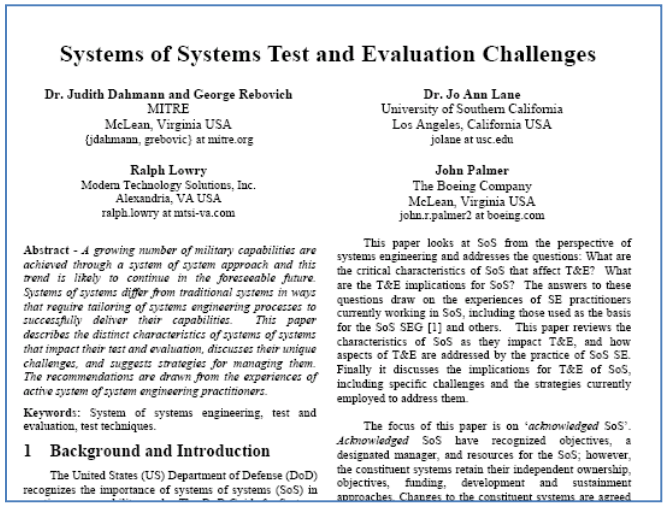
Abstract

This report presents an approach to integrated systems engineering (SE) and test and evaluation (T&E) for SoS based on work underway by the National Defense Industry Association Systems Engineering Division Systems of Systems and Developmental Test and Evaluation Committees. The report focuses on how to approach T&E for SoS given the challenges of large scale SoS development as a continuous improvement process that provides information on capabilities and limitations for end users and feedback to the SoS and system SE teams toward SoS evolution.

Task

- NDIA Strategic Initiative: Best Practices Model for SoS T&E
  - Product of one-day facilitated SoS and T&E Workshop sponsored by NDIA SoS SE and DTE committees, held August 17, 2010, MITRE, McLean VA
  - Adopted by NDIA SoS SE Committee to work with T&E Committee to address this as a 2011 action
  - Purpose: Outline the fundamentals of the model of SoS T&E as a:

"Continuous improvement process supporting capabilities and limitations information for end users and feedback to the SoS and system SE teams toward evolution of the SoS"



Systems of Systems Test and Evaluation Challenges

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Abstract - *A growing number of military capabilities are achieved through a system of system approach and this trend is likely to continue in the foreseeable future. Systems of systems differ from traditional systems in ways that require tailoring of systems engineering processes to successfully deliver their capabilities. This paper describes the distinct characteristics of systems of systems that impact their test and evaluation, discusses their unique challenges, and suggests strategies for managing them. The recommendations are drawn from the experiences of active system of system engineering practitioners.*

Keywords: System of systems engineering, test and evaluation, test techniques.

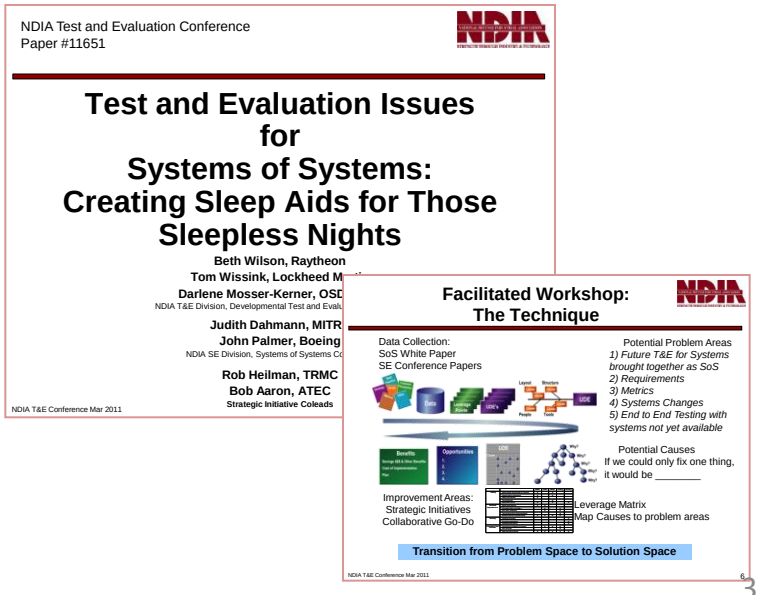
1 Background and Introduction

The United States (US) Department of Defense (DoD) recognizes the importance of systems of systems (SoS) in

This paper looks at SoS from the perspective of systems engineering and addresses the questions: What are the critical characteristics of SoS that affect T&E? What are the T&E implications for SoS? The answers to these questions draw on the experiences of SE practitioners currently working in SoS, including those used as the basis for the SoS SEG [1] and others. This paper reviews the characteristics of SoS as they impact T&E, and how aspects of T&E are addressed by the practice of SoS SE. Finally it discusses the implications for T&E of SoS, including specific challenges and the strategies currently employed to address them.

The focus of this paper is on '*acknowledged* SoS'. *Acknowledged* SoS have recognized objectives, a designated manager, and resources for the SoS; however, the constituent systems retain their independent ownership, objectives, funding, development and sustainment approaches. Changes to the constituent systems are agreed

2010 IEEE SoSE Conference



NDIA Test and Evaluation Conference
Paper #11651

Test and Evaluation Issues for Systems of Systems: Creating Sleep Aids for Those Sleepless Nights

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NDIA T&E Conference Mar 2011

Facilitated Workshop: The Technique

Data Collection:
SoS White Paper
SE Conference Papers

Potential Problem Areas
1) Future T&E for Systems brought together as SoS
2) Requirements
3) Metrics
4) Systems Changes
5) End to End Testing with systems not yet available

Potential Causes
If we could only fix one thing, it would be _____

Improvement Areas:
Strategic Initiatives
Collaborative Go-Do

Leverage Matrix
Map Causes to problem areas

Transition from Problem Space to Solution Space

NDIA T&E Conference Mar 2011

SoS Definition, Types and Domains

SoS: A set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities

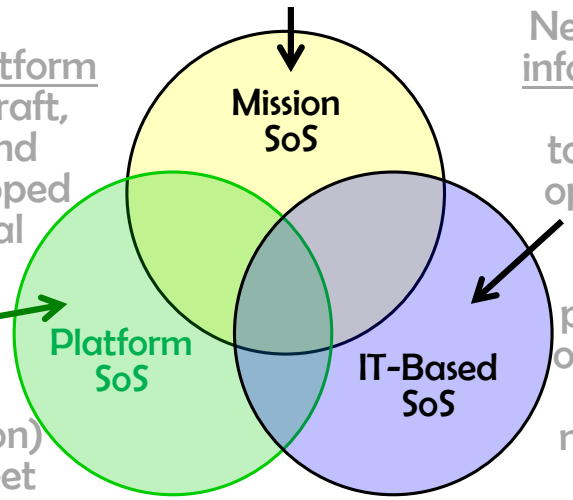
Types of SoS

- Directed: SoS objectives, management, funding and authority; systems are subordinated to SoS
- **Acknowledged: SoS objectives, management, funding and authority; however systems retain their own management, funding and authority in parallel with the SoS**
- Collaborative: No top down objectives, management, authority, responsibility, or funding at the SoS level; Systems voluntarily work together to address shared or common interest
- Virtual: Like collaborative, but systems don't know about each other

SoS Domains

Sets of systems working together to provide a broader capability or mission

A military platform (e.g. ship, aircraft, satellite, ground vehicle) equipped with additional independent systems (e.g. sensor, weapons communication) needed to meet platform objectives



Networked information systems to support operations within or across platforms or systems to meet mission or platform objectives

Model focuses on Acknowledged Mission Level SoS

Comparing Systems and SoS

	System	Acknowledged System of Systems
Management & Oversight		
Stakeholder Involvement	Clearer set of stakeholders	Two levels of stakeholders with mixed possibly competing interests
Governance	Aligned PM and funding	Added levels of complexity due to management and funding for both SoS and systems; SoS does not have control over over all constituent systems
Operational Environment		
Operational Focus	Designed and developed to meet operational objectives	Called upon to meet operational objectives using systems whose objectives may or may not align with the SoS system's objectives
Implementation		
Acquisition	Aligned to established acquisition processes	Cross multiple system lifecycles across acquisition programs, involving legacy systems, developmental systems, and technology insertion; Capability objectives but may not have formal requirements
Test & Evaluation	Test and evaluation the system is possible	Testing more challenging due systems' asynchronous life cycles and given the complexity of all the moving parts
Engineering & Design Considerations		
Boundaries & Interfaces	Focuses on boundaries and interfaces	Focus on identifying systems contributing to SoS objectives and enabling the flow of data, control and functionality across the SoS while balancing needs of the systems
Performance & Behavior	Performance of the system to meet performance objectives	Performance across the SoS that satisfies SoS user capability needs while balancing needs of the systems

Reference: US DoD Guide for Systems Engineering of Systems of Systems

T&E Implications

Validation criteria more difficult to establish

Cannot explicitly impose SoS conditions on system T&E

System level operational objectives may not have clear analog in SoS conditions that need T&E

Depends on constituent system test of SoS requirements as well as SoS level

Difficult to bring multiple systems together for T&E in synchrony with capability evolution

Additional test points needed to confirm behavior

Increased subjectivity in assessing behavior, given challenges of system alignment

SoS SE as the Framework for SoS T&E

- Effective application of SE at the SoS level provides a structured framework to address SoS T&E challenges
  - Approaches to managing asynchronous system development and test
  - Architecture approaches which shelter the SoS from changes in systems
- Effective T&E is grounded in a clear understanding of objectives and requirements of the 'test item'
  - The value of an SoS is accrued from the collective behavior of the SoS toward user capabilities
  - Systems engineering conducted at the SoS level provides the basis for T&E
  - DoD SoS SE Guide, SoS SE artifacts and wave model provide fundamentals of SoS SE for DoD

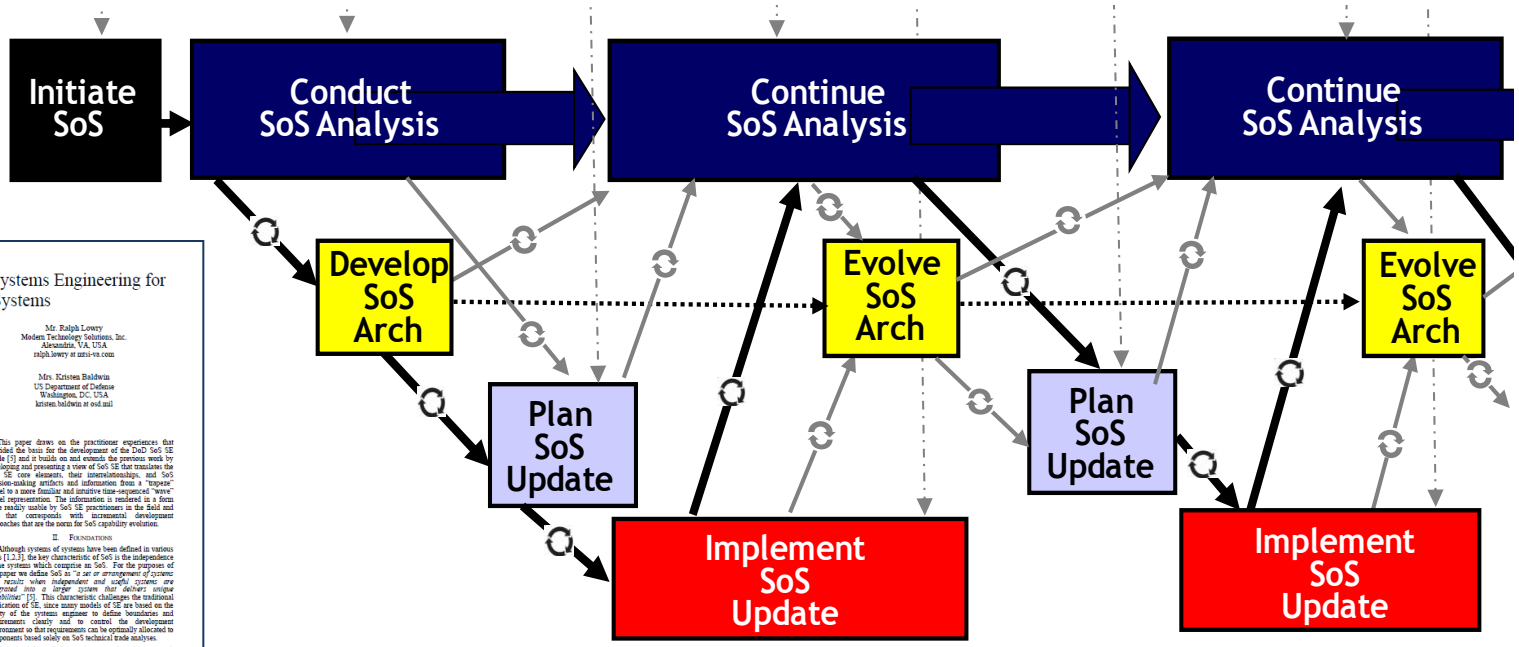
SoS SE and SoS T&E share key common elements
It can be difficult to tell where SoS SE stops and SoS T&E begins

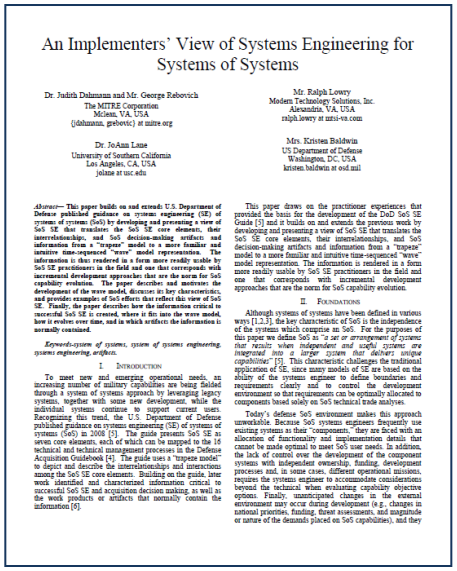
Aspects of 'T&E' for SoS

- SE and T&E To Support SoS Evolution
  - Address risk of changes in constituent systems including this planned for support of the SoS objectives and those planned by the constituent systems independently from the SoS
  - Can be viewed as SoS Verification and Validation (V&V)
  - Done as part of the SoS evolution, not as a separate process
- T&E Feedback on Fielded SoS
  - Assess overall performance and identify operational problems and 'emergent' (unexpected) behavior
  - Typically draws on data from operationally realistic environments
  - May be periodic and not tied directly to SoS update cycles
- SoS T&E is also needed when testing individual systems in an SoS context
  - This approach may apply there as well, but the focus at the SoS level

Focus here is on T&E Support to SoS Evolution

Wave Model: Framework for Model





An Implementers' View of Systems Engineering for Systems of Systems

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Abstract— This paper builds on and extends U.S. Department of Defense published guidance on systems engineering (SE) of systems of systems (SoS) by developing and presenting a view of SoS SE that translates the SoS SE core elements, their interrelationships, and SoS decision-making artifacts and information from a "trapeze" model to a more familiar and intuitive time-sequenced "wave" model representation. The information is thus rendered in a form more readily usable by SoS SE practitioners in the field and one that corresponds with incremental development approaches that are the norm for SoS capability evolution. The paper describes and motivates the development of the wave model, discusses its key characteristics, and provides examples of SoS efforts that reflect this view of SoS SE. Finally, the paper describes how the information critical to successful SoS SE is created, where it fits into the wave model, how it evolves over time, and in which artifacts the information is normally contained.

Keywords—system of systems, system of systems engineering, systems engineering, artifacts.

I. Introduction

To meet new and emerging operational needs, an increasing number of military capabilities are being fielded through a system of systems approach by leveraging legacy systems, together with some new development, while the individual systems continue to support current users. Recognizing this trend, the U.S. Department of Defense published guidance on systems engineering (SE) of systems of systems (SoS) in 2008 [5]. The guide presents SoS SE as seven core elements, each of which can be mapped to the 16 technical and technical management processes in the Defense Acquisition Guidebook [4]. The guide uses a "trapeze model" to depict and describe the interrelationships and interactions among the SoS SE core elements. Building on the guide, later work identified and characterized information critical to successful SoS SE and acquisition decision making, as well as the work products or artifacts that normally contain the information [6].

This paper draws on the practitioner experiences that provided the basis for the development of the DoD SoS SE Guide [5] and it builds on and extends the previous work by developing and presenting a view of SoS SE that translates the SoS SE core elements, their interrelationships, and SoS decision-making artifacts and information from a "trapeze" model to a more familiar and intuitive time-sequenced "wave" model representation. The information is rendered in a form more readily usable by SoS SE practitioners in the field and one that corresponds with incremental development approaches that are the norm for SoS capability evolution.

II. Foundations

Although systems of systems have been defined in various ways [1,2,3], the key characteristic of SoS is the independence of the systems which comprise an SoS. For the purposes of this paper we define SoS as *"a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities"* [5]. This characteristic challenges the traditional application of SE, since many models of SE are based on the ability of the systems engineer to define boundaries and requirements clearly and to control the development environment so that requirements can be optimally allocated to components based solely on SoS technical trade analyses.

