SoS thinking: an approach to conceptualising and understanding military systems-of-systems

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Abstract: Systems-of-systems (SoS) are acknowledged as an engineering challenge for defence organisations, due to high complexity of various military SoS and their development processes. Challenges in achieving a clear and shared understanding of SoS problems and difficulties in managing complexity have undermined not only application effectiveness of architectural approaches and SoS methodologies, but also quality of their outcomes. This paper introduces SoS thinking that offers a language and process to effectively conceptualise, understand, communicate about and assess military SoS. Based on the proposed critical thinking in multi-dimensions, high complexity of SoS problems can be explored, contextualised and addressed through using a set of SoS lenses in a number of important aspects, including the engineering factor, diversity, relationships, design paradigm, development states and technical statuses.

Keywords: system-of-systems; SoS; SoS thinking; SoS engineering; SoSE; military SoS; complexity; categorisation; interdependency; development states; technical status; SoS design.


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1 Introduction

A system(s)-of-systems (SoS) is generally defined as a set or arrangement of systems that results when independent and useful systems are integrated into a larger system that delivers unique capabilities (DoD, 2004). SoS are acknowledged as a significant engineering challenge due to high complexity. The main engineering and management challenge for defence organisations in relation to SoS is how to effectively integrate, manage, evolve and operate multiple interdependent heterogeneous systems and capabilities in a human-cyber-physical systems environment. They need to be deployed with various force elements as a joint force and meet a variety of potential operational challenges, such as joint network centric operations (NCOs). Due to strong interdependencies and high integration requirements, military systems, capabilities and force elements and their integration form a SoS problem space. Such a problem space could become very difficult for management and sustainable evolution if complicated interrelationships and integration issues are not properly addressed and managed. Note that the challenges are not limited to the development of a single SoS, but more often are about how to deal with multiple interdependent SoS in both development and operations. The high complexity of military SoS, if not managed adequately, directly contributes to dramatic increases of costs and schedule overruns in development, acquisition and operation of integrated systems and capabilities.

Military SoS challenges are observed and experienced in many important areas or activities in defence organisations, from envisioning, planning, developing, generating to operating a variety of interrelated force elements and capabilities across multiple contexts in a complicated SoS problems space. These SoS can be in different development states or stages of their life-cycles. Some of them are enduring in nature, while others may only exist for the duration of an operation or deployment. In addition to the development, SoS management and operation also become challenging tasks. Applications of current engineering practice and architectural approaches to military SoS have proved to be unsatisfactory in many cases in addressing these challenges. Due to difficulties in understanding and managing the complexity, many SoS problems have become very complicated and have been considered as ‘wicked problems’ or messy situations in many studies (Kovacic and Sousa-Poza, 2013; Armson, 2011). There are needs to further develop SoS theory, concepts and methods in order to more systematically and effectively understand and analyse complicated military SoS problem spaces, and control and manage SoS complexity.

This paper proposes a SoS thinking approach and its applications in military domains to underpin the understanding and management of SoS complexity when facing a problem space with multiple systems and SoS. It employs systems thinking (Richmond, 1993; Checkland, 1999) in a number of important perspectives in order to build up a sound foundation for developments of new SoS concepts, methods, metrics and tools. In particular, through offering a language and a set of complexity lenses, SoS thinking seeks to explore:

- what potential categories of SoS should be considered and identified in military domains
- what relationships exist between SoS
- what development states SoS could be in and will go through
A seven-step SoS thinking approach is proposed to help researchