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A Systems Thinking Approach to Engineering Challenges of Military Systems-of-Systems

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Joint & Operations Analysis Division
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Updated version - minor errors corrected

ABSTRACT

Systems-of-Systems (SoS) are broadly acknowledged as an engineering challenge for defence organisations, due to high complexity of various military SoS and their development processes. Inadequate understanding of SoS problems and inability to manage complexity encountered in planning, development and operation of multiple interdependent SoS can undermine not only performance and effectiveness of engineering practice and development activities, but also quality of their products and outcomes. This report introduces a systems thinking-based approach, SoS thinking, which offers a language and a thoughtful process to conceptualise, understand, communicate about and assess military SoS. Based on the multidimensional thinking, high complexity of SoS problems can be explored and addressed through using a set of SoS lenses in a number of important aspects, including the problem space, diversity, interdependencies, design paradigm, development states and technical statuses. SoS thinking provides a foundation for further developments of adequate methods, metrics and solutions for SoS engineering practice.

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A Systems Thinking Approach to Engineering Challenges of Military Systems-of-Systems

Executive Summary

Systems-of-Systems (SoS) are broadly acknowledged as an engineering and management challenge for defence organisations, in particular in pursuing joint force integration and delivering integrated capabilities for network centric operations. Military SoS vary across Defence, ranging from information-based SoS, platform-based SoS, capability-based SoS, to operation-based SoS. The ubiquity of military SoS is a reality facing planning, analysis, development and operation of modern defence force and capabilities. Inadequate understanding of SoS problems and inability to effectively manage the complexity of multiple interdependent SoS can undermine performance and effectiveness of architectural approaches, systems engineering practice and development activities. This also results in problems and quality issues of products and outcomes generated in force design and integrated capability development. The high complexity of military SoS directly contributes to major cost and schedule overruns in development, acquisition and operation of integrated systems and capabilities.

In many areas within Defence, there is often a collection of interdependent human-cyber-physical systems or SoS to be dealt with in various changing technical and operational contexts. Concurrent and evolutionary developments and integration of such a collection of systems or SoS are challenging tasks, and can become chaotic if their interdependencies and interrelationships are not properly specified, engineered, and managed, or in a messy condition. Dealing with a messy collection of interdependent systems by different stakeholders or development activities with no adequate conceptualisation practice and contextualisation control is a serious problem of engineering and management that an organisation must address. The applications of traditional systems engineering practice and architectural approaches may become problematic or even fail if they are applied to such a messy collection of systems with no specific methods and tools.

Understanding the difference between a single SoS and a SoS problem space where there are multiple interdependent and interrelated military SoS is important. An inability to effectively conceptualise the SoS problem space or meaningfully and manageably identify the SoS is one of the underlying causes resulting in major problems in undertaking engineering activities and developing architectures involving multiple SoS.

The challenge of effectively designing and successfully delivering SoS is a reality facing the whole Defence. It requires clear guidance and a commonly agreed approach that can enable key stakeholders and professionals to systematically design adequate processes for joint force integration and capability development, and consistently deal with SoS challenges.

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The SoS thinking approach proposed in this report is an extension of systems thinking, specifically introduced as an enabler for tackling SoS problems. It offers a language and an approach to conceptualising, understanding, communicating about and assessing military SoS. It proposes a methodology to address the high complexity of SoS problems so that they can be contextualised, explored and addressed through using a set of SoS lenses in a number of important perspectives, including:

- awareness of a SoS problem space with its engineering factors
- SoS categorisation and identification
- SoS interdependencies
- SoS development states
- SoS technical statuses
- SoS design relevance and paradigm
- extended SoS community of practice.

SoS thinking offers a strategy and approach to establishing a systematic understanding of SoS, which, based on a set of SoS concepts associated with those perspectives, can be used to potentially address SoS engineering challenges. SoS thinking can be applied as a 7-step-based process to help SoS activities (from planning, analysis, design, development, integration, assessment, management to operation) and engineering practice. In particular, it enables practitioners to effectively conceptualise and manage a SoS problem space and avoid dealing with a messy collection of systems or SoS.

SoS thinking has the potential to help review and examine various problems and issues encountered in architecture and engineering practice. It can also provide a shared foundation for further developments of adequate methods, metrics, solutions and tools for SoS engineering practice. Further applications of SoS thinking can help address a number of important issues or tasks of military SoS development and management in a joint and coherent manner, including:

- categorisation-based SoS design (or architecture) requirement specifications
- development state-based SoS development control and management
- SoS thinking-based mission space (scenarios) and capability design management
- SoS identification and relationship-based SoS engineering artefacts management
- SoS identification and relationship-based SoS integration management and assessment
- SoS design and technical status assessment and management
- SoS identification and relationship-based SoS lifecycle management.

This research introduces SoS thinking with new SoS concepts, metrics and methods for Defence to use in its engineering practice for military SoS. In particular, it helps development activities achieve conceptualisation with theory, shared understanding, and consistent contextualisation in a SoS problem space. SoS Thinking provides approaches

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and potential solutions to facilitate Defence in developing adequate processes and guidance for joint force design and integrations of capabilities.

The challenge of military SoS requires an enhancement of professional skills in many areas in Defence to effectively understand and deal with various military SoS. SoS thinking is specifically developed to help defence stakeholders and professionals understand and communicate about SoS problems they face. The application of SoS thinking can potentially enhance the force design process and bring significant benefits to activities in planning, development and management of joint force integration and integrated capabilities. It also has the potential to help warfighters effectively understand complexity of various military SoS and improve their confidence in management and operation of SoS-based joint force and integrated capabilities.

The following recommendations are made in this report:

- Defence needs clear and authoritative guidance on effective use of the term, SoS, as part of relevant development or process guidance, in order to effectively address SoS challenges and get real benefits from relevant disciplines;
- Defence needs the best practice and innovative approaches in conceptualisation and contextualisation for its military SoS problems;
- Defence should establish the lifecycle management concept for military SoS in different categories, in order to achieve objectives and outcomes of force design and joint force integration with required interoperability;
- Defence should establish accountability management against military SoS in different categories for key stakeholders in different areas;
- Defence needs to develop and use adequate methods, solutions and tools for practices of SoS thinking and SoS engineering (SoSE); and
- Defence should develop and offer adequate training courses on SoS thinking and SoSE.

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Contents

1. INTRODUCTION.....	1
2. SOS ENGINEERING OVERVIEW.....	2
3. SOS THINKING	4
4. MILITARY SOS PROBLEM SPACES AND ENGINEERING FACTORS.....	7
5. SOS CATEGORISATION AND IDENTIFICATION.....	11
6. SOS INTERDEPENDENCIES	17
7. SOS DEVELOPMENT STATES AND TRANSITION PATHS	22
8. SOS TECHNICAL STATUSES.....	27
9. SOS DESIGN RELEVANCE AND PARADIGM.....	30
10. EXTENDED COMMUNITY OF PRACTICE (COP) FOR SOSE AND SOS ACTIVITIES.....	34
11. SOS THINKING APPROACH.....	36
12. APPLICATIONS OF SOS THINKING.....	38
13. FURTHER STUDIES AND RECOMMENDATIONS	42
14. CONCLUSIONS.....	43
REFERENCES	44

Glossary

AOC	Air Operation Centre
BMDS	Ballistic Missile Defence System
BMS	Battlespace Management systems
C2	Command and Control
C4ISR	Command, Control, Computer and Communications Intelligence Surveillance and Recognisance
CASG	Capability and Sustainment Group (formerly DMO)
CDG	Capability Development Group
CLC	Capability Life Cycle
CMS	Combat Management System
CONOPS	Concepts of Operation
CoP	Community of Practice
CIOG	Chief Information Officer Group
C_SoS	Capability-based SoS
DIE	Defence Information Environment
DMO	Defence Materiel Organisation (now CASG)
DoD	Department of Defence (US)
DST Group	Defence Science & Technology Group
ESE	Enterprise Systems Engineering
FCS	Future Combat System
IOCD	Integrating Operational Concept Document
IN	Integration Needs
INCOSE	International Council of Systems Engineering
IER	Information Exchange Requirements
ISR	Intelligence Surveillance and Recognisance
JSF	Joint Strike Fighter
I_SoS	Information-based SoS
LHD	Landing Helicopter Dock (Amphibious Assault Ship)
LISI	Levels of Information Systems Interoperability
MCM	Mine Counter-Measures
MOE	Measures of Effectiveness

MOP	Measures of Performance
M_SoS	Mission-based SoS
NCO	Network Centric Operation
OR	Operations Research
O_SoS	Operation-based SoS
P_SoS	Platform-based SoS
SCOTS	SoS Characterisation of Operation and Technical Status
SE	Systems Engineering
SoS	System(s)-of-systems
SoSE	SoS Engineering
T&E	Test and Evaluation
TBS	Theatre Broadcast System
TRA	Technical Risk Assessment
U_SoS	Unit (force)-based SoS
VCDF	Vice Chief Defence Force
V&V	Verification and Validation

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1. Introduction

The conceptualisation, design and implementation of system(s)-of-systems (SoS) is broadly acknowledged as a significant engineering challenge due to its high complexity in multiple aspects. SoS engineering challenges differ from developing a single large complex system. For many large organisations, in particular defence organisations, this challenge encompasses how to effectively integrate, manage, evolve and operate multiple heterogeneous systems and capabilities. Defence's human-cyber-physical systems need to be deployed in a range of joint operations with integrated capabilities in various forms of SoS. Due to the multitude of interdependencies and high integration requirements, military systems, capabilities and force elements and their integration form a SoS problem space where there may be multiple SoS. This SoS problem space will become messy if the interdependencies and interrelationships are not systematically defined and adequately managed. The high complexity of military SoS can significantly contribute to dramatic increases of costs and schedule overruns in development, acquisition and operation of integrated systems and capabilities.

The INCOSE Systems Engineering Handbook describes SoS as “systems-of-interest whose systems element are themselves systems; typically, these entail large-scale interdisciplinary problems involving multiple, heterogeneous, distributed systems. These interoperating collections of component systems usually produce results unachievable by the individual system alone.” [INCOSE, 2015]

Military SoS challenges are experienced in many important areas or activities. Defence needs to envisage, plan, develop, generate and operate a variety of interrelated force elements, systems and capabilities across multiple contexts in a complicated SoS problem space. These SoS are often in different development states or stages of their life-cycles and need to evolve. Processes of planning, design, development, management and operation become difficult or challenging tasks, due to high complexity of both military systems and development activities.

To date, the effectiveness of the current engineering and architectural approaches used for military systems and SoS has proved to be less than ideal. Viewed from a ‘soft systems’ perspective, this is mainly due to an inability to adequately understand and effectively cope with high complexity of military SoS. One of main issues commonly facing existing SoS concepts, engineering practice and architectural approaches is how to meaningfully and consistently identify SoS with manageability or effectively conceptualise a SoS problem space, in order to avoid dealing with a messy collection of systems or SoS.

This report introduces a SoS thinking approach to underpin understanding, development and management of military SoS. It employs soft systems philosophies and principles to establish a foundation specifically for the development of SoS concepts, solutions, methods, metrics and tools. In particular, through offering a language and a set of complexity lenses, SoS thinking seeks to clarify in a SoS problem space:

- what potential categories of SoS should be considered in military domains

- what relationships or interdependencies between SoS exist and should be modelled and addressed in architecture and integration and how
- what development states they are in and will go through
- what technical statuses they could end up with and why
- how different SoS could be in operation if they are designed and developed differently.

A 7-step-based SoS thinking approach is proposed to help researchers and practitioners conceptualise a SoS problem space with theory, establish a holistic and shared understanding of SoS involved and their situations of development states and technical statuses, and capture and manage important engineering artefacts.

The main contributions from this research are in two folds. To the literature, first, it proposes a new thinking strategy and an innovative approach of systems thinking specifically to SoS problems. SoS thinking introduces new concepts, metrics, methods and a language to the research and practice of systems engineering for SoS. In particular, it helps development activities achieve conceptualisation with theory, shared understanding, and characterisation of engineering influence and outcomes for multiple and related SoS in a SoS problem space. Secondly, it provides approaches and potential solutions to facilitate Defence in addressing SoS engineering challenges in joint force design and integration to develop integrated capabilities.

2. SoS Engineering Overview

The efforts by Systems Engineering (SE) community to address many engineering issues and difficulties caused by the concept of SoS started two decades ago. Maier [1996] discussed architecting principles for SoS. Levis [2000] explored the relations between SE process and applications of US DoD C4ISR Architecture Framework. Cook's effort [2001] was to further investigate features of SoS and innovative SE methods based on Systems Thinking. Combining architecture frameworks (such as C4ISR Architecture Framework) or enterprise architecture initiatives (for example, TAGOF or Zachman framework) with IT strategic planning, Carlock [2001] presented the Enterprise Systems Engineering (ESE) as a SoS engineering solution to engineer whole business and systems as a whole for information-intensive organisations. Based on Handy's principles of a 'new-federalism', Sage [2001] first recommended a canonical approach to engineering and management of SoS that combines federated SE principles with evolutionary acquisition life cycles. By suggesting the expansion of traditional SE process that is often a project-based or is targeted to deliver a single final product, many SoS SE studies are intended to provide better solutions for the task of 'developing a SoS'. High engineering complexity in development and management of SoS discussed in [Sage, 2001; Carlock, 2001] shows great challenges for SE practitioners to effectively organise SE processes and activities in evolutionary development of SoS and also indicates a need of considering different SE strategies at a level above individual projects.

SoS Engineering (SoSE) practice is an emerging discipline and has been proposed or conducted with different foci using different methods and processes, after a decade long journey of development. Keating's team have continuously worked on theory and design of SoSE methodologies [Keating, 2003, 2010, 2011] since 2003. Chen and Clothier [Chen, 2003] explored philosophical and methodological difference between SE and SoSE, that is, 'developing a system (or SoS)' and 'developing systems in a context of a SoS environment'; and suggested a focus shifting from systems development to systematic SoS evolution management enabled by systematic architecture management at an enterprise level. SoS management study [Sausser, 2008] reveals and explores the SoS philosophy and paradox in SoS engineering and management. After publishing the US DoD SE guide for SoS [DoD, 2007], Dahmann and her colleagues continued their efforts in defining SoS processes and models as shown in Figure 1, and studying challenges and requirements of artefacts management for SoSE [Dahmann, 2008, 2010, 2011]. Understandings of SoSE requirements were further developed by Gorod's efforts on SoSE management framework [Gorod, 2008]. SoS problems are studied as 'wincked problems' or 'complex/messy situations' in management and engineering [Kovacic, 2013].

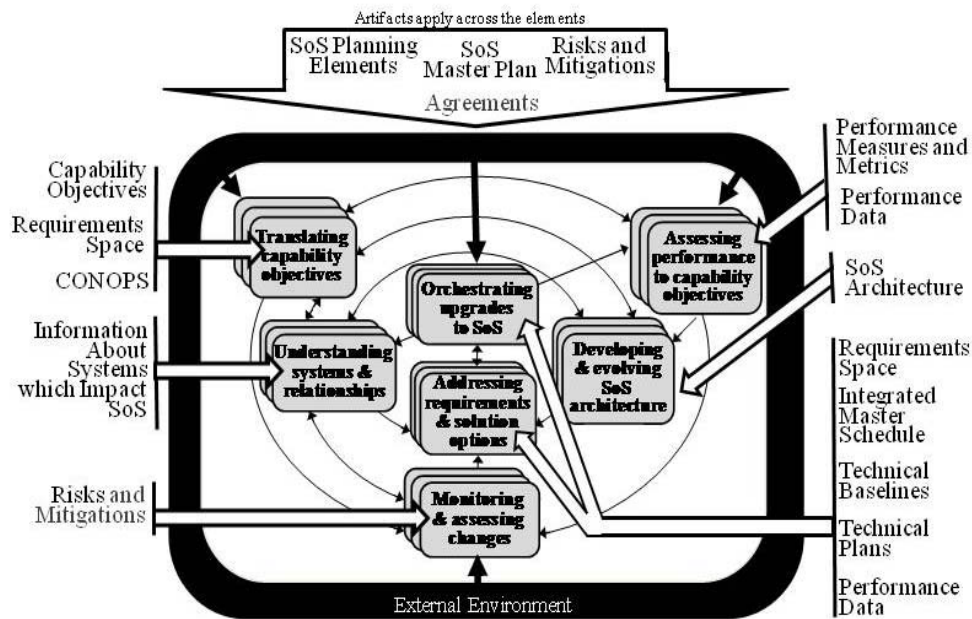


Figure 1 A SoS analysis and engineering paradigm quoted from Dahmann's work (2008)

Despite the various efforts made in the methodology development, as shown in the Pain Points Survey conducted by INCOSE SoS Working group in 2011 [Dahmann, 2014], SoSE remains a challenging task for practitioners. This situation is not a surprise because SoSE itself is often not clearly presented, for example, when applied to the problem space of military SoS. SoSE as a discipline is still in its embryonic stages of development [Keating, 2011] without clear definitions in its scopes, tasks, processes and objectives, and with confusion in the SoS identification, nature, operation characteristics, boundaries, relationships and evolution or lifecycles.

Many existing concepts and principles of SoS are mainly based on the consideration of a single SoS (evident by the definition of SoS, Maier's architecting principles and Adams' systems principles [Adams, 2011]). They are however not sufficient or applicable to a situation where either there are many interdependent systems or multiple inter-related SoS co-exist in a SoS problem space. The SoS analysis and engineering paradigm become extremely complicated in practice for the whole SoS problem space. From the viewpoints of both manageability and the satisfaction to the definitions of SoS, it is a problematic exercise of conceptualisation to consider such a collection of multiple SoS as a 'big' or 'super' SoS. It is also methodologically not encouraged when applying some engineering or architectural approaches.

Inadequate or inconsistent identification or conceptualisation of SoS (including no identification of SoS, no matter whether actually using the term, SoS) is one of the main causes of problematic development of architectures and failures of engineering practice involving multiple SoS. It is because of these problems that both SoS concept and SoS Engineering have not been widely considered and accepted by the defence community. However, this SoS reality is facing the whole Defence, which cannot be avoided by simply not using the term, SoS.

Engineering efforts or factors, from planning decisions, design products, engineering practice to development outcomes, all have impact on SoS. There are certain common challenges and issues for all SoS activities, which have direct impact on effectiveness of SoS activities and SoSE practice. They include: 1) high complexity and a variety of SoS, and their different features and requirements in formation and development; 2) interdependencies or relationships between various SoS; 3) architecture/model management; 4) lifecycle management; 5) engineering artefacts management; and 6) evaluation and assessments of SoS. Without a clear understanding and adequate solutions to these challenges and issues, architectural and engineering approaches, including SoSE, may still have difficulties in successfully delivering complex military SoS. This reflects in fact an urgent need of an important ability in effective and consistent conceptualisation and contextualisation to common problems spaces for various activities and tasks to be able to work collaboratively in shared and commonly agreed contexts in consistent, coherent and responsive manners.

3. SoS Thinking

Systems Thinking [Checkland, 1999] offers a powerful perspective, a specialized language, and a set of tools that people can use to address complex problems of various systems in the modern world. It provides a way of understanding reality through focusing on the relationships among a system's parts, rather than the parts themselves. Also drawing upon systems thinking, as mentioned in the previous section, the SoSE community developed methods and approaches to address some SoS issues by combining them with relevant disciplines and approaches. However, some fundamental questions remain to be considered, while facing multiple interrelated SoS in a SoS problem space.

The high complexity of military SoS involves four inter-dependent domains, namely: force development & management, military operations, capabilities & systems, and processes & activities conducted for development and management of various capabilities and systems. The high complexity is contributed from a number of main sources or by a number of factors, including diversity, interdependency, context, development states and technical statuses of SoS, and a variety of SoS activities and stakeholders.

Defence organisations face three major challenging engineering tasks related to realising complex and interrelated military SoS.

- Task 1: how to define SoS meaningfully and manageably in the military SoS problem space and systematically identify and manage their interrelationships
- Task 2: how to cost-effectively develop new SoS or evolve existing SoS in parallel in a collaborative manner in a complicated and changing SoS environment
- Task 3: how to effectively manage and operate many related SoS in an integrated and coordinated manner throughout their lifecycles.

In order to be able to conduct these tasks in an integrated manner, Defence needs an effective systems thinking ability or approach to help establish a good understanding of a SoS problem space, which can present coherent worldviews of multiple interacting SoS throughout their lifecycles, and establish a foundation that will support SoSE research and practice.

When applying systems thinking to a SoS problem space, an important ability, called as SoS thinking, is needed to understand and examine specific issues of SoS, which can effectively facilitate:

- conceptualising a problem space as a series of wholes that are different SoS with specified interdependencies or interrelationships
- contextualising SoS and provide understandings of multi-type and multidimensional complexity, focusing on manageability, context, interrelationships and interdependencies between systems or SoS
- examining unintended consequences and potential states and statuses of systems and SoS under different development conditions.

In order to achieve an understanding of complexity of SoS problems and requirements for SoSE, SoS thinking seeks both critical thinking strategies and methods in multi-dimensions to address those fundamental SoS issues through specifically exploring the following main perspectives in a coherent manner:

1. **Awareness of a SoS problem space with its engineering factors:** A SoS problem space can range from a single defined SoS, a domain with multiple interrelated SoS, to an organisation with multiple interrelated domains. It should be clearly identified since different SoS problem spaces need different engineering tasks and efforts for their specific development requirements and issues.

2. **SoS categorisation and identification:** Understanding and management of the diverse range of SoS can be aided by effectively conceptualising and categorising SoS, according to their different natures and features in creation, composition, formation, development, management and operation. Each SoS should be identified meaningfully and manageably with its constituents in a SoS problem space, if possible, against a proper categorisation.
3. **SoS interdependency:** The complex web of SoS interdependencies in various contexts and conditions should be understood and addressed with adequate concepts, methods and solutions, lest it cause confusion, complications and even chaos in SoS development and management.
4. **SoS development states:** SoS can be in different development states and go through different state transition paths under influences of different development efforts and decisions made, which significantly increases the complexity of SoS activities and engineering. Given interdependencies between SoS and concurrent development activities, the development states, transition paths and their associated issues are important lifecycle concepts in a SoS problem space.
5. **SoS technical status:** Even with the same composition of constituents, a given SoS can end up (or be realised) in different operational conditions or technical statuses with different operation features and performances, due to different development conditions in integration between its constituents and other engineering factors. Like the development states, SoS technical statuses are important engineering and management issues in a SoS problem space.
6. **SoS design relevance and paradigm:** In addition to the difference to conventional system design or design of a single SoS, SoS design in a SoS problem space can be very complicated, with a combination of multiple design tasks undertaken by different stakeholders at different stages of development. These design tasks produce various defined and required outcomes and design products for different aspects, along with development state transitions of those interrelated SoS.
7. **Extended SoS community of practice (CoP):** The community interested in or responsible for various SoS can be much broader than one involved in the traditional SE applied to a single development project, including not only professionals involved in SE, architecting and integration, but also planners, analysts and other stakeholders. Effective communications, organisational learning and knowledge sharing through common worldviews established across the SoS community are essential to enable the required coordination, orchestration and collaboration of SoS activities to deliver responsive and coherent outcomes.

Each of these perspectives offers a particular viewpoint to a SoS problem space through a specific complexity lens. The applications of SoS thinking in military domains are discussed in details in the following sections, with relevant concepts, methods and metrics introduced specifically for addressing issues and challenges of military SoS. The SoS thinking is an extension to the systems thinking and a conceptualisation approach to a SoS problem space and outcomes of engineering factors. It is introduced to help SoS development activities avoid dealing with a messy collection of systems and hopefully to

offer a firmer and shared foundation to further develop and improve relevant disciplines and methodologies. It is not however intended to be used as an engineering practice handbook or to replace those relevant engineering disciplines and architectural approaches.

4. Military SoS Problem Spaces and Engineering Factors

Based on the SoS definition from Section 1, a SoS can be considered as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities [DoD, 2004]. SoS are characterised by the design and system principles [Maier, 1996] [Adams, 2011], with five distinctive features that differentiate them from very large and complex systems:

- Operational independence of the elements
- Managerial independence of the elements
- Evolutionary development
- Emergent behaviours
- Geographic distribution.

A collection of systems is to be considered as a SoS, according to the SoS definition, because of the acknowledgement to the considerations and outcomes from two main factors. One is the compositional factor that is related to either a conceptualisation activity or a selection decision, which decides what the constituent systems or elements are. The other is the engineering factor that determines what arrangements among the constituent systems and elements are and how they are integrated or cooperate.

It has been a confusing and debatable question what impact the engineering factor may have on a SoS, in particular on its operational features or conditions. In order to meaningfully and effectively assess how well a SoS operates as a whole and manage the conditions of operation and technical status, a new SoS concept is introduced, called as SoS Characterisation of Operation and Technical Status (SCOTS). The SCOTS concept is considered for each SoS identified, rather for any collection of systems or a SoS problem space. It can be benchmarked at 4 levels as shown in Table 1, according to their features in four important aspects. Interoperability (characterised by LISI model [C4ISR AWG, 1998]) is only one of many aspects that show the quality features and technical statuses of SoS. These 4 levels are characterisations of technical conditions or statuses of SoS at a given point of time. Which level among these 4 levels a SoS is realised at is determined by the engineering efforts made and resultant outcomes.

Due to the features of SoS formation and development, it is the engineering factor that results in a SoS at a particular SCOTS level. The SCOTS levels can thus indicate different levels of efforts made by the engineering factor and quality of outcomes delivered by the efforts. SoS performance and quality (or how well it performs or operates) as a whole, in other words, is the outcomes generated by four main tasks contributing the engineering factor, that is, planning, design, development and management. The engineering factor has on-going impact to the performance of SoS throughout its lifecycle. As discussed in the later sections, it is the engineering factor that not only determines a SoS at a particular SCOTS level but also can potentially make a given SoS change in its technical status or change from one SCOTS level to another. Because of features and requirements of military systems, in principle, no military SoS is expected to operate at the SCOTS level 0.

Table 1 SCOTS Matrix

SCOTS Levels	Conditions of constituent's involvement	Conditions of cooperation and integration/Interoperability between constituents	Emergent Behaviours or joint effects	Cooperation uncertainty or disorder
SCOTS Level 3	Roles/functions/ capacity designed adequately, tested and certified as required	Complete integration of processes, information and systems, adequately designed cooperation, defined interoperability requirements (LISI Level 3 or above) specified in architectural views	Adequately designed, assessed and facilitated, and highly achievable, mitigation solutions for negative ones	Very low level with solutions to cope with, except designed operational flexibility
SCOTS Level 2	Roles/functions/ capacity designed; involvements required and well coordinated based on design or certification	Partial integration of systems and information, confirmed process awareness and coordination, defined cooperation, partially defined interoperability above LISI Level 2 required	Expected, assessed, and achievable if coordinated and enabled by required integration, control and management of negative ones	Low level with solutions to control and manage
SCOTS Level 1	Roles/functions planned, involvements expected and based on agreements	Agreements on cooperation, common sense-based awareness of processes, cooperation based on human-in-loop and existing conditions, LISI level 1 required	Envisaged and analysed with expectation but no assurance, mainly human-driven	Medium level, anticipated but not fully appreciated
SCOTS Level 0	Not planned, not coordinated, possible involvements based on availability	Ad hoc cooperation based on willingness, interoperability not specified, LISI Level 0 in worst cases	Envisaged or surprises and not well-prepared	High level and uncontrolled

In the real world, SoS problems vary from a single SoS to a SoS problem space where many SoS and systems are interrelated and interdependent in various ways, as often observed in defence organisations. Military SoS are ubiquitous in a human-cyber-physical environment and cross many areas within Defence, rather than only for areas related to systems development. Many existing SoS concepts, principles and processes, which consider mainly a single SoS, are not applicable to address engineering issues involving multiple SoS. Thus, there are gaps in the theory and methodology that need to be filled in order to make SoS concepts and methodologies work in situations facing a SoS problem space. In other words, there is a need of shifting to a new way of thinking, that is, from considering a single SoS to dealing with multiple interdependent SoS. This new thinking

strategy offers different perspectives to view issues and requirements of SoS architecture and engineering.

In military domains where there are nested concepts and inter-related purposes of systems, SoS problem spaces facing various activities are considered in three typical cases:

- Case 1: where there is a single well-defined SoS in isolation from others or with clearly specified interfaces and relations to the external world
- Case 2: where multiple SoS co-exist and are inter-related, may partly overlap each other, and are planned and developed in parallel
- Case 3: where there are multiple domains of Case 2 that overlap or are interrelated in an organisation or crossing organisations.

Despite of the unawareness or mainly focusing on specific systems, many areas or domains defined for management purposes in Defence actually fall into the situations of Case 2, such as acquisition projects, programs, capability development or operations. Each of them faces a specific problem space of systems or SoS, as discussed later on. These areas or domains are often overlapping or interdependent, which becomes the situation of Case 3. SoS engineering issues and challenges are very different in these three cases. For Cases 2 and 3, there are some important issues and aspects, such as:

- inter-relationships between SoS
- integration of multiple SoS
- context dependency
- relevance and coordination of design and development
- architectures or artefacts management crossing SoS.

These specific engineering requirements and issues in Cases 2 and 3 are not well explored and addressed by existing SoS concepts, studies, engineering practice and architectural approaches. (Note enterprise architectural frameworks, which are applicable mainly for information and business management systems, do not consider specifically SoS in human-cyber-physical environments.)

Understanding and clarifying the case of a SoS problem space is thus the first thing that SoS thinking suggests all SoS activities and SoSE practice need to look at. Simply considering any collection of systems as a 'SoS' can potentially cause a number of issues and problems in conceptualisation. First, it compromises the conditions of the SoS definition and lacks considerations of system rationale and purposes. Secondly, this conceptualisation could face serious issues of manageability and complexity in architecture if the collection involves a large number of interdependent systems. Thirdly, it increases the difficulty and complexity of architecting or application of architectural approaches or frameworks if they do not provide clear guidance on how to identify SoS and how to deal with multiple SoS.

In Cases 2 and 3 the complexity of their interdependencies and interrelationships can become conceptually and contextually unmanageable if they are not properly specified, engineered and managed. Such a messy collection of systems, from a viewpoint of architecture and integration, is a failure of engineering and management for an organisation. The consequence of becoming a messy collection is great difficulties to effectively achieve required integration and interoperability, and to maintain sustainability. A messy collection of interrelated systems or its associated high complexity often results in a high level of risks for projects and capability developments, as pointed out by many Technical Risk Assessment (TRA) reports for defence acquisition projects.

In order to prevent such multiple SoS problems turning into a 'mess' a critical task is to effectively conceptualise SoS problem spaces, namely, to purposefully and meaningfully identify and define multiple related and interdependent SoS, and systematically and effectively deal with their complicated relationships.

In order to adequately deal with SoS problem spaces and their engineering issues, an important thinking ability is required for all SoS activities in two aspects, that is, conceptualisation and contextualisation (or context management). These two aspects are critical for people and activities to effectively work together, which are further explored when the other perspectives of SoS thinking are discussed in the following sections. This thinking ability needs to ensure a SoS problem space to be conceptually maintained as a managed and sustainable SoS world, as shown in Figure 2, rather than becoming a messy collection of systems.

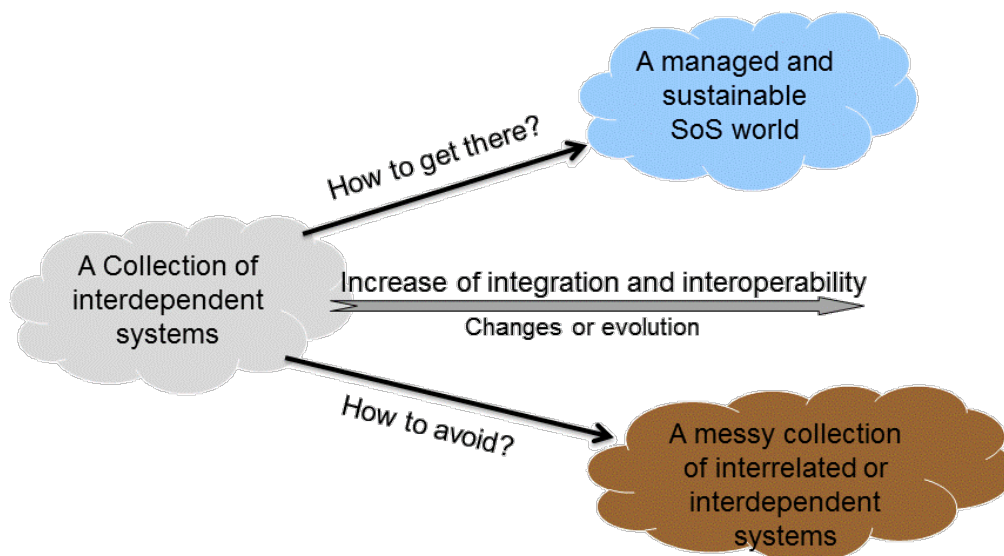


Figure 2 A risk for a collection of interdependent and interrelated systems to become messy

5. SoS Categorisation and Identification

A SoS needs to be clearly identified with its constituents in conceptualisation, and then if required, designed or implemented accordingly. Apart from the SoS definition, there has been no standard or clear guidance on how to identify a SoS in the current architecture or engineering practice. Inconsistent or ad hoc identification of SoS (including no identification) in a SoS problem space is problematic and can cause major confusions, problems and difficulties in architecture and engineering practice. The rationale to identify SoS in a problem space, suggested by SoS thinking, is based on the following considerations:

- There is a need (such as a good practice and ability in conceptualisation and contextualisation for engineering purposes or management practice) and there are benefits to consider and identify a SoS of interest (e.g., if SoS concepts can help address engineering challenges as discussed in this report)
- A SoS should be identified with its constituents in accordance to the SoS definition and can be assessed in its technical status according to SCOTS levels
- SoS identification can help clarify contexts, scopes and responsibilities
- SoS identification should consider both manageability and complexity
- SoS identification should enable definitions and specifications of interdependencies and interrelationships between different SoS
- SoS identification should be based on features of formation, composition, development and lifecycle of SoS in a specific domain
- SoS identification should be made consistently within an organisation if possible and agreed by relevant stakeholders as required.

Given the diversity of SoS and SoS issues, it is unrealistic to think or believe that a single architecture methodology or the same engineering practice would be suitable for different SoS and their complicated engineering issues. The awareness of SoS diversity leads to the consideration of SoS categorisation that can potentially bring benefits to understanding of SoS and requirements for its engineering practice. An appropriate categorisation can offer a basis to consider different and appropriate concepts, methods, processes and solutions for different SoS, and to treat their engineering issues differently. Such a practice encourages and enables development activities to treat SoS and their issues differently according to the requirements associated with their natures and features in creation, composition, development states and technical statuses.

In order to achieve a consistent conceptualisation practice, military SoS in a human-cyber-physical systems environment can be considered in the following main categories according to features in composition, design, management and operation:

- **Information-based SoS (I_SoS)** is based on joint networks and provides functions and information services by its constituent information systems which are integrated through their interfaces, interactions, information flows and integration solutions.

- **Platform-based SoS (P_SoS)** encompasses the various on-board systems, force elements and SoS that are physically located and operated on a specific platform but deliver different functions and capabilities in a joint and integrated manner in operations (note that military bases and infrastructures¹ can be viewed as special cases of platforms).
- **Capability-based SoS (C_SoS)** is a specific set of force elements, capabilities and systems to form a specific military capability such as: air defence; sea denial; amphibious; or intelligence, surveillance and reconnaissance (ISR).
- **Unit (of force)-based SoS (U_SoS)** is a defined organisational unit with capability elements and systems designed for conducting force and operation management and delivering warfighting capability, which are usually generated in the force planning and generation processes.
- **Operation-based SoS (O_SoS, also called Mission-based SoS or M_SoS)** includes all participating force and capability elements, systems and their relations that jointly form an operation context. The O_SoS is often partly described or defined in a text-based form in doctrines, operation plans or concepts of operation documents, or presented as a mission thread or in an operational view of architecture.

These five categories are initially introduced as a reference based on the rationale and considerations for SoS identification (that is, identifying both SoS name and its category). Among these five categories, some (such as I_SoS, P_SoS or C_SoS) are relatively familiar to the engineering community as systems, or sometime have been considered as SoS in practice. Some (i.e. O_SoS and U_SoS) are familiar concepts or areas for military, but not treated as SoS, except in some case studies. The categorisation introduced in such a manner, in addition to the considerations of SoS identification rationale, has its specific significance in two folds. First, it can enable SoS activities or engineering practice to target specific SoS for design, development management and assessments, in order to avoid dealing with either a 'super' SoS or a messy collection of systems. Secondary, it can ensure that responsibilities of various stakeholders in development and management can be adequately mapped to specific SoS.

A list of SoS examples considered in different categories is given in Table 2. Some of these categories can span multiple levels of scale in the same category if required. For example, an U_SoS can range from a section of soldiers to divisions in Army, or from capability element groups to task groups in Navy. Similarly, an I_SoS may range from a suite of integrated software to a force wide information network.

Table 2 Examples of military SoS in different categorise

Name	Acronym	Category
Battlespace Management Systems	BMS	I_SoS
Combat Management System	CMS	I_SoS
Theatre Broadcast System	TBS	I_SoS
Defence Information Environment	DIE	I_SoS

Navy Info. Management Portal	NIMP	I_SoS
.....	
Amphibious Assault Ship	LHD	P_SoS
Joint Strike Fighter	JSF	P_SoS
Bushmaster (Protected Mobility Vehicle)	PMV	P_SoS
.....	
Ballistic Missile Defence System	BMDS	C_SoS
Future Combat Systems	FCS	C_SoS
Mine Countermeasure capability	MCM	C_SoS
Amphibious capability		C_SoS
.....	
Air Operation Centre	AOC	U_SoS
Army Company/Brigade	Coy/Bde	U_SoS
Navy Force Element Groups	FEG	U_SoS
.....	
Amphibious Assault		O_SoS
Surface operation of a task group		O_SoS
Combat Air Patrol Operation	CAPO	O_SoS
Battgroup in deployment	BG	O_SoS
Task Force in deployment	TF	O_SoS
.....	

The military SoS categorisation provides a reference and guidance to the community to meaningfully and consistently identify SoS in a military domain. New categories or changes can be considered and introduced if needed. How SoS in these categories could be effectively developed and maintained in terms of their required SCOTS levels is a question yet to be addressed. Through using SoS thinking, each of these categories offers a specific basis to explore important features and requirements of specific SoS in development and management.

Adequate identification (both SoS names and their categories) of all important SoS in a SoS problem space is critical and can provide a shared basis to contextualise engineering and management activities, and to control and manage complexity. One of main outcomes/effects resultant from the SoS identification is the 'complexity reduction' from the whole SoS problems space to a number of sub-spaces associated with a number of SoS identified. It is the conceptualisation with SoS identifications, as explored in the other thinking perspectives, that makes many engineering issues be more clearly focused on or addressed for specific SoS, including SoS interdependency identifications, development control and management, assessments and lifecycle management.

Defence acquisition programs and projects are usually responsible for development and delivery of I_SoS, P_SoS and C_SoS after planning and studies by Strategy, Capability and Sustainment Group (CASG) and DST Group. Traditional SE practice applied in defence acquisition is thus focussed mainly on development of systems, platforms and capabilities, namely, SoS in these three categories. In the current practice, there is no explicit

consideration of either O_SoS or U_SoS in the current SE practice. It may be clear in defence organisations who should be responsible for operations and force management. But it becomes unclear and confusing when asking how and when they should be developed in an engineering manner for joint force integration, and how they are related to SoS in other categories in architecture and engineering practice. SoS thinking suggests a different approach to force development and operation design through conceptualising adequate operations and force elements as O_SoS [Chen, 2016] and U_SoS.

As discussed in the previous section, there are often multiple interrelated SoS in different categories in a military domain (or a SoS problem space). As an example, a number of different viewpoints of potentially different SoS in the domain of Amphibious are shown in Figure 3, which have different constituents in the composition (that is, (a) presents a C_SoS; (b) is a view of an I_SoS deployed in amphibious operations; (c) shows a P_SoS; and (d) is a view of an Army U_SoS deployed in an amphibious operation).

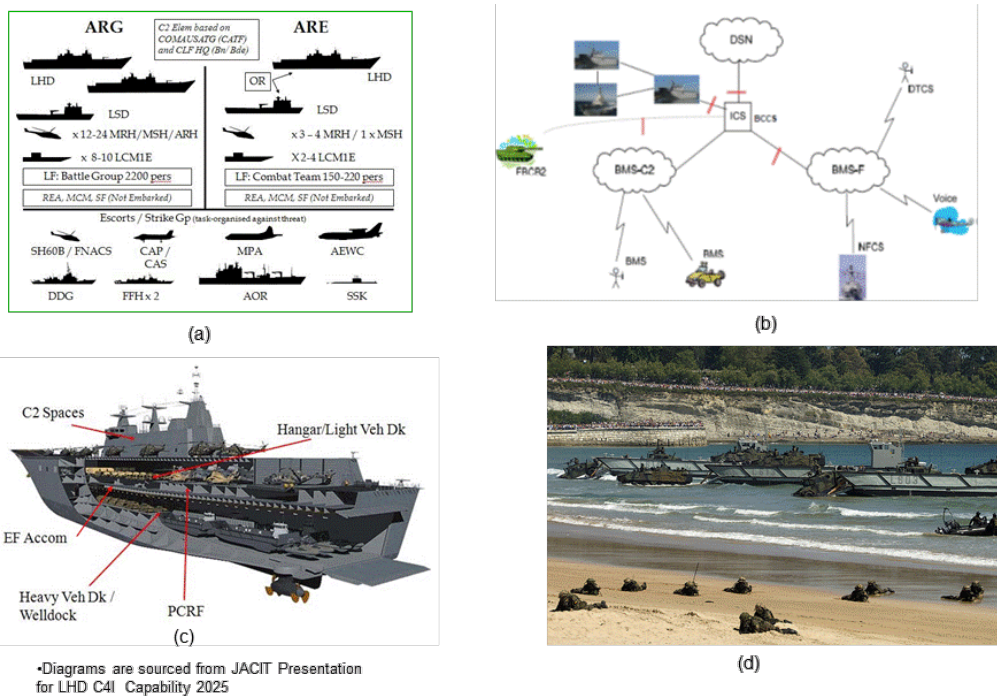


Figure 3 Multiple military SoS in Amphibious

In addition to the missing of the guidance on conceptualisation when applied to a SoS problem space, many engineering or architectural approaches or frameworks, however, also do not make distinctions between SoS in different categories. They thus lack specific considerations for different features of SoS in different categories in development, integration and management. In the current practice, moreover, SoS in some categories are often not considered as SoS, and consequently not treated accordingly in an engineering manner in development. As a result, their development requirements (including architectures) and lifecycle management are not adequately addressed. A further study on the development features and requirements based on these categories is needed in order to help Defence guide identification of SoS and establish adequate SoSE for SoS in different

categories.

Without considering the existence of multiple SoS, engineering or architecture activities conducted in parallel often encounter uncontrolled and on-going development conflicts, gaps or holes, and incoherent or uncoordinated development of relevant architectures, due to missing identification of some SoS concerned, as discussed in Section 9. Based on SoS categorisation and identification, many engineering issues and requirements can be well-contextualised and considered specifically against particular SoS identified in those categories. For example, as shown in Table 3, the further considerations on architecture, design and integration can be given specifically to SoS in different categories, in addition to the general guidance from architectural approaches.

Given that many existing architectural approaches or frameworks do not provide clear guidance on how to identify SoS in a SoS problem space, SoS Thinking specifically suggests architecture developers and other stakeholders be aware of and consider:

1. development activities may need to deal with multiple SoS with different architecture and design requirements based on their categories as indicated in Table 3
2. for each SoS there may be multiple potential higher SoS, or operation contexts that are SoS as well by themselves, and should be shared with different constituent systems or SoS
3. how design activities or architectures of different SoS are related
4. who should be responsible for design of these SoS, in particular O_SoS and U_SoS (in particular those related to mission-based C2 functions and processes, and specific warfighting functions, such as joint fires and situation awareness) and when.

Table 3 Categorisation-based SoS design aspects and architecture requirements

SoS Category	SoS Design Aspects and Architecture Requirements					
	Structure/ Composition	Functions /Roles	Process	Networks	Info	Integration
O_SoS	<ul style="list-style-type: none"> • OV • C2 structure • Constituent systems and elements 	<ul style="list-style-type: none"> • Task lists • Mission effects • Logistics • Emergent behaviours 	<ul style="list-style-type: none"> • C2 process • Op vignettes • Op phases • Op control • SOP 	<ul style="list-style-type: none"> • Networks • Comms. • Standards • Security 	<ul style="list-style-type: none"> • Info flows • IER • Interfaces to external 	<ul style="list-style-type: none"> • Crossing elements or systems • Both internal and external
U_SoS	<ul style="list-style-type: none"> • Org. • Cap elements • Systems • Security 	<ul style="list-style-type: none"> • OVs(of O_SoS) • Task lists • FPS • Logistics 	<ul style="list-style-type: none"> • C2 process • Planning • Mgt process • SOP 	<ul style="list-style-type: none"> • Networks • Comms. • Standards • Security 	<ul style="list-style-type: none"> • Info/data • Info flows • IER • Security 	<ul style="list-style-type: none"> • Crossing elements or systems • Both internal and external
P_SoS	<ul style="list-style-type: none"> • Physical • Space • Standards • Elements 	<ul style="list-style-type: none"> • OVs(of O_SoS) • Deployment patterns • FPS/MOE/MOP 	<ul style="list-style-type: none"> • Op process • SOP 	<ul style="list-style-type: none"> • Networks • Standards • Others 	<ul style="list-style-type: none"> • Info flows • IER • Interfaces • Security 	<ul style="list-style-type: none"> • Cooperation • Partnerships • Coordination
C_SoS	<ul style="list-style-type: none"> • Elements • Systems • Standards 	<ul style="list-style-type: none"> • OVs(of O_SoS) • Deployment Patterns • FPS/MOE/MOP 	<ul style="list-style-type: none"> • Mgt process • Deployment processes • SOP 	<ul style="list-style-type: none"> • Networks • Standards • Others 	<ul style="list-style-type: none"> • Info/data • Info flows • IER • Security 	<ul style="list-style-type: none"> • Interoperability • Cooperation • Security
I_SoS	<ul style="list-style-type: none"> • Systems • Software 	<ul style="list-style-type: none"> • OVs(of O_SoS) • Funct. Specs. • Deployment patterns 	<ul style="list-style-type: none"> • Applications 	<ul style="list-style-type: none"> • Networks • Standards • Security 	<ul style="list-style-type: none"> • Info/data • Info flows • Interfaces • Security 	<ul style="list-style-type: none"> • Systems • Software • Security

The categorisation of military SoS provides a reference and guidance to consistent identification or conceptualisation of SoS. It also offers a foundation for Defence to consider how to achieve effective military SoS governance [Keating, 2014] and how to more systematically develop and effectively manage SoS in different categories, according to their features, and to further explore other more complicated SoS development issues as discussed in the following sections.

The terms, such as capability, platform, force elements/units and operations, are familiar to Defence community, and used widely in acquisition, development and management. Why are they suggested to be considered as SoS? While facing multiple interdependent or interrelated systems, first, development activities often face difficulties, inconsistency and uncertainties in defining scopes/contexts, identifying interdependencies, specifying design products and integration requirements, coordinating relevant activities, and assessing development outcomes. Identifying them as adequate SoS can effectively conceptualise a SoS problem space and provide a good context management solution. It can change complexity control and development management from whole projects or whole capability programs to directly against individual SoS. Such a change can make a big difference for development activities and processes as discussed in the following sections, thanks to many concepts, methods and metrics introduced with SoS thinking. In other words, Defence can benefit significantly by effectively using SoS concepts in force and capability development and engineering practice as discussed in the following sections.

However, not every capability, platform, information system, force unit or operation needs to be considered as a SoS. Given the rationale of considerations for military SoS identification, it is suggested that only those, which appear to need special attention in two aspects or areas, should be considered as SoS. One is high complexity in development and management due to high requirements in integration and interoperability. The second is a

need of systematic engineering practice for architecture development and evolution management. Using SoS thinking, Defence can consistently treat them (namely, capability, platforms, information systems and force units) as adequate SoS but in different categories for development, integration and management. Such a practice effectively makes it possible to systematically and consistently conceptualise and contextualise many domains of development, management and operations.

The term, 'capability', is over-utilised and means many different things to different people. Some warfighting concepts or functions, such as C4ISR, joint fires, battlespace awareness, battlespace manoeuvre, force protection and logistics, are sometimes also called as 'capability'. They are in fact special context-based functions, emergent behaviours or requirements (as indicated in Table 3) of SoS in different categories (especially O_SoS), rather than SoS by themselves. There are also cases where some capability (or C_SoS, for example, Amphibious) is considered mainly for planning, acquisition and management purposes since their constituents (often subsets) are organised or arranged as specifically designed particular deployment patterns (subsets of the C_SoS) for real operations.

Such categorisation of SoS can help stakeholders (from both the defence and industry) understand the nature of SoS they are facing and their responsibilities in development and management. It also increases awareness of SoS issues within defence organisations and can lead to consideration of changes and improvements in relevant processes of force and capability planning and development, towards a holistic and joint engineering practice across military SoS problem spaces. More detailed discussions on the justifications of the categorisation and requirements in development and management of SoS in each category will be reported in separate reports [Chen, 2016].

6. SoS Interdependencies

Each SoS has its own web of interdependencies with or relationships to others in a SoS problem space. (For the purpose of a uniform treatment, interdependencies between a system and SoS can be modelled in the same manner as between SoS, that is, considering a system as a SoS in its simplest form.) These interdependencies or relationships are important to a SoS. They have significant impact on its effectiveness and performance in operation, and thus should be treated adequately in planning and development in an engineering manner.

Relationships between different SoS both internal and external are important features of military SoS. If only considering the SoS definition, a SoS of interest may have relationships with other SoS in three different ways, as illustrated in Figure 4:

- internally, it may have a number of constituent systems or SoS that are either **fully** or **partially** (that is, parts of a (distributed) SoS) aggregated with others into the SoS (Note these constituent SoS or their parts can also be constituents to other SoS)
- hierarchically, it may be 'part-of' (i.e. a constituent SoS) or contribute to other 'higher' SoS

- externally, it may interact, interoperate or partner with a number of lateral SoS.

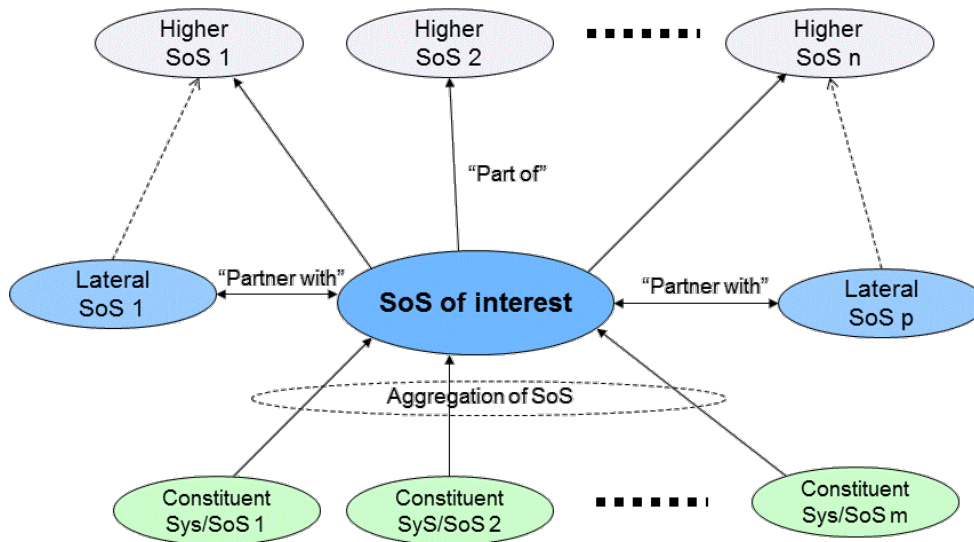


Figure 4 A generic model of the relationship web of a SoS of interest.

In a SoS problem space, any relationship or interdependency links two systems or SoS identified with semantic meanings. The relationship web of SoS is further semantically complicated by the complex relationships between military SoS in different categories, and can be captured through a categorisation-based reference model as illustrated in Figure 5. They appear in various forms involving SoS in different categories, as indicated by arrow lines from a SoS in one category to another SoS in either the same category or different ones. The categorisation-based reference model provides further guidance in a military domain to help identify all potential constituent systems or SoS for each SoS identified. Different relationships (e.g. 'Part-of', 'Contribute-to', 'Be-deployed-to', 'Be-stationed-on', 'Be-transported-by' or 'Be-used-by') indicate potential and different architecture issues and integration requirements. Some relationships are on-going. Others may be optional or required as needed.

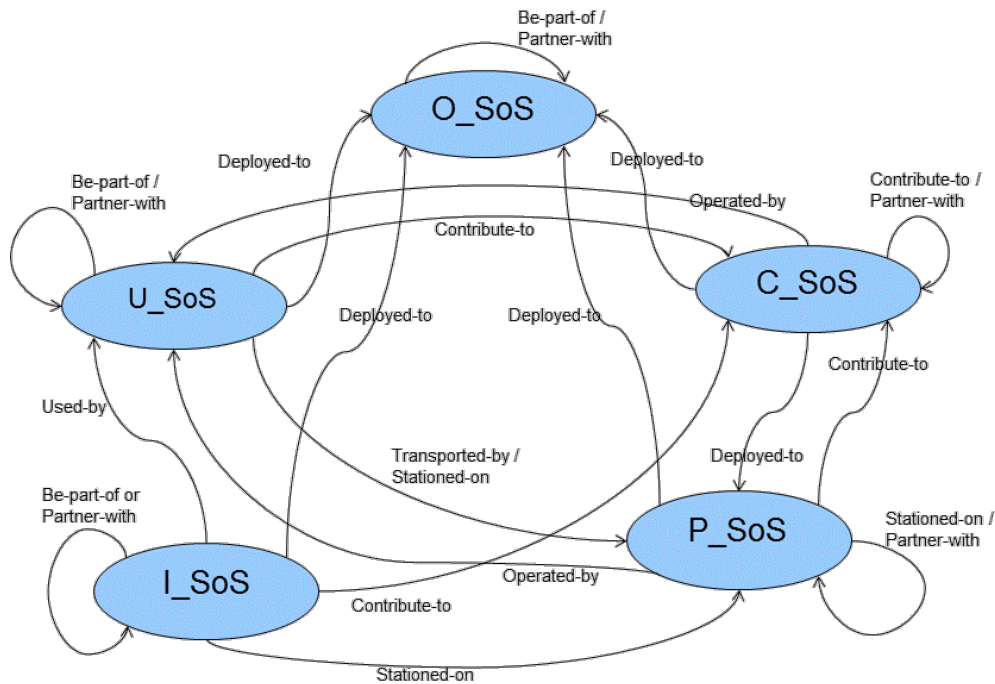


Figure 5 Categorisation-based reference model for interrelationship and interdependency between military SoS

Two interdependency reference models (Figures 4 and 5) can jointly guide the identification of interdependencies between SoS. For instance, an I_SoS (e.g. a battlespace awareness system) can be stationed (as a constituent) on a P_SoS (e.g. an amphibious warship or a land vehicle) and crosses a number of SoS; a P_SoS (such as a submarine) can contribute to an intelligence, surveillance and reconnaissance (ISR) capability (or a C_SoS); and several SoS in other categories can be jointly deployed to an O_SoS (as constituents). Some land vehicles need to be transported by a navy ship. It is the operation context (O_SoS) or operation requirements that determine which SoS in these categories and what relationships are involved and should be addressed accordingly as required. Many of these relationships and interdependencies are currently not adequately handled either in traditional SE or by relevant disciplines. In particular for relationships between different SoS, they are neither issues of individual constituent systems nor required as formal outcomes of SoS design, according to the current practice guidance.

Lateral SoS (or systems) are those which may interact or partner with the SoS of interests and have some impact and constraints to operations, but are totally controlled and managed by others. However, these lateral SoS may also contribute to the same higher SoS. In other words, both SoS are deployed to (or constituents of) the same O_SoS. A lateral relationship between two SoS indicates potential interactions, information flows and interoperability, which need to be articulated and captured as integration needs in right contexts.

The number and semantic meanings of these relationships or interdependencies crossing various SoS in those categories are the main contributors to the SoS complexity. The number of interdependencies increases dramatically as the numbers of constituent systems and relevant SoS increase, as observed in joint operations or development of integrated

capabilities. It would become really messy and difficult to deal with if they are all captured in a single model as Figure 5. The consequence of this increase is difficulties and problems for architecting and development if relationships or interdependencies are unspecified and unmanaged. Thus, understanding and managing these SoS relationships becomes a critical issue of military SoS analysis, engineering and management.

The relationships complexity of military SoS can be further explored or better controlled and managed when the reference model in Figure 5 is split into five sub-models as shown in Figure 6. They illustrate potential relationships between a SoS in each category and other SoS in the same and different categories. Each of these sub-models helps stakeholders directly identify and capture interdependencies of a given SoS to other SoS in a SoS problem space. These category-based sub-reference models can be used by SoS stakeholders and activities to identify engineering contexts for all SoS identified and concerns with their relevant interdependencies.

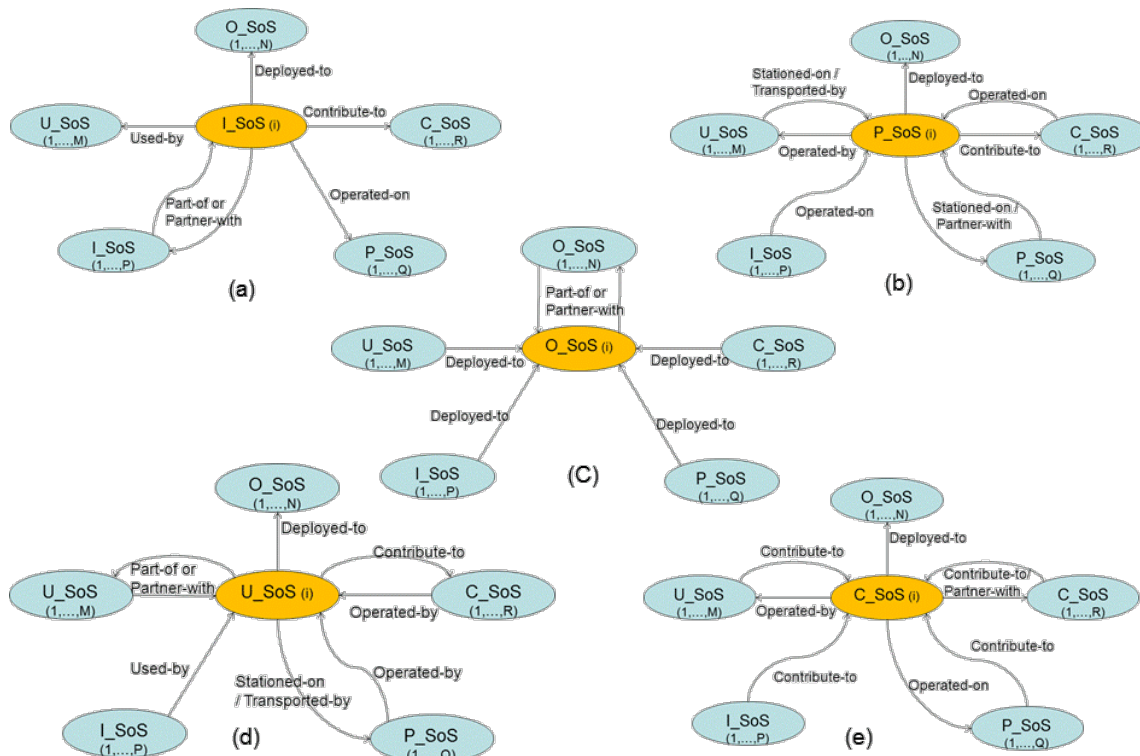


Figure 6 Sub-reference models between military SoS

These relationships can be further specified and explored through considering domain knowledge and relevant engineering needs and management rules. In an engineering practice, definitions and specifications of these relationships implicitly express potential architecture or integration requirements in structures, functions and information between relevant SoS. These interdependency descriptions thus need to be addressed in various forms, including requirements, architectures, interface specifications and design, configuration charts, or even doctrines or operational manuals. Engineering and management concerns and issues associated with these relationships and their implementation are yet to be formally examined by relevant disciplines as the part of SE

practice for Case 2 and Case 3 of SoS problems. Adequate methods, metrics and solutions or tools should be introduced to deal with SoS interdependencies and relationships.

Based on the identifications of SoS, through using Figures 5 and 6, each SoS has a subspace in the SoS problem space, which can be captured by its web of SoS interdependencies or interrelationships, and defines the engineering context. This context provides not only a clear view for its engineering scope and activities, or awareness shared by the stakeholders on the relevant relationships or interdependencies of SoS concerned, but also an effective measure to control and manage complexity. It means that the engineering complexity for a specific SoS can be effectively separated and controlled in a subspace, rather than mixed up with others in the whole SoS problem space.