Today's defense SoS environment makes this approach unworkable. Because SoS systems engineers frequently use existing systems as their "components," they are faced with an allocation of functionality and implementation details that cannot be made optimal to meet SoS user needs. In addition, the lack of control over the development of the component systems with independent ownership, funding, development processes and, in some cases, different operational missions, requires the systems engineer to accommodate considerations beyond the technical when evaluating capability objective options. Finally, unanticipated changes in the external environment may occur during development (e.g., changes in national priorities, funding, threat assessments, and magnitude or nature of the demands placed on SoS capabilities), and they

An implementer's view of SoS SE

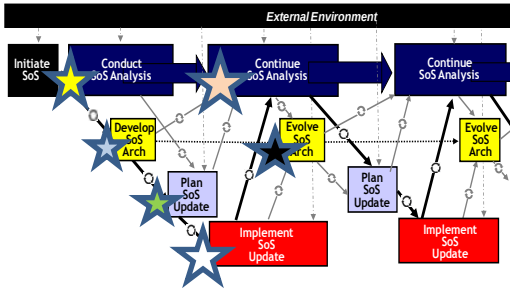
- More familiar and intuitive time-sequenced "wave" model representation
- Information is thus rendered in a form more readily usable by SoS SE practitioners in the field
- Representation that corresponds with incremental development approaches that are the norm for SoS capability evolution

Presented at
IEEE Systems Conference
April 2011 [1]

[1] "An Implementers View of Systems of Systems" Dahmann, Baldwin, Rebovich, Lane and Lowry

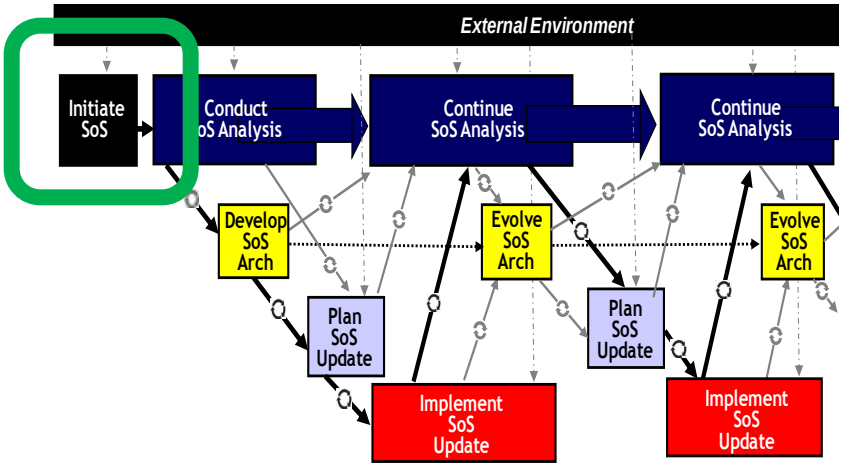
Concept of Wave Planning was developed by Dr. David Dombkins See "Complex Project Management" Booksurge Publishing, South Carolina: 2007.

SoS SE and T&E Evolution at Each Step

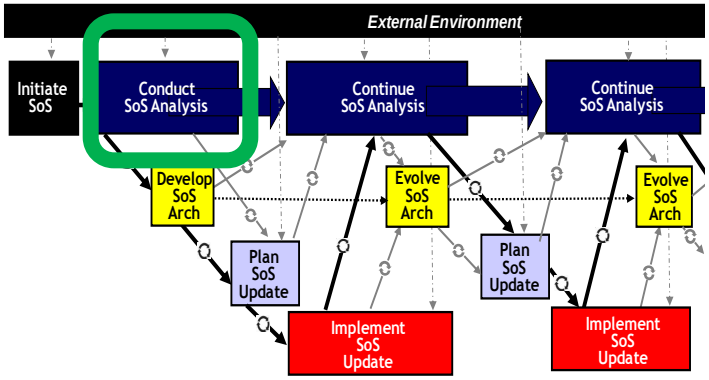


- Recognize SoS T&E constraints
  - Full SoS T&E to address changes in constituent systems is not feasible given the size and complexity of many SoS and the dynamic nature of constituent systems
    - Includes conventional live testing and approaches using various forms of virtual and constructive simulation
- Focus T&E specifically on areas of risk
  - Begin with the changes which have been made in the SoS
  - Identify where changes could have adverse impacts on the user missions
  - Assess the risk using evidence from a range of sources including live test
    - Evidence can be based on activity at the SoS level, as well as roll-ups of system level activity and can be explicit verification testing, results of models and simulations, use of linked integration facilities, and results of system level operational test and evaluation
- Results 'Continuous improvement' feedback to
  - End users in the form of 'capabilities and limitations' rather than as test criteria for SoS 'deployment'
  - SE teams of both the SoS and systems on progress and issues

Approach Assumes "Initiation" of an Acknowledged SoS



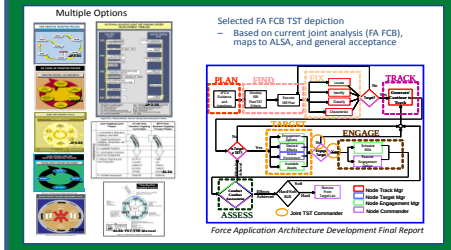
- Decision has been made to establish an SoS SE organization
  - An entity is responsible for the SoS with SE support to the SoS
  - As an acknowledged SoS, the systems which constitute the SoS maintain operational and management independence
- At the initiation of an SoS, the information typically available includes initial or first order
  - Statement of top-level objectives for the SoS (SoS capability objectives)
  - Description of how systems in the SoS will be employed in an operational setting (SoS CONOPS) and
  - Programmatic and technical information about systems that affect SoS capability objectives (systems information)
  - Risks are identified when an SoS is launched and mitigation actions are tracked and updated throughout each cycle, along with new risks (Risks and Mitigations)



SoS SE: Conduct SoS Analysis

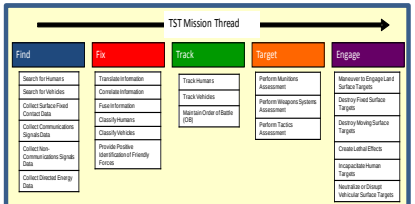
Provides analysis of the 'as is' and basis for SoS evolution

CONOPs



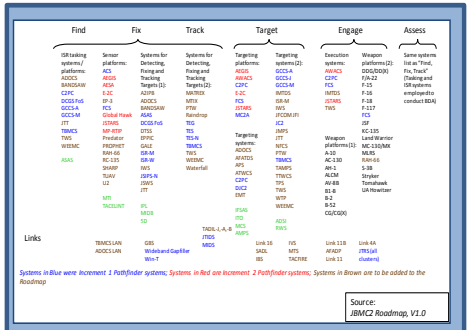
Understand operational context and developing a CONOPS -- Includes key steps in process and constraints on those steps; may be a set of mission threads, conditions, players and performance objectives

Functional Baseline



Layout the specific tasks for each component of the activity sequence to further delineate the functionality supporting the E2E capability objective

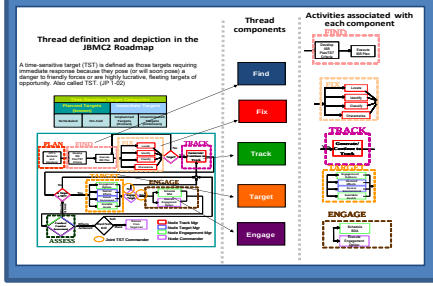
Current System Baseline



Identify systems supporting the capability objectives and align them to the components and functionality needs, with data on current performance

SoS Analysis

Requirements Space



Develop an 'functional architecture' for the SoS by looking at the key functions to be supported across the 'thread' or activity sequence, including performance objectives

Results provide basis for architecture development and planning for SoS updates

SoS SE Artifacts

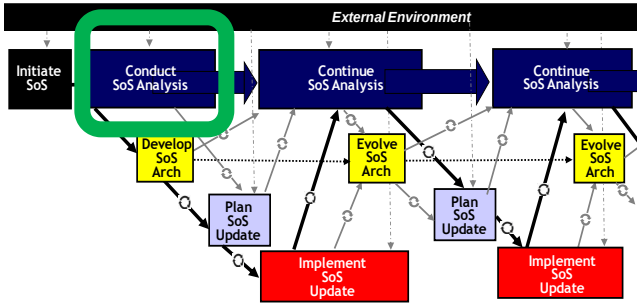
Characterize SoS

- Capability objectives
- SoS CONOPs
- Constituent system info
- SoS Technical Baselines
- SoS Performance Measures & Methods
- SoS Performance Data
- SoS Requirement Space
- SoS Risks & Mitigations

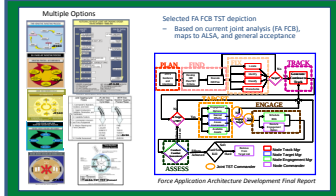
Plan for SoS SE

- SE Planning Elements
- SoS Master Plan
- Agreements

T&E Component of SoS Analysis



CONOPs



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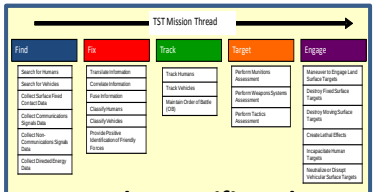
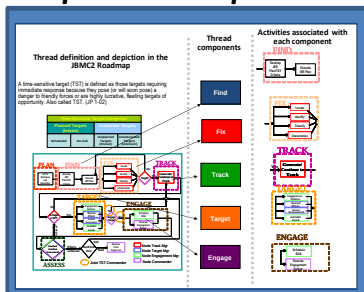


Layout the specific tasks for each component of the activity sequence to further delineate the functionality supporting the E2E capability objective

Requirements Space



Develop an 'functional architecture' for the SoS by looking at the key functions to be supported across the 'thread' or activity sequence, including performance objectives

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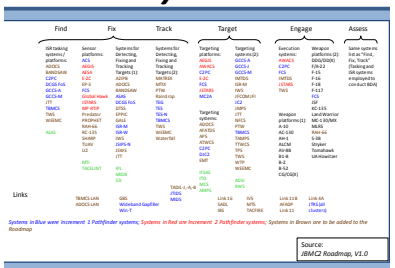


Identify systems supporting the capability objectives and align them to the components and functionality needs, with data o current performance

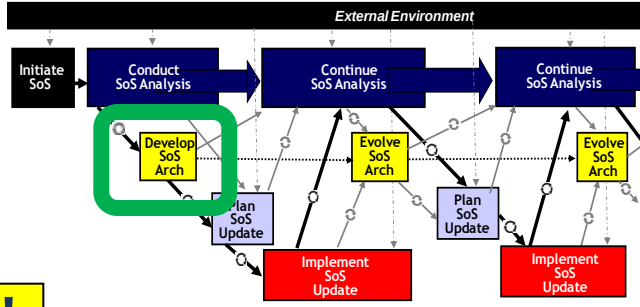
CONOPs, mission threads and tasks are all needed elements for structuring test

Capability and performance objectives provide a foundation for T&E

- Systematic development and analysis of this data is core to SoS analysis and supports the development of the architecture, planning of updates
- Cases where more data is needed (and testing may be required) are identified

Understanding current system performance draws on available evidence from various sources, including systems T&E

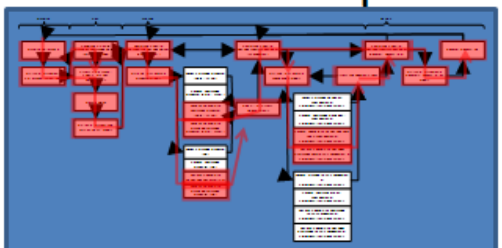
T&E foundations are established in SoS analysis which draws on T&E of fielded systems



SoS SE: Develop SoS Architecture

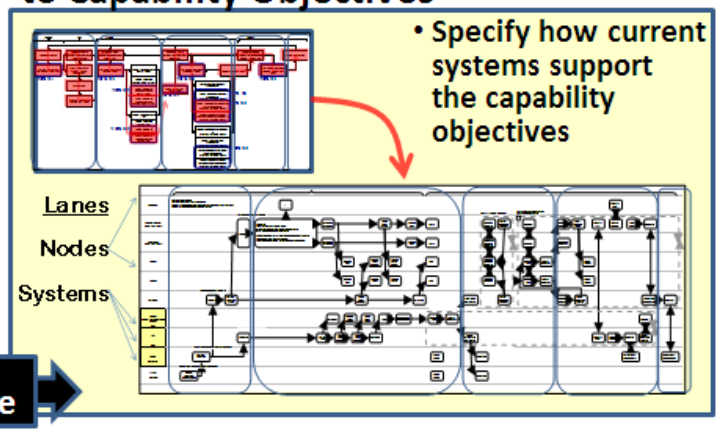
Develops and evolves the persistent technical framework for addressing SoS evolution