These relationships also come with certain information on development statuses and technical conditions, such as availability of system/SoS and development/ integration progresses and quality, which may change over time due to engineering progresses and management decisions. These relationships and their development statuses have great impact on the behaviours and performance, or technical statuses, of a SoS. This perspective of SoS thinking leads to one of main tasks that should be conducted by SoSE teams, that is, engineering artefacts management [Chen, 2015]. It is carried out to ensure these relationships and interdependencies between SoS with their development statuses to be first conceptually captured as engineering artefacts and then to be addressed adequately throughout lifecycles across SoS as required.

Conducting identifications of both SoS (including their key stakeholders) and their interdependencies fulfils the task of conceptualisation of SoS thinking to a SoS problem space. Semantics captured with the interdependencies and relationships between SoS provides relevant stakeholders with a context to consider their specific perspectives or worldviews to these SoS, including engineering (development and integration), management, technical, personnel, financial and legal. Through these interdependencies and relationships identified, stakeholders can more effectively: 1) communicate about issues concerned in context; 2) assess and manage progresses, gaps and risks; and 3) consider options or trade-offs.

The conceptualisation based on the categorisation and relationship reference models (Figure 4, 5 and 6) of military SoS enables engineering efforts and management activities to be clearly and properly planned, organised and carried out for specific SoS identified, rather than for ad hoc definitions of scopes/contexts or a messy collection of systems.

Another important benefit from the proposed conceptualisation practice is an effective approach to exploring and designing emergent behaviours and joint effects based on relevant military SoS identified. Many important operation features and requirements for joint force integration or integrated capabilities are actually delivered or presented as positive or desirable emergent behaviours and joint effects. These emergent behaviours are not well or fully designed when constituent systems or SoS are designed individually. This proposed conceptualisation approach enables investigation and design of some important joint warfighting functions, such as C2, battlespace awareness, joint fires, battlespace manoeuvre, force protection and logistics, to be conducted in right context, that is, directly against defined sets of O_SoS (or M_SoS) and U_SoS in an integrated and consistent

manner [Chen, 2016]. If needed, on the other hand, some operation conflicts or uncertainties can be examined and addressed accordingly.

7. SoS Development States and Transition Paths

Given the SoS diversity and the development complexity shown in Figure 1, it has been a difficult question for SE community [Dahmann, 2008 and 2011] how SoS are created or developed or whether the development can be effectively controlled and managed and how. Depending on progresses and outcomes from engineering factors/efforts (i.e. planning, design and development), SoS may appear in very different development states and have more complicated lifecycle management issues than a traditional system. Each SoS is in one of development states at a given point of time throughout its lifecycle. From an engineering management viewpoint, these development states can be characterised as below:

- **Envisaged SoS** is a conceptual description of SoS to enable study, analysis and planning, which defines at a high level the constituent systems and indicates their roles, relationships and interdependencies. An envisaged SoS in any category is created with an expectation on what it needs to deliver and how it might operate.
- **Planned SoS** is a SoS context defined in an endorsed agreement or plan for a central purpose, which specifies requirements for constituent systems or involvements of elements, and indirectly specifies responsibilities of relevant stakeholders. This context is used as an agreement for verification, systems development and capability acquisition. It usually defines 'what' but not 'how'. A planned SoS means the assurance and requirements for the SoS to be achieved at SCOTS level 1, or potentially SCOTS level 2 or even SCOTS level 3 if the development is to continue.
- **Designed SoS** is a design with technical details on all relations/interdependencies and interactions/cooperation between constituents or their elements, and is captured in models, architecture views or other forms of specifications. It is created for validation, development and implementation, and provides details on 'how the SoS operates as a whole. A designed SoS can be achieved at SCOTS level 2, or SCOTS level 3 if the development is completed accordingly.
- **Realised SoS** is a real world SoS that has all its constituent systems and components available and brought together. How a SoS is realised is determined by the engineering factor or its development state transition path as shown in Figure 7.
- **Deployed SoS** is a specific state or application of realised military SoS in exercises or operations, which is generated through campaign planning and configuration. A deployed SoS may differ from the realised one due to operation needs and flexibility requirements for military SoS. The closer or the more similar (if not same) a deployed SoS to a realised SoS, the quicker, more efficient and more predictable the deployment.

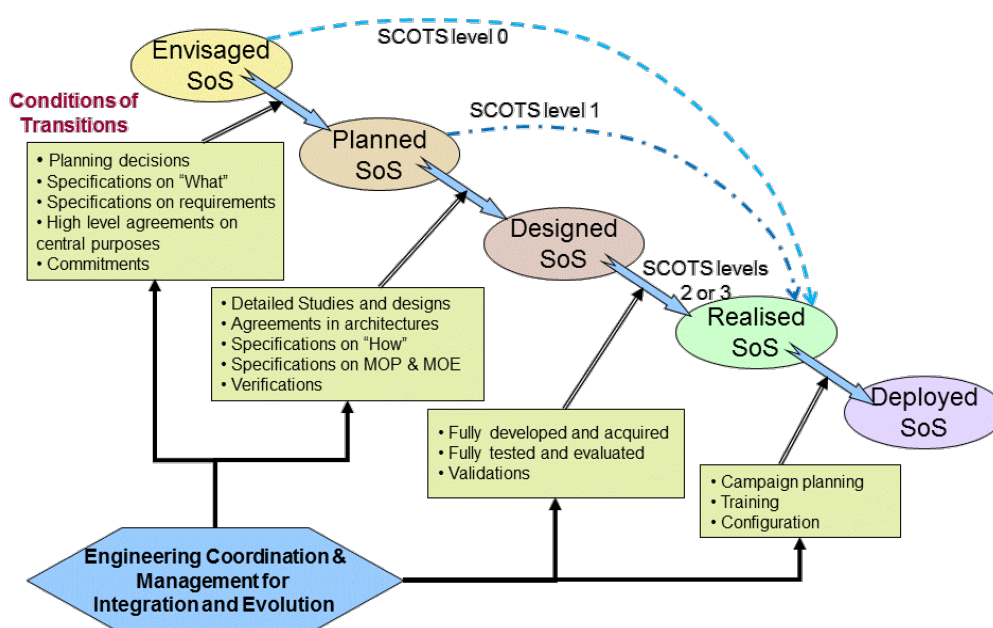


Figure 7 Military SoS development states and transitions

The lifecycle of a SoS, therefore, starts once it is conceptually defined or created, resultant from a decision of planning, study or design, no matter whether its constituents exist or not. This lifecycle continues and may formally involve a complete or ideal development process for the SoS as a whole, from planning, design, development to realisation (becoming a real world SoS). In practice, however, lifecycles of some SoS may go through different development processes or skip some development states as indicated by dotted lines in Figure 7, due to features of their formations, conditions of its constituents and decisions from the engineering factor. As indicated in Figure 7, there are three typical state transition paths where the SCOTS levels indicated are what the transition paths can ensure.

How well can a SoS operate as a whole? If using the characterisation of SCOTS levels to assess, it is determined by how the design and development is conducted, as indicated in Table 1, including both what was designed previously for individual constituents and what was done to the SoS as a whole. If a SoS is targeted for a particular SCOTS level, its development requirements (state transition path) and engineering products required are implicitly defined as illustrated in Figure 7. A targeted SCOTS level may not be achieved if there are significant failures in development or improper decisions or arrangement along with its state transition path.

An important issue specifically for SoS explicitly explored in Figure 7 is potential development state transition paths and their consequences mapped to SCOTS matrix. This is not considered in the typical 'V' model of system development or reflected in the 'wave model' for SoSE [Dahmann, 2008]. A development state transition for SoS occurs when certain development milestones are achieved or some management decisions are made. The transitions from the envisaged or the planned directly to the realised means the SoS (if assume it was not previously designed to a certain extent before) did not go through proper design and development processes for the SoS as a whole. This situation occurs if

all constituent systems exist or available after acquisition, and are brought together, without adequate engineering efforts made in design and integration. Such a SoS, as indicated in Figure 7, is most likely to be at SCOTS level 1.

The realisation state is thus resulted from either the completion of development and integration or a management decision for implementation of a new arrangement (based on the envisaged or the planned) of the constituents that already exist. A realised military SoS, based on the existing conditions of development, can operate in training, exercises or real operations at a particular SCOTS level. A formal announcement of the realisation for some military SoS, such as a warship, is made through a certification process, in which a particular SCOTS level (either a targeted or a different one) can be confirmed through adequate assessments, or testing & evaluation (T&E). A realised SoS does not have to be in operation all the time or all its constituents must 'physically stay together' as a whole, especially for O_SoS. Once a SoS is realised, it remains in that state so long as no significant changes to conditions and statuses of its constituents.

SoS in different categories may have different state transition conditions and paths in practice. Due to the reality and requirements of concurrent development of its constituents, evolutionary or incremental SoS development may result in partial state transitions, which no doubt further increases complexity and uncertainties, and is required to be carefully controlled under the engineering coordination and management across constituent systems or SoS.

Force planning and capability development processes within Defence are carried out to ensure that no military SoS works at SCOTS level 0. Efforts made by warfighters before and during operations ensue all military systems are planned adequately, and would operate for particular mission purposes under military instructions and practice. This is usually achieved through great efforts made in capability development, military training and force preparation. These efforts can be made to different extents with different outcomes in terms of SCOTS levels, as shown in Figure 7. Depending on the development conditions, in other words, a SoS could possibly work at different SCOTS levels for defined mission purposes or operation objectives. It means it operates in different ways or manners with very different performances and effects, in particular in aspects of cooperation, interoperability, joint effects, emergent behaviours and uncertainties.

SoS development state management is proposed as a new task throughout the capability development lifecycle. The part of the task is to raise the awareness of the Defence community that adequate attentions should be paid to SoS design and development for SoS in all those categories and their impact to operations. The development state transitions indicated in Figure 7 are general cases with common features and their most likely resultant outcomes and SCOTS levels, but do not offer detailed descriptions of these transitions for various SoS. Given the development complexity, it may be necessary to further develop methods and solutions for SoS assessments, integration management or T&E, in order to achieve effective development state control and management for SoS in different categories.

The proposed conceptualisation to a SoS problem space makes the development state management possible and be directly conducted against identified SoS. Some specific

issues or development requirements (in models, architectural views and integration) for particular SoS categories should be considered, in particular in association with defence processes and stakeholder responsibilities. For example, force design, capability concept development, force generation and preparation should generate design products or be conducted against identified O_SoS. High SoS interdependencies lead to a need of systematic SoS development state management and coordination cross SoS. It is a key to the success of concurrent developments, acquisitions and evolutions across multiple relevant military SoS in different categories, as discussed in Section 9.

The targeted SCOTS level and expected performance (or technical status) for a SoS can be achieved only if it is delivered through the adequate state transition path with required engineering products. In the real world practice, due to inadequate identification of SoS and the development histories, it is possible that the design is only partially achieved for a given SoS. This is likely to result in increased uncertainty for the technical status, as discussed in the next section, and high complexity for development management, and consequently increased operation difficulties, in fact being passed onto the warfighters.

Real world SoS can be either enduring in nature or only exit as a whole when in exercises or operations. The state transitions illustrated in Figure 7 have been drawn, for sake of simplicity, as a one-way process. In reality, due to the need of evolution, a SoS may need to repeat some development activities (further completion and improvement in design) in order to improve its design and technical status (based on feedbacks, lessons learnt, experimentation, trials and exercises), or to maintain its required SCOTS level after some component systems or SoS change.

The realisation of O_SoS, such as achieving the readiness for amphibious operations, is a very complicated process and can take a long time if it has high requirements for integration, cooperation and interoperability. It may have difficulties to achieve desired outcomes, even after a long period of development, if relevant SoS involved in all categories are not properly designed and managed. O_SoS has its unique features in development and often involves an iterative process from planning to realisation, in order to complete and improve some aspects of operation design, in particular in human-related aspects, such as C2 processes, cooperation and interoperability. Military trials, exercises and trainings conducted to test, experience and improve operations should be considered as a part of design and development process for O_SoS and U_SoS.

The deployed SoS is a special state of military SoS after realisation when they are in deployment, which can be either same or different from the realised one as a special requirement for military SoS. A number of sets of O_SoS can be produced up to the realised state by joint efforts in force generation, training or campaign planning. In the process of development, these O_SoS are used as shared contexts for SoS involved in other categories to be planned, designed and tested.

Due to potential different outcomes resultant by different state transition paths, Defence organisations should appreciate and pay attention to difference in performance and joint effects when operating at different SCOTS levels for a given O_SoS. In particular, note the difference in integration and cooperation, with the same set of constituent systems or SoS (that is, same force units, platforms and capabilities). In the joint force design, it is

necessary to decide and specify which SCOTS level should be targeted for future operations (O_SoS), which indirectly defines integration needs (INs) in relevant aspects. The responsibility for O_SoS design is shared between warfighters and capability developers, as discussed in Section 9.

In the current force and capability development without using SoS thinking, operations and force units/elements are not formally identified as O_SoS or U_SoS. Consequently, their design practice is usually not formally established and conducted with defined design products (i.e. models or architectural views). It means, as indicated in Figure 7, that many O_SoS or U_SoS could not operate as intended or wished if they did not adequately go through the state of the designed or in fact transitioned directly from the planned to the realised. Missing or incomplete design of operations (O-SoS) and force elements (U_SoS) is considered as a main cause to many problems and delays of joint force integration and development of integrated capabilities, as discussed in Section 9.

For the best interests of military operations, the shorter the realisation process the better, in particular for an O_SoS at a given targeted SCOTS level. Is it possible that an O_SoS could be quickly realised at a desired SCOTS level (e.g. SCOTS level 2 or above) from the planned state or even the envisaged, without going through a long development process? There are two ways to help achieve such a goal:

1. Fully designing, developing and testing a number of reference O_SoS to, or close to, their realisation through force design and generation, and making them as close as possible to potential real operations
2. If possible, developing adaptive or pre-designed modular components of SoS in other categories, under well-established guidance of SoS integration and cooperation patterns, such that they could be quickly aggregated and 'plug-in and play' to form different O_SoS as needed.

It is suggested that Defence consider a well-designed combination of these two ways in force and capability development.

In order to deliver joint force and integrated capabilities, Defence should consider more rigorous processes for SoS design and clear specifications on development requirements (in areas such as integration and cooperation), targeted SCOTS levels and required design products (i.e. architecture views or models), according to Tables 1 and 3. Introducing the SoS development state concepts and the state transition diagram enables the Defence to consider the 1st order assessment of military SoS, namely, SoS development assessments, to examine its development history and how it has come to as a SoS. For a given SoS of interest identified, the assessment begins with examining the specification of a targeted SCOTS level for its development. Based on the state transition diagram, the decision on the targeted SCOTS level made in envisaging or planning, to a certain extent, determines the development process requirements or the required state transition path. The 1st order assessment can be continuously carried out throughout development stages to ensure relevant development activities or processes to be timely conducted for various SoS in different categories and required development products/artefacts to be generated in right context.

The information on SoS development states and its transition paths should be recorded and maintained as engineering artefacts since it shows engineering facts. These artefacts indicate or reflect both possible outcomes generated and potential risks or gaps that have impacts on integration or interoperability with other relevant SoS [Chen, 2015]. Understanding of SoS development states, transition paths and their relations to progress and quality of planning, design and development is an important part of the understandings of lifecycles of SoS and their specific engineering issues.