Delineate E2E SoS Capabilities



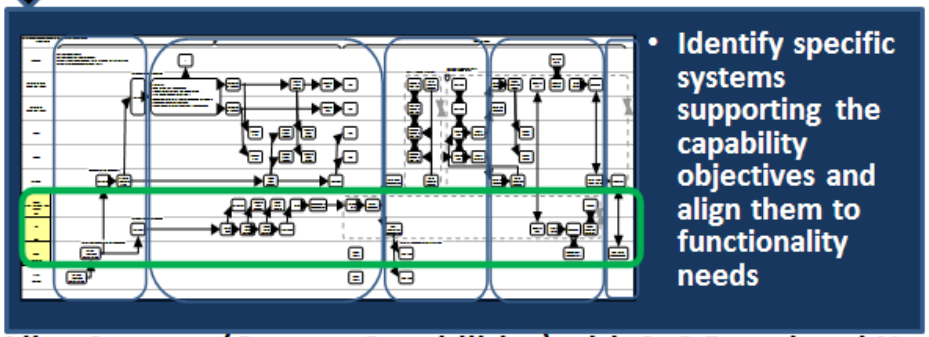
- Each mission plan / CONOPS / COA describes a path through the various steps in the mission

Identify Systems Contributing to Capability Objectives



SoS Architecture

Identify and evaluate alternative approaches to organizing and augmenting systems to meet SoS needs



Align Systems (Current Capabilities) with SoS Functional Needs

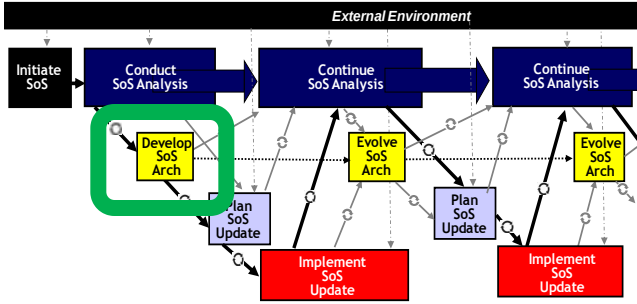
SoS SE Artifact

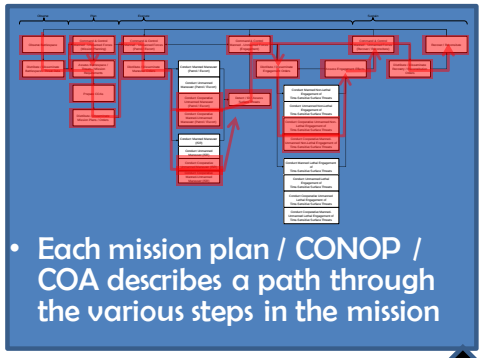
- SoS Architecture

Defines the way in which the constituent systems work together

Includes systems, SoS functions, relationships and dependencies, as well as end-to-end functionality, data flow & communications

T&E Component of SoS Architecture





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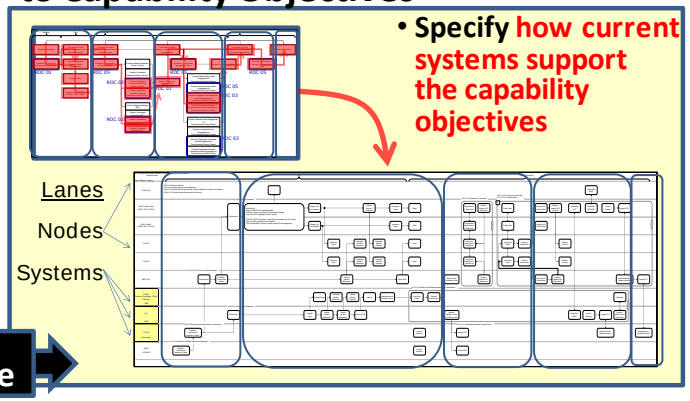
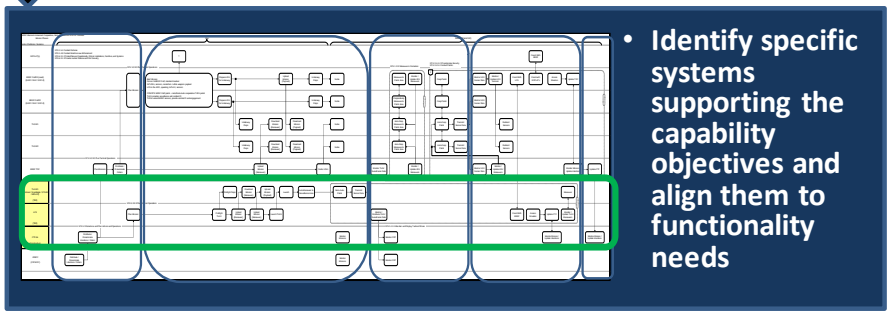


SoS Architecture

Identify and evaluate alternative approaches to organizing and augmenting systems to meet SoS needs



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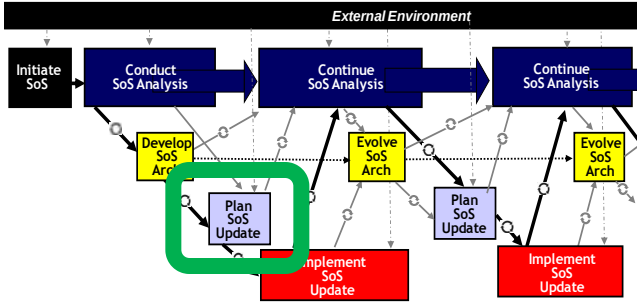
Data on attributes and performance of systems (typically drawn from system T&E) is key to identification and analysis of architecture approaches