8. SoS Technical Statuses

The technical status is a complementary concept to the SoS development states and is introduced to examine how well a SoS is realised and how well it can operate under the influence of the engineering factor, according to conditions in benchmarked aspects defined in SCOTS matrix (Table 1). It is only considered for the realised or the deployed SoS and used for development control and engineering management, assessments, or preparation for T&E. Different engineering efforts and outcomes can result in a SoS in different technical statuses, even with the same constituents. After realisation, a SoS may typically appear in the following situations in terms of the ability to function.

- **Situation A** (functional 'as it is') where the constituents exist and are brought together, mainly based on the existing conditions of constituents and without additional efforts made in design as a whole (that is, the state transition from either the envisaged or the planned). Consequently, it may operate at any SCOTS level. It is rare, if not impossible, that a SoS could operate at a targeted SCOTS level, without adequate design and integration efforts unless its constituents were well designed and developed for such a purpose. In a case at a lower or unsatisfied SCOTS level, it generally requires extensive intervention by the operators or even developers to continue or redo some design or development and integration work in order to improve its technical status.
- **Situation B** (partly functional as planned and designed) where, due to previous engineering efforts or evolutionary development for both the constituents or the SoS as a whole, this SoS is realised but integration and development are only partially completed; or some constituents or parts of the SoS cannot function as planned or designed due to uncompleted development or changes. In other words, this SoS is realised with incomplete or inadequate engineering efforts, and consequently is unlikely to achieve its full potential as expected.
- **Situation C** (fully functional as designed) where all constituents are fully planned, designed, developed and integrated as required to achieve its targeted SCOTS level.
- **Situation D** (not functional) where, despite in the state of the realised, some constituents of the SoS are not available due to some reasons (e.g. in processes of upgrading or maintenance).

Due to the features of SoS formation and development, the first three situations are results of different development state transitions as shown in Figure 7. Among them, Situation A would be the most preferable for military SoS if the targeted SCOTS level could be achieved. In practice, however, many SoS are often in the Situation B, largely due to

development features of SoS, such as evolutionary and concurrent developments. The difference in the technical status between Situation C and Situation A or B for a given SoS is potential gaps between the targeted SCOTS level and what is actually achieved. If the engineering efforts are adequately made, in theory, the more efforts the less the gap. If there is still a gap even in Situation C to the targeted SCOTS level, it means that the quality or outcomes of design and integration are not satisfactory. Situation D is a special situation for a realised SoS, in which it is temporally not functional or not available, due to technical failures of its main constituents, maintenance needs or a management decision. The awareness of these situations helps stakeholders effectively plan and organise engineering activities, such as test and evaluation (T&E), and assess their outcomes accordingly.

Thus, the examination on the technical status of a SoS can be considered as the 2nd order assessment through looking at both the ability to function (that is, 4 situations) and the way it operates (namely, 4 SCOTS levels). Key stakeholders and SoSE teams need to consider and prepare from both engineering and management viewpoints how to deal with these situations. To arrange and conduct effective T&E, for example, stakeholders need to work out aspects, focusses and schedules of T&E for different SoS when they are in proper operation conditions.

Specific assessment (as part of the 2nd order assessment) for military SoS can be undertaken in particular aspects, such as: integration, cooperation, emergent behaviours and sustainability, plus some specific considerations based on different categories of SoS. In practice, appropriate metrics need to be developed and the appropriate information should be captured in these aspects in order to assess the technical status. For some SoS, in particular O_SoS and U_SoS, the technical assessment in Situation B (or in military training and exercises) can help continuous design and improvements of these SoS. For others, the assessments may provide useful lessons learnt, but is generally too late to provide effective feedback to the development of those SoS and their components. Thus, appropriate indicators and proxies, through conducting the 1st order assessment (including some T&E efforts for constituents), must be identified as early as possible in the earlier development stages such that more timely feedback can be provided to ensure a SoS can be successfully realised at a targeted SCOTS level. This is extremely important for the situation involving multiple SoS in different categories, due to their interdependencies.

Specifications on targeted SCOTS levels for military SoS in different categories, as suggested in the last section, can effectively shape the up-front design requirements for SoS and their constituents, in particular in areas such as integration, cooperation and interoperability requirements. In fact, the technical status assessment of a SoS can be partly done through examining the development state, the state transition path and quality of design and development (i.e. models and architectures), as part of the 1st order assessment, against a targeted SCOTS level.

Another important aspect of SoS complexity related to the technical status of a SoS, which is worth to point out specifically, is the disorder (the worst case is a chaos) in SoS operation, namely the 4th column in the SCOTS matrix. It is mainly contributed by uncertainties and disagreements [Stacey, 2000] between its constituents and associated with relationships between them. One of main purposes or outcomes of planning and development of SoS is in fact to reduce or minimise uncertainties and disagreements to ensure that a targeted SCOTS level can be achieved. As shown in Figure 7, the more

systematic and more complete the development process (or the transition path) the higher the possibility for a SoS to be realised at its targeted SCOTS level.

The technical status of SoS is development condition-based operation features in cooperation and interoperability resultant by the engineering factor. After being realised, the technical status of a SoS still can possibly change from one situation to another, even sometime without involving formal changes of its development state. Thus, it is the task of SoSE teams or relevant stakeholders to effectively monitor and manage the technical statuses throughout their lifecycles.

SoS can change from one SCOTS level to another when certain management conditions change or development progresses are achieved. The technical status of a given SoS can be improved if appropriate development is carried out or certain management decisions for more effective cooperation are made. Of course, it could also change undesirably if quality and conditions of elements involvements and relationships change or are not maintained. In general, some quality features of a SoS may change if it changes from one SCOTS level to another, as illustrated in Figure 8. Thus, no design or no management of SoS means no assurance for the technical status, as indicated in Figures 7 and 8.

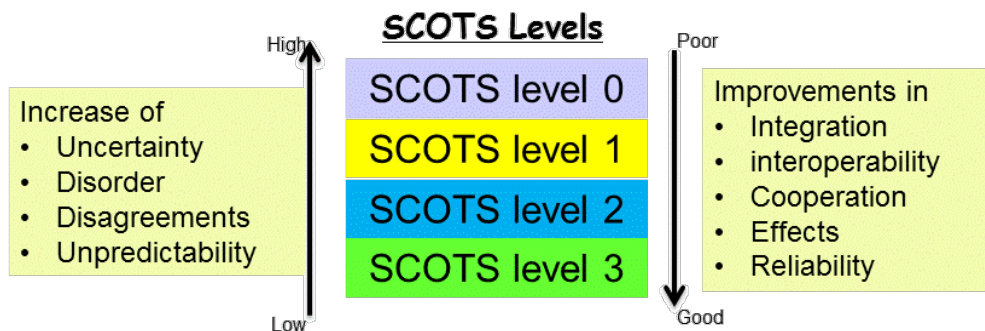


Figure 8 Quality features change at different SCOTS levels

Technical status assessment and management of SoS (including SoS integration assessment) is important but has been difficult, largely due to missing effective identification of SoS and lacking adequate measures for development management. SoS thinking offers a good foundation for considering and developing methods and metrics for SoS technical status assessment and management. Based on the SoS thinking, a given SoS can be identified and assessed accordingly in terms of its development states, technical statuses, and gaps to a targeted SCOTS level through conducting both the 1st order assessment and the 2nd order assessment. More detailed discussions on concepts and methods for SoS assessments will be reported in a separate report. The assessment for different SoS can be conducted as parts of various processes of evaluation, testing or certification by relevant stakeholders within Defence.

9. SoS Design Relevance and Paradigm

SoS design is a key part of the iterative process of SoSE suggested by [Dahmann, 2008] [DoD, 2008] as illustrated in Figure 1, but becomes very complicated and unclear while facing a SoS problem space in Defence, because of issues associated with various SoS in those categories and their interdependencies. It remains as a question to be addressed what SoS design is about or how it can be undertaken adequately and effectively for multiple SoS in different categories. It is not clearly described and discussed by either SoS architecting principles for a single SoS or architecture development guidance from many existing architecture frameworks or engineering methodologies.

Without a good practice of the conceptualisation based on the SoS categorisation, ad hoc development of various models or architectures in a SoS problem space may serve purposes of individual activities to a certain extent. However, it may create confusion or additional complexity for development of other systems or SoS (even using architectural frameworks). It is because they may not be developed with full considerations of relationships and interdependencies to other relevant SoS. Each category of SoS, because of its features, not only requires its designers to achieve its own specific design objectives and outcomes (as indicated in Table 3), but also has its own design context or environment. The design activity should be coordinated accordingly with activities for other relevant SoS in the SoS problem space.

It is important to remember the difference between a large complex system and SoS in design. The design for each SoS, if conducted, should be focussed on cooperation and integration between its constituents, rather than designing their individual functions and architectures. The SoS thinking considerations in the categorisation, development states and interdependencies between different SoS can provide better definitions or exploration for SoS design activities and their outcomes in a joint manner. Design activities for SoS in different categories need to be organised, carried out and coordinated in an integrated design paradigm, as illustrated in Figure 9.

The design of military SoS should be conducted in a collaborative and responsive practice, which involves multiple stakeholders from strategic planners, war-fighters, capability planners, capability analysts and designers of systems and capabilities. There are two main collections of SoS design products (models and architectures) as shown in the middle of Figure 9. One is design products of O_SoS and U_SoS. The other includes design products of C_SoS, P_SoS and I_SoS. Current main design or architectural activities and traditional SE practice are mainly conducted for design products of C_SoS, P_SoS and I_SoS. Due to the missing identification of O_SoS and U_SoS, their design products are currently either not formally generated or only partially produced in ad hoc manners in a mixture with the products for C_SoS, P_SoS and I_SoS.

There are two main reasons to separate them in the two collections in the paradigm. First, they are generated in very different processes or activities by different stakeholders. Design products for C_SoS, P_SoS and I_SoS are mainly generated from one of four process boxes in Figure 9, that is, in capability and systems development and acquisition by architects, systems engineers and integrators. Design products for O_SoS and U_SoS

are produced very differently, as illustrated, in fact from three different process boxes (as indicated by red arrows in Figure 9) for different aspects respectively by mainly force planners and warfighters. Secondly, the interdependencies or relevance between design products in these two collections are important, but are currently ignored or unaddressed in the current practice. As observed, missing, incomplete or inconsistent development or designs of O_SoS and U_SoS often cause significant problems for development and acquisition of C_SoS, P_SoS and I_SoS. These problems appear not only in areas of integration, interoperability, agility, design for changes and standards, but also for those important emergent behaviours such as C2, joint fires and battlespace awareness.

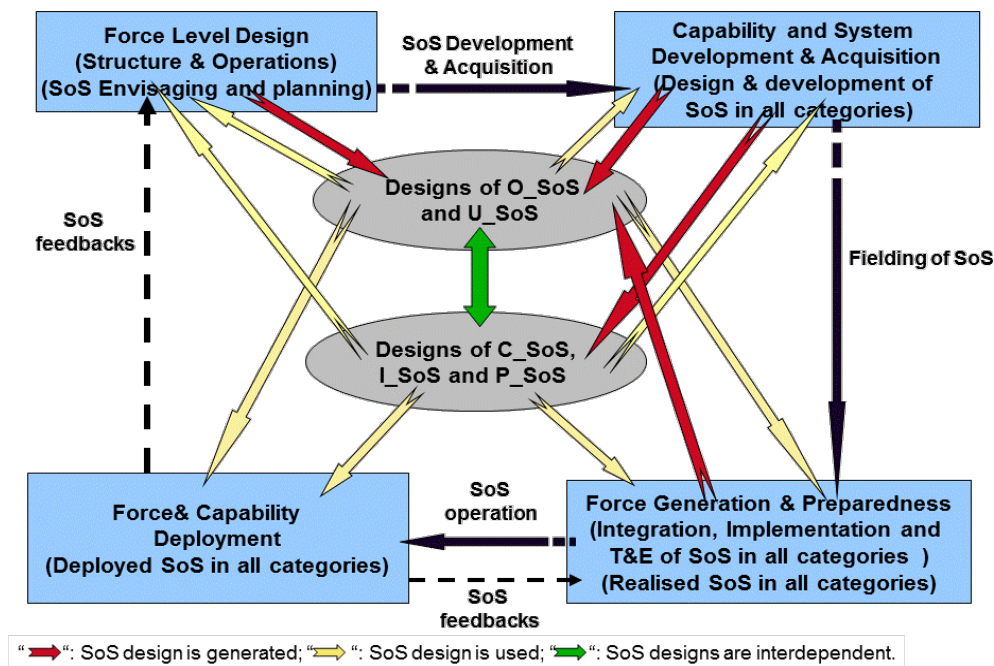


Figure 9 Military SoS design paradigm

There are many important issues in SoS design for military SoS in different categories (which will be discussed in a separate report). For examples, there are some specific issues related to O_SoS, briefly discussed as below:

- O_SoS design should be undertaken by appropriate stakeholders. It needs to cover a number of important aspects, including mission CONOPS, mission objectives (MOE and MOP), aggregation requirements of constituents and participating elements, processes (C2) and information models, joint functions, logistics and other emergent behaviours. O_SoS design should starts from force design and continuously to be carried out to force generation and preparedness.
- V&V activities for O_SoS by relevant stakeholders need to examine issues of relevance, integration and coordination between or crossing all constituent SoS and their designs. These activities can be carried out in relevant processes or activities for the constituents as needed, in a similar manner as described by 'Wave Model' in [Dahmann, 2008].

- Some aspects of design for C_SoS, I_SoS or P_SoS in relation to cooperation and integration, such as joint fires, should be based on relevant aspects of designs of relevant and commonly shared O_SoS (potentially crossing a set of O_SoS). In order to be able to play their potential roles in different operations, functions and CONOPS of individual systems and capabilities should be designed to meet requirements of planned operations and fit to all their operation contexts and environments.
- An adequately defined set of relevant O_SoS can be viewed as a mission space for a specific domain (such as Amphibious). The defined sets of O_SoS for different domains can jointly present a shared defence mission space, that is, a uniform conceptualisation and contextualisation to defence operation needs, as a core part of force design. (This topic will be further explored and discussed in a separate report.)

In addition to considering the architecting principles for a single SoS [Marie, 1998], the design of O_SoS is a complicated process involving multiple design activities, starting from the force level design and being continuously carried out to processes of force generation, and preparedness, in order to cover all aspects of operations. These designs of O_SoS are used (as indicated by yellow arrows) for various purposes from planning, analysis, training, development agreements to references for V&V or T&E of relevant SoS in other categories. Thus, relevant military SoS should be designed, developed and evaluated in an integrated and coordinated manner as shown in Figure 9, rather than in isolation or based on assumptions with a high level of uncertainty.

In order to achieve expected outcomes or effects, especially for joint force operations, selected O_SoS (or M_SoS) need to be further explored in a number of aspects at either the stage to be envisaged or the stage to be designed. These aspects are not usually well covered by either traditional SE or Operations Research (OR) /operations analysis (OA), such as:

- Confirmation of the endorsement by relevant stakeholders to this context (O_SoS) if required
- Relations to task lists (addressed in the combination with designs of relevant U_SoS)
- Relations to warfare concepts, mission areas or mission threads
- Relations to C2 arrangements (addressed in the combination with U_SoS involved and supporting I_SoS)
- Relations to force and capability design or SoS in other categories
- Design processes and requirements produced in the current practice
- Integration requirements
- Characterising operation features as they work at different SCOTS levels and main potential risks or gaps to achieve the targeted SCOTS level

- Management and engineering focusses (such as model/architecture management, development state transition management and certification process) for O_SoS.