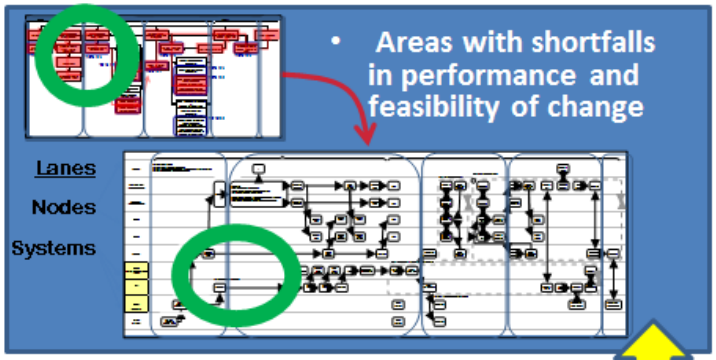
T&E contributes to the assessment of alternative architectures through application of various approaches including LVC environments to assess alternatives against desired architecture objectives

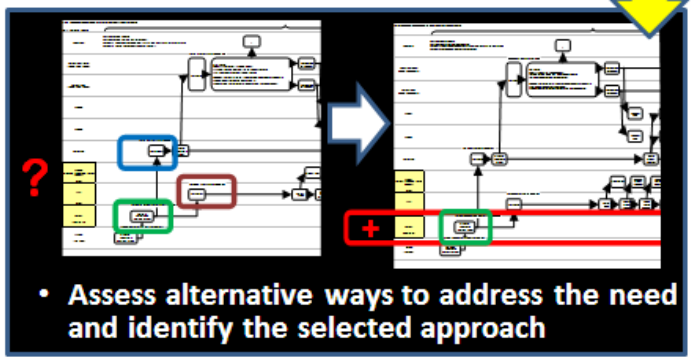
SoSE: Plan SoS Update



Evaluates the SoS priorities, options and backlogs to define the plan for the next SoS upgrade cycle.

Identify Needs to be Addressed in this Wave



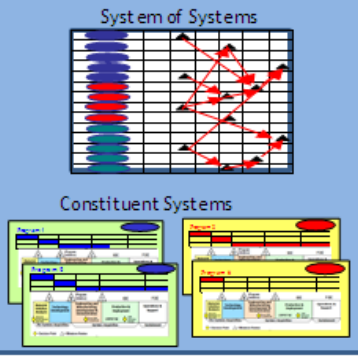


Evaluate Options for Addressing Needs

Plans for System and SoS Development, Integration and Test

SoS
- Integrated Master Schedule (Key sync points (not aggregation of plans)
- Risks and Mitigation Plans
- SoS changes and dependencies which drive testing

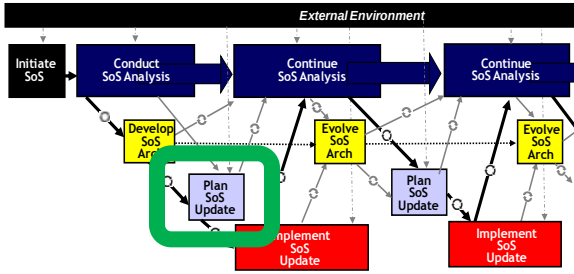
Systems
- Additions to system plans for development and test



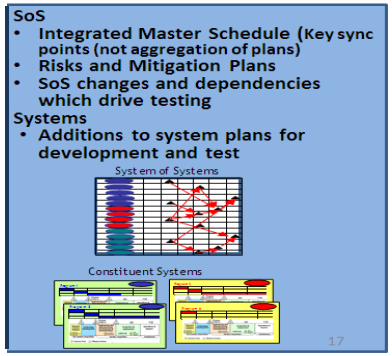
Artifacts

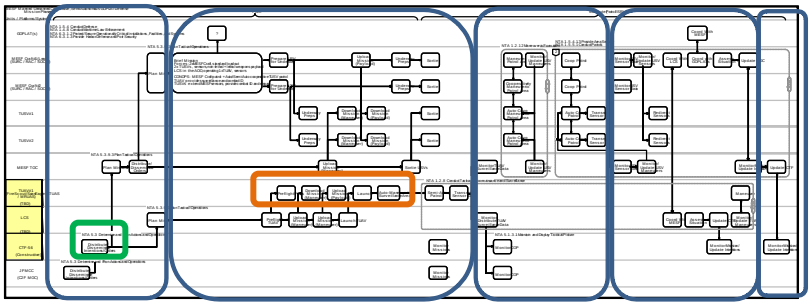
- An allocated baseline
- Risks and mitigations
- Agreements
- Implementation, integration & test plans
- An integrated master schedule (IMS)
- Updated
  - Master Plan,
  - Technical baselines
  - Requirements space

T&E Component of Plan SoS Update



Plans for System and SoS Development, Integration and Test



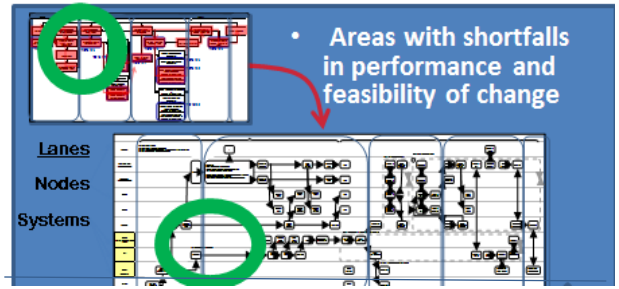


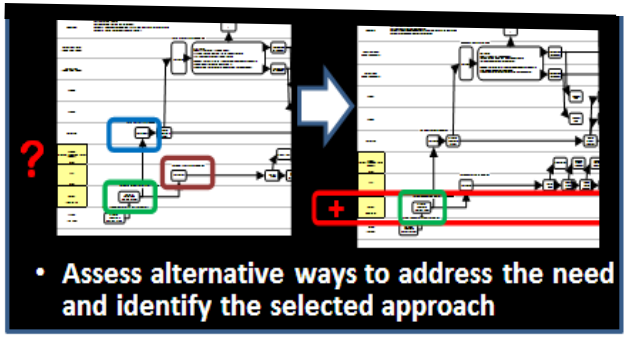
Analysis of Impacts of Changes

A critical part of planning an SoS update is the analysis of changes and risks to identify the areas to be addressed by T&E

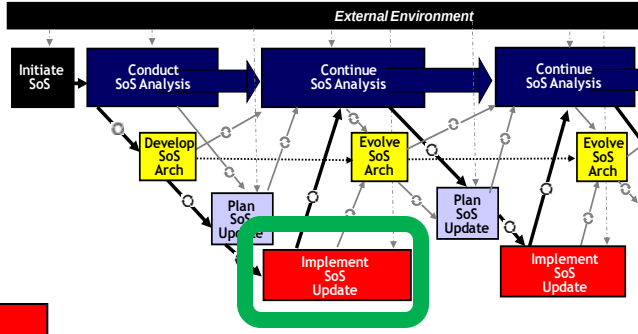
- Changes in the SoS are identified (both planned by the SoS and planned independently by the constituents)
  - What are the potential impacts of these changes? What are the risks?
  - What evidence is there that these changes will not adversely impact other systems and mission objectives?
- What data is needed and how can this data be obtained?
  - Can this be done as part of the system tests?
  - Are added test events needed?
  - How are these incorporated into the overall plan and IMS?
- What testing tools and environments are needed to address the specific challenges?
  - Test drivers to address asynchronous development?
  - Use of Live, Virtual and Constructive (LVC) environments to address specific risks?

Identify Needs to be Addressed in this Wave





Evaluate Options for Addressing Needs



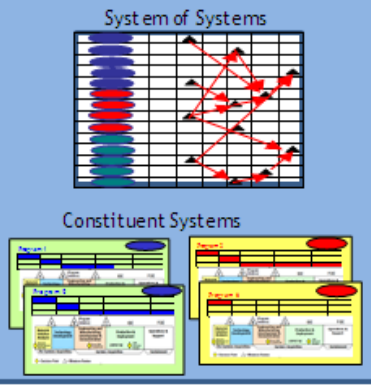
SoS SE: Implement SoS Update

Monitors implementations at the system level and plans and conducts SoS level testing, resulting in a new SoS product baseline

Monitor System and SoS Development, Integration and Test

SoS
- Integrated Master Schedule (Key sync points, not aggregation of plans)
- Risks and Mitigation Plans
- SoS changes and dependencies which drive testing

Systems
- Additions to system plans for development and test



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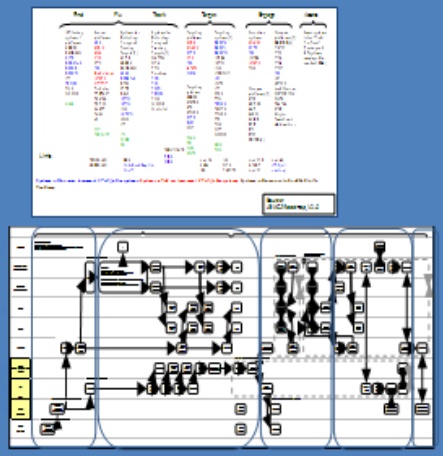
Review Progress And Inform Users and SE Process

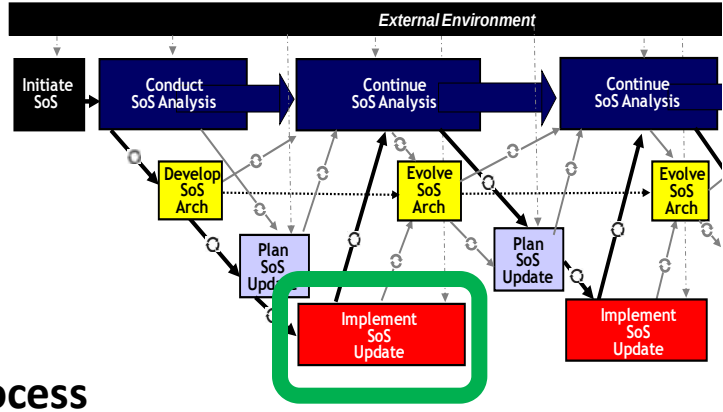
- Collect and assess data from system and SoS development technical reviews and tests
- Update product baseline, architecture, performance assessments, and requirements space
- Provide input into 'Continue SoS Analysis'



SoS Artifacts

- SoS Test Report
  - SoS Technical Plans, Requirements Space, Performance Data
  - System Test Reports
- SoS IMS
- SoS Technical Baselines

T&E Component of Implement Update



Monitor System and SoS Development, Integration and Test

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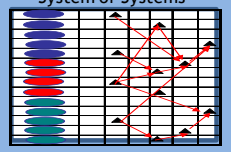
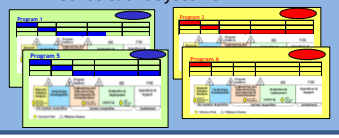
System of Systems



Constituent Systems



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Review Progress And Inform Users and SE Process

- Collect and assess data from system and SoS development technical reviews and tests
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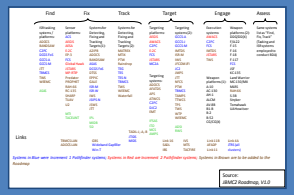
- Provide input into 'Continue SoS Analysis'



- T&E is a key part of implementation for both the SoS and the systems
- Systems making updates conduct T&E at the system level

- SoS level T&E activities include
  - Monitoring implementation of system testing, conducting added testing to address SoS risks, and evaluating the results, recommending changes in plans as needed
- Results of the SoS capability are identified (both planned and unplanned)
  - Does performance meet expectations for this increment? What are the potential impacts on the next increment? What are the risks?
  - What evidence is there that these changes will need to be regression tested in the next increment?

Summary and Next Steps

- Key elements of the approach to SoS SE and T&E
  - Addresses the key challenges facing T&E in an SoS environment – complexity, system independence and asynchronous development
  - Integrates T&E with SE throughout the evolution of an SoS based on the SoS 'wave model' – T&E contributes to all steps in the evolution
  - Focuses T&E on risks to systems and SoS – recognizing full end to end testing with each system change is intractable
  - Emphasizes use range of information types to address these risks
- Presentation is the product of the 2011 joint task of the NDIA SoS SE and T&E committees
  - Represents initial product in this area
  - Open areas and considerations for next steps