Ultimate goals for defence force and capability development are their successes in operations (i.e. the success of O_SoS). Many existing development methodologies, such as platform-based or capability-based planning and development focussing on I_SoS, P_SoS or C_SoS, should be examined in terms of scopes and limits in the design. Defence needs to pay specific attentions to the relevance to and the gaps or inconsistency in design and development of O_SoS and U_SoS, in particular in order to achieve joint force integration.

The high complexity and complicated interdependencies between designs (or architecture and models) of relevant SoS in different categories make design and architecture management a key to success of the whole SoS design practice [Chen, 2013a]. Individual development tasks or projects work as parts in this paradigm and make their contributions to the design of SoS and the body of knowledge of military SoS. The completeness of designs and coherence, consistency, relevance and traceability between design products (i.e. models or architectures) must be ensured and maintained for success of SoS integration and evolution. Design activities of individual SoS in projects or tasks can greatly benefit from successful SoS design management not only in costs and productivity but also more importantly in quality. It is the SoS design management (which is one of main tasks of SoSE) that can provide consistent and adequate solutions for context management, relationship management, development state management and integration management.

Accountability has been considered as a critical issue for force and capability development. However, it is difficult to address due to lacking effective guidance or methods to articulate responsibilities of stakeholders, and to assess outcomes or products of their work and activities. The categorisation-based SoS design paradigm offers a context to define responsibilities of relevant stakeholders in design and integration of SoS, as illustrated in Figure 10. It can also be used as a basis to define or specify relevant design products (i.e. architecture views and models, as indicated in Table 3) of various SoS and issues of SoS interdependencies and relationships. In particular, accountabilities of stakeholders in addressing interdependencies between SoS for required integration and interoperability can be defined and monitored in a clear engineering context for SoS identified (as discussed in Section 12), after consistent conceptualisation and contextualisation.

The exploration and discussions on the categorisation, development states and design paradigm of military SoS provide a better understanding and context setting for defence organisations to review and improve processes and practices. The rationalisation and improvements can be considered not only for capability planning and acquisition but also in force planning, design and generation, in order to ensure all SoS in different categories to be properly planned and designed for targeted SCOTS levels, if a governance framework can be systematically established.

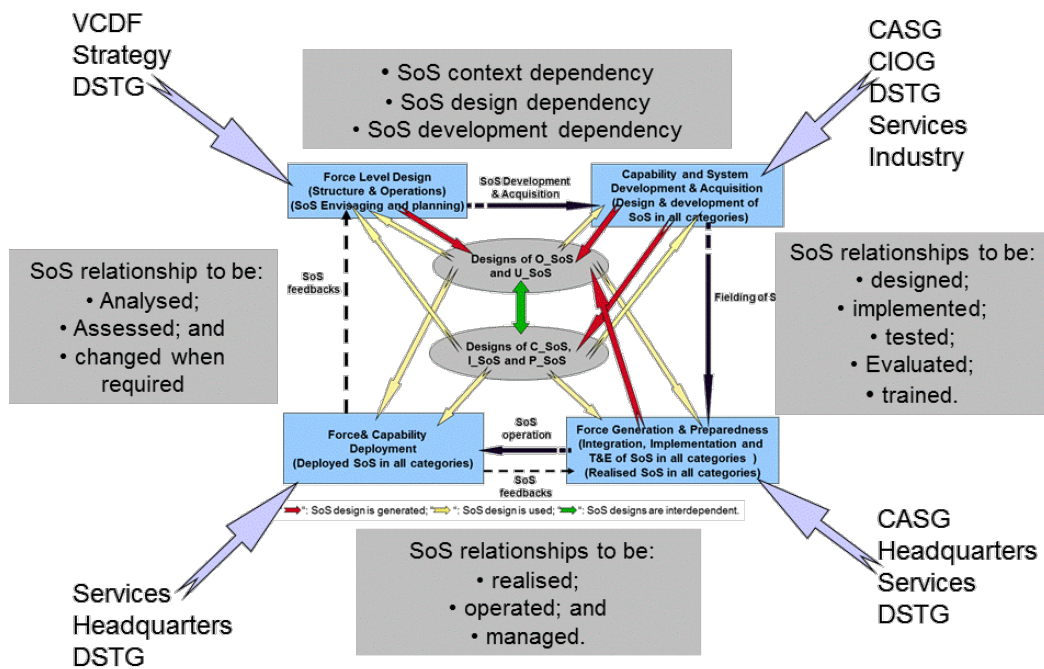


Figure 10 Responsibility and accountability in military SoS design paradigm

10. Extended Community of Practice (CoP) for SoSE and SoS Activities

A CoP is a group of people who share a craft and/or a profession, who can evolve naturally because of the members' common interest in a particular domain or area [Wenger, 1998]. It is through the process of sharing information, knowledge and experience that the members can learn from each other, and work jointly and effectively in a shared knowledge environment.

It is true that every project, every activity or every practitioner has specific focuses and scopes for their work. Why is SoS thinking needed? While facing a SoS problem space, efficiency, effectiveness or success of their works is highly dependent on what and how other people do in their works due to high interdependencies between systems or SoS. Ad hoc conceptualisation and inadequate specifications and management of interdependencies would result in serious problems and difficulties, and even further increase unwanted complexity for engineering and management. A consistent thinking approach becomes important and is needed to help various SoS activities arrive at a shared understanding and consistent conceptualisation through using a common practice and a common language (that is, a set of terminology and concepts about SoS).

There are various SoS activities that all have roles to play or somehow contribute to SoS success, as shown in Figure 11. Many proposed SoS methodologies or practices are often only focused on traditional areas of development for some systems or SoS. Through

introducing the categorization, SoS thinking helps more stakeholders be aware of being part of the SoS community. This SoS stakeholders community, in addition to the traditional one involved in SE, also involves warfighters, planners, analysts, project managers, capability managers and decision makers at various levels. They all need to understand their roles and responsibilities for SoS success. The community, based on a shared thinking strategy and a common language, can effectively communicate about military SoS.

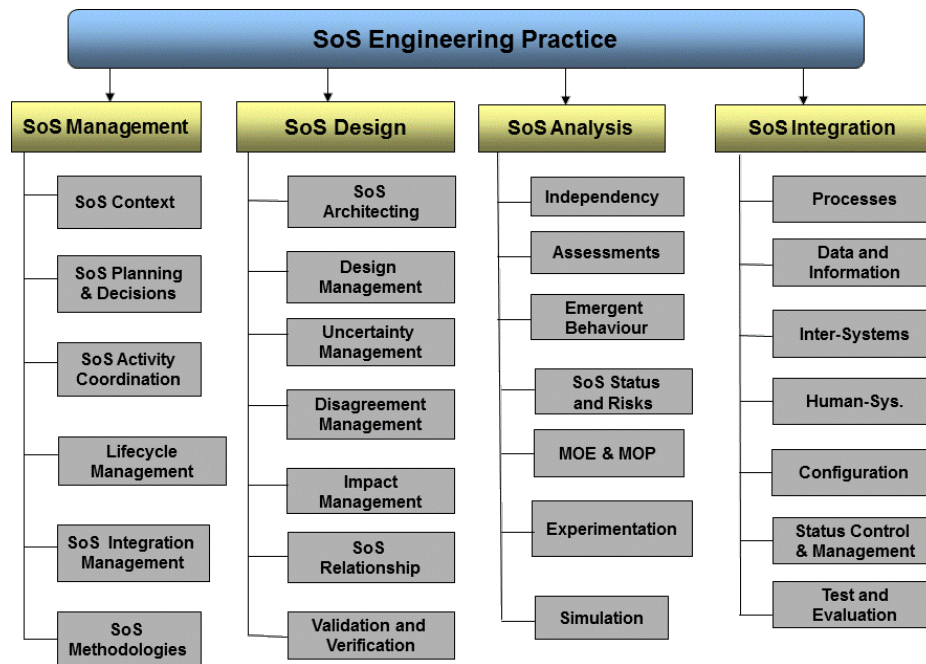


Figure 11 Variety of SoS activities

High complexity of SoSE practice and activities, which is hidden in the SoS process model (Figure 1), is now explored from different perspectives of SoS thinking. This complexity makes the SoS CoP perspective become more critical to SoS success, which requires stakeholders (not only SoSE teams but also other stakeholders) and SoS activities to work very differently from the past in the following aspects:

- being aware of their responsibilities in SoS design, development, management and operation
- being aware of multiple SoS perspectives and worldviews of different stakeholders
- sharing a common body of knowledge of SoS understandings and architectures
- using a consistent approach and language in conceptualising and communicating about SoS
- planning, studying and developing SoS in appropriate contexts in coherence with relevant SoS and SoS activities
- presenting, assessing, testing and managing work outcomes of SoS activities in appropriate contexts as part of SoS body of knowledge

- capturing, controlling and managing uncertainties and disagreements to reduce or minimize disorder in planning and development (avoiding chaotic development)
- being more responsive and collaborative to changes, impact, uncertainties and disagreements, and acting timely and coherently
- increasing coordination, communications and knowledge sharing to avoid duplications and incorrect definitions and specifications of SoS.

This extended SoS CoP requires both the organizational learning and knowledge sharing to be achieved through and featured by a structurally established body of knowledge of military SoS, rather than a document-based practice or solutions. In order to facilitate and achieve such a SoS CoP for defence organizations, two important practice enablers are required: 1) the SoS thinking considered and applied as part of organizational thinking, processes and practice; and 2) an adequate SoSE practice supporting environment created and used to enable SoS design management and facilitate SoS activities and collaboration [Chen, 2007] [Chen, 2013a].

The core part of the SoS CoP is a designed SoSE practice covering all development states or stages of lifecycles, with a number of processes (or sub-practices) for SoS in different categories or different development activities. SoS thinking can be used to support the design and tailoring of such SoSE practice, and to develop methods and metrics addressing specific SoS issues, requirements and complexity in those perspectives. (A separate report is planned to discuss in details on a designed SoSE practice for Defence.)

11. SoS Thinking Approach

These SoS thinking perspectives are specifically introduced to tackle common problems and difficult issues in engineering practice for SoS. The categorisation and relationship reference models of military SoS together offer an approach to conceptualising a military SoS problem space. Such a practice enables engineering efforts and management activities to be more clearly and effectively planned, organised and carried out for the SoS of interest identified in a conceptualised and contextualised SoS problem space. In particular, SoS thinking is introduced to:

- emphasize the importance of both understanding SoS problems from multiple perspectives, and developing adequate concepts, methods, solutions and metrics based on those perspectives
- help SoS researchers and practitioners to first get SoS conceptualisation and contextualisation right, and understand the SoS complexity in a SoS problem space
- offer an appropriate language for effective discussions and communications on various issues of SoS, which is currently missing but important for achieving a good and shared understanding of SoS
- encourage and facilitate effective communications common issues in appropriate contexts, sharing of knowledge and coordination across areas, stakeholders and SoS activities

- help organisations or projects to clearly identify SoS of interest and requirements of SoSE practice, and then to design or tailor a suitable SoSE practice
- facilitate consideration, analysis and management of various engineering issues (such as SoS assessment and integration management) across life-cycles of multiple and relevant SoS involved.

To help understand and communicate about various engineering issues, SoS thinking perspectives discussed in Sections 4 to 10 can serve as a set of complexity lenses, as shown in Figure 12, to jointly explore and deal with high complexity of a SoS problem space. The conceptualisation and contextualisation achieved through using SoS thinking can help effectively deal with and control complexity of SoS development and management.

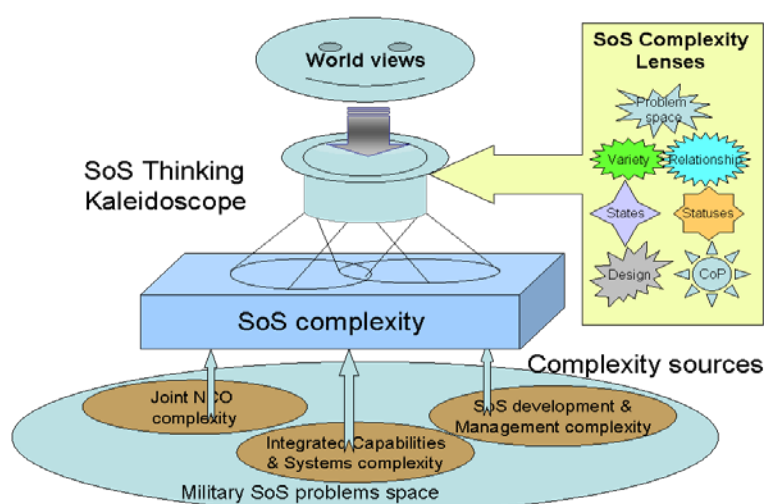


Figure 12 SoS thinking complexity lenses

Based on this set of the lenses, it is proposed that SoS thinking can be applied as a 7-step-based process or method, as shown in Figure 13, to help stakeholders and SoS activities effectively communicate about SoS and systematically establish understandings of SoS problems they are facing.

As shown in Table 4, at each step through asking and answering the those questions, relevant SoS lenses or SoS thinking methods are used to help analyse and examine relevant issues. This process can effectively lead to much needed conceptualisation and contextualisation in a SoS problem space. The SoS thinking approach is thus a process of conceptualising with theory. After going through these 7 steps, stakeholders and SoS activities should be able to achieve an improved understanding of given SoS problems.

The process can be repeated to update information and understanding of relevant SoS as the problem space changes or evolves. Through such an iterative process, a SoS problem space can be maintained and managed as a set of SoS identified with specified interdependencies, rather than becoming a messy collection of systems. In addition to

support generation of specific outcomes to underpin planning, analysis, design and development, SoS thinking has the potential to encourage individual SoS activities to work together as part of the SoSE practice and commonly pay attention to:

- SoS identification and specifications (including constituent systems or SoS, targeted SoS types, and expected state transition paths)
- interdependencies between SoS identified
- Stakeholder identifications and coordination
- Development state control and transition management
- Technical status control and assessments
- SoS design coordination and management (including model and architecture management)
- SoS integration and evolution management
- SoS complexity management in relation to diversity, relationships, context, development states and technical statuses.

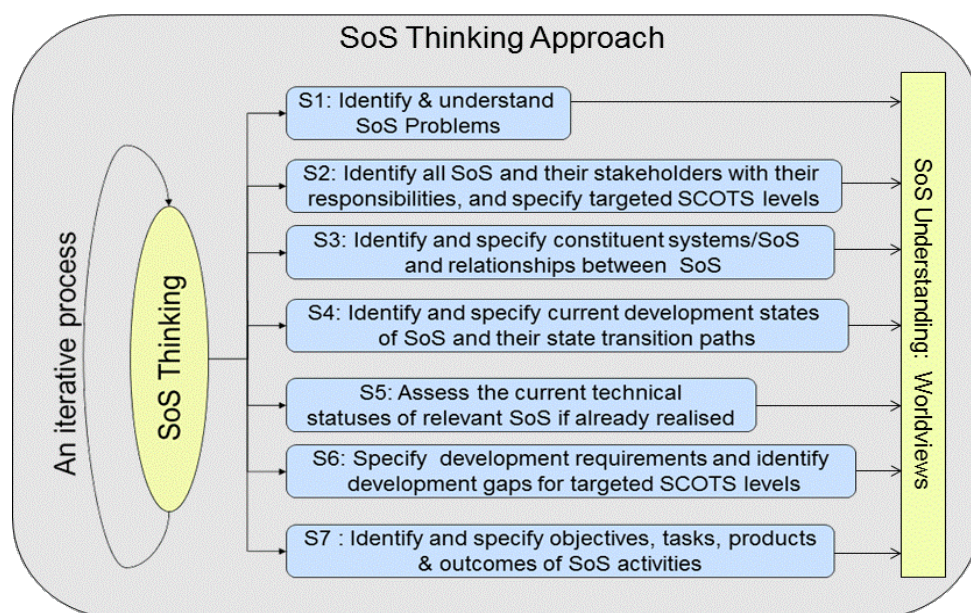


Figure 13 7 Step-based SoS thinking approach

12. Applications of SoS Thinking

The value of SoS thinking can be realised only through its applications by the SoS community. The SoS thinking process is complementary to systems engineering practice, rather than a replacement, and can be considered and used as a component of architecture frameworks or engineering practice. SoS thinking is an innovative approach and new skills to be used to support SoS-related activities, rather than extra overheads or additional workloads for development or management. It is a useful activity to be conducted as part

of many SoS-related activities, such capability analysis, scoping studies, architecture development, systems/integration analysis and assessments, and project/program management. A summary of direct benefits and difference resulted from applying SoS thinking to a SoS problem space is given in Figure 14.

Table 4 Descriptions of SoS thinking approach.

Step	SoS thinking Methods	Main questions to answer	Outcomes
S1	<ul style="list-style-type: none"> ▪ SoS problem space case analysis 	<ul style="list-style-type: none"> ▪ Which case of SoS problem spaces are you facing? 	<ul style="list-style-type: none"> ▪ Confirming SoS problems & engineering factors
S2	<ul style="list-style-type: none"> ▪ SoS identification using SoS categorisation ▪ SCOTS matrix 	<ul style="list-style-type: none"> ▪ Which SoS are you facing or interested (SoSI)? ▪ Which stakeholders are concerned or responsible for SoS identified? ▪ What SCOTS levels should they be targeted at? 	<ul style="list-style-type: none"> ▪ A SoS list and a set of SoS web contexts ▪ Specification of their targeted SCOTS levels ▪ Specification of stakeholders concerned and their responsibilities
S3	<ul style="list-style-type: none"> ▪ SoS relationship reference models ▪ Engineering context management schema (or SoS web context) 	<ul style="list-style-type: none"> ▪ How are these SoS related each other? ▪ How should these relationships between SoS be modelled and managed? 	<ul style="list-style-type: none"> ▪ Understanding and specifications of relationships in SoS web contexts ▪ Engineering context management
S4	<ul style="list-style-type: none"> ▪ SoS development states ▪ State transition paths ▪ SoS design relevance and paradigm; ▪ Category-based design guidance 	<ul style="list-style-type: none"> ▪ What development states are they in and what transition paths they went through? ▪ What design products have been generated? ▪ What design products are required but yet developed? 	<ul style="list-style-type: none"> ▪ Understanding of situations of SoS development ▪ Accesses to models or architecture ▪ Understanding of current problems of development
S5	<ul style="list-style-type: none"> ▪ SoS technical status analysis ▪ SoS design and development assessments 	<ul style="list-style-type: none"> ▪ What technical statuses are they likely to be? ▪ What development gaps exist in association with these SoS? 	<ul style="list-style-type: none"> ▪ Assessments of design products required and their availability and quality; ▪ Notices and requests to relevant stakeholders
S6	<ul style="list-style-type: none"> ▪ SoS technical status assessments ▪ SoS design and development assessments 	<ul style="list-style-type: none"> ▪ what are expectations or development requirements for SoSI though they are already exist? 	<ul style="list-style-type: none"> ▪ Expectation and specifications on the quality of technical status or the targeted SCOTS level of SoSI
S7	<ul style="list-style-type: none"> ▪ Category-based design guidance ▪ SoS design relevance and paradigm ▪ Engineering context management schema 	<ul style="list-style-type: none"> ▪ Which design products are required and will be generated and for which SoS? ▪ Which are main problems or risks facing this activity? 	<ul style="list-style-type: none"> ▪ Understanding of development gaps between the current development states of SoS and the design required for targeted SCOTS levels; ▪ Well-defined purposes of activity outcomes

The application of the SoS thinking approach with the associated methods and metrics can bring great benefits to not only SoS activities but also the engineering-related processes and practice of organisations in a long run. One of these benefits, for example, is the effective management of engineering artefacts generated in planning, development and management, which are important information or knowledge assets. A broad range of engineering artefacts [Dahmann, 2010] created, kept, used and changed in various SoSE activities shown in Figure 11 includes:

- systems information (outcomes of conceptualisation and contextualisation, such as systems or SoS identification and specifications of interdependencies)
- development information (development requirements, development states, current conditions, targeted SCOTS levels) and products (plans, requirements, architectures, progress and documents for testing and evaluation)
- important data, information and reports generated from analysis and assessments
- configuration management information
- activity coordination information.

Engineering artefacts are produced and used always in a certain context. It is thus important for complex systems development, such as acquisition projects or capability programs, to ensure generation, use, management and traceability of engineering artefacts in right contexts. A poorly framed and inadequately defined context could not only have impact on the efficiency of artefacts generation but also undermine quality and value of work outcomes or even cause misuse of artefacts produced. Due to high complexity and difficulties in traceability and manageability, specific requirements for artefacts management, when facing a SoS problem space, need to be adequately addressed, specifically in the following aspects:

- artefacts are related to multiple SoS and context-based
- artefacts are related to interrelationships and interdependencies crossing SoS
- artefacts require traceability in development, applications and management
- artefacts management is an on-going task throughout lifecycles
- artefacts management should be method-based and tool-enabled, rather than a document-based practice.

<ul style="list-style-type: none"> • Before applying SoS thinking <ul style="list-style-type: none"> <input type="checkbox"/> Limited shared awareness of the SoS problem space; <input type="checkbox"/> Ad hoc identification and consideration of SoS concerned; <input type="checkbox"/> No effective enabler in context management for effective communications and engineering management; <input type="checkbox"/> No consideration on diversity of military SoS and their different features in formation, development and management; <input type="checkbox"/> Ad hoc or inconsistent specifications and management of SoS relationships; <input type="checkbox"/> No or limited consideration on SoS development states and state transition paths; <input type="checkbox"/> No consideration on technical status management; <input type="checkbox"/> No adequate metrics and method for SoS assessments; <input type="checkbox"/> Difficult to effectively orchestrate SoS activities, and relate and manage relevant outcomes; and <input type="checkbox"/> No effective and systematic solution for engineering artefacts management. 	<ul style="list-style-type: none"> • After applying SoS thinking <ul style="list-style-type: none"> <input type="checkbox"/> A shared understanding of the SoS problem space; <input type="checkbox"/> Multiple SoS of interest and concerned are identified consistently, according the defined categories; <input type="checkbox"/> Key relevant stakeholders can be identified for their responsibilities; <input type="checkbox"/> Development requirements for different SoS can be specified against their categories; <input type="checkbox"/> Engineering context can be effectively established and managed for SoS identified and handled consistently across SoS; <input type="checkbox"/> Important relationships or interdependencies between SoS can be captured and their development or integration requirements can be specified accordingly; <input type="checkbox"/> Development states and transition paths of SoS identified can be effectively planned and examined; <input type="checkbox"/> SoS assessments can conducted from both perspective of development and technical status; and <input type="checkbox"/> Engineering artefacts management can be supported by an engineering context management schema.
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Figure 14 Difference resulted from applying SoS thinking.

The effective conceptualisation to a SoS problem space, as suggested by SoS thinking, offers a sound foundation for managing context for generation, use and management of engineering artefacts. Based on such conceptualisation, a SoS thinking-based approach to SoS engineering artefacts management has been presented in [Chen, 2015]. Based on the engineering context schema shown in Figure 15, this method has a number of desirable features that are directly based on:

- identification of SoS according to the defined categories

- identified and captured interdependencies and interrelationships between SoS and semantics associated with them
- defined development states and technical statuses
- correspondences and associations between SoS and their engineering products (e.g. plans, architectures, reports).

Using such a schema, stakeholders or projects/programs can effectively conceptualise and contextualise their problem spaces, communicate with other stakeholders or areas, and plan and coordinate development or integration activities. Integration needs (INs) and integration gaps/risks, for example, can be systematically identified and analysed in specified contexts across SoS between stakeholders, through using Tables 1, 3 and 5, and Figures 4 to 6.

SoS Name	Amphibious Ship		SoS Category		P_SoS		
Owner/Manager	Navy		Architectures/Docs		® Links to architectures and docs.		
Development State	Realised		Targeted SCOTS Level		SCOTS Level 2		
Related SoS/Sys.	Name	SoS Category	Owner/Manager	Development State	Interdependency Description	Interdependency Engineering Status	Integration requirements / Solutions
Constituent SoS	Helicopter 1	P_SoS	Navy	Realised	Be-deployed-on	To be tested	@links to integration req.
	Land vehicle 1	P_SoS	Army	Realised	Be-transported-by	To be tested	@links to integration req.
	C4I systems	I_SoS	HQ + Services		Be-stationed-on	To be integrated	@links to architectures
						
Higher SoS	Amph. Op1	O_SoS	HQ	Planned	Deployed-to	To be tested	@links to integration req.
	Amph. Op2	O_SoS	HQ	Planned	Deployed-to	To be analysed	@links to integration req.
						
Lateral SoS	AWD 1	P_SoS	Navy	Planned	Partner-with	To be analysed	@links to integration req.
	Submarine 1	P_SoS	Navy	Planned	Partner-with	To be analysed	
	FFG 1	P_SoS	Navy	Realised	Partner-with	To be integrated	@links to integration req.

Figure 15 SoS-based Engineering context management

Apart from support to individual SoS activities, the SoS thinking approach can help as well the SoSE community in designing specific SoSE frameworks for either a given domain or an organisation as a whole, which will be reported in a separate research report. Through using SoS thinking, as mentioned earlier, a number of important integration issues or difficult engineering tasks for Defence can also be addressed or conducted accordingly, including:

- how to adequately architect military SoS in different categories
- how to address main problems in current defence architecture practice or in use of architectural frameworks

- how to systematically identify and specify integration needs (INs) and analyse potential integration gaps and risks, based on interdependencies identified between relevant SoS
- how to achieve coherent engineering context management across projects, programs and areas, which can effectively facilitate communications and collaboration
- how to evaluate and assess multiple aspects of military SoS in an integrated and coordinated manner with adequate concepts, methods and metrics
- how to systematically manage joint force integration and effective control and manage changes and evolution.

Some studies on these issues or topics have been reported, including:

- Modelling and management of relationships and interdependencies between military SoS [Chen, 2013b]
- SoS engineering artefacts management approach [Chen, 2015]
- Design and development management of operation-based SoS (or mission-based SoS) [Chen, 2016].
- Concepts, Methods, Metrics and Processes for Assessments of Military Systems-of-Systems (to be submitted).

13. Further Studies and Recommendations

SoS thinking is complimentary to SE or SoSE and architectural or analytical approaches, rather than a replacement, and can have a broad impact to many challenging issues and areas facing military SoS. As mentioned earlier in this report, there are a number of areas or topics where SoS thinking can be used to explore and address specific engineering issues and tasks, more importantly in a joint fashion (namely, using a shared thinking and conceptualising strategy), which will be discussed in details in the following areas or topics in separate reports or papers:

- Revisiting challenges and issues facing architecture practice for military SoS
- Category-based design and development management for different military SoS
- Evaluation and examination of architectures or design products for various SoS, or integrated capability development and joint force integration
- Concepts and methods for military SoS assessments
- Emergent behaviours design and implementation for military SoS (focussing on C2, joint fires, battlefield awareness, battlefield manoeuvre, and force protection)
- Force and capability design management for both products and processes
- V&V and T&E for military SoS in different categories
- Integration management for military SoS.

Based on the discussions on importance and potential benefits of applying SoS thinking, the following main recommendations are made to Defence:

- Key stakeholders, including VCDF, CASG, DSTG, CIOG and Services, should jointly discuss common issues of military SoS and develop a shared understanding on SoS engineering challenges, through conducting some SoS case studies or workshops.
- In order to develop a good CoP for SoSE across key areas, Defence needs to develop and provide clear and authoritative guidance on effective use of SoS concepts as part of relevant development and process guidance (such as Integrating Operational Concept Documents (IOCD) and Capability Life Cycle manual).
- If SoS concepts are accepted and will be used by Defence, it is suggested to introduce the best practice or clear guidance in conceptualisation to a SoS problem space for all activities and processes of force and capability planning, design and development. It could include a shared master list of main or selected SoS in different categories to enable consistent conceptualisation and SoS lifecycle management for force design, capability development and joint force integration management.
- Defence should consider and effectively establish lifecycle management and accountability management for military SoS in different categories.
- Through using SoS thinking, key stakeholders should clearly consider and effectively identify their focusing areas in design, development and management of military SoS in different categories, in terms of their responsibilities and accountabilities.
- If SoS thinking and SoSE will be considered and used within Defence, adequate funding and resources should be available in relevant areas, including: a) further development of guidance and frameworks for adequate SoSE practice for key areas, processes or domains; b) the training requirements for skills and professionalism in SoS thinking and SoSE; c) improvements of some key processes or activities; and d) further development of specific methods, metrics and tools as SoSE enablers.

14. Conclusions

SoS thinking systematically explores many concepts and critical engineering issues for military SoS from a number of perspectives. It can help the community understand and address complexity of military SoS, and makes consistently conceptualising a SoS problem space with theory possible. It is intended to offer a language and an approach for large organisations and relevant communities to effectively communicate about, understand and deal with engineering challenges and issues of multiple SoS. It specifically provides insights on SoS diversity and identification, SoS interdependencies, SoS development states and technical statuses, SoS design, and SoS CoP. The conceptualisation to a SoS

problem space through using SoS thinking can help avoid a situation of dealing with a messy collection of systems in SoS engineering and management practice. It also offers an effective contextualisation mechanism to facilitate communications for SoS development activities, and control and manage high complexity of SoS development and management. SoS thinking can help defence stakeholders to effectively use SoS concepts and methods in force and capability planning and development, and work more effectively and collaboratively in joint force design and integration, and development of integrated capabilities.

The SoS thinking perspectives are only briefly explored and discussed in this report, and as mentioned, yet to be further investigated in depth for more findings and insights on specific issues or topics of military SoS. SoS thinking is an emerging approach and can be further developed if other important perspectives are identified and explored. Based on these perspectives as a shared foundation, SoSE researchers and practitioners are invited to consider how to address specific challenges and issues of military SoS in a joint and coherent manner.

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19. ABSTRACT System(s)-of-Systems (SoS) is broadly acknowledged as an engineering challenge for defence organisations, due to high complexity of various military SoS and their development processes. Inadequate understanding of SoS problems and inability to manage complexity encountered in planning, development and operation of multiple interdependent SoS can undermine not only performance and effectiveness of engineering practice and development activities, but also quality of their products and outcomes. This report introduces a systems thinking-based approach, SoS thinking, which offers a language and a thoughtful process to conceptualise, understand, communicate about and assess military SoS. Based on the multidimensional thinking, high complexity of SoS problems can be explored and addressed through using a set of SoS lenses in a number of important aspects, including the problem space, diversity, interdependencies, design paradigm, development states and technical statuses. SoS thinking provides a foundation for further developments of adequate methods, metrics and solutions for SoS engineering practice.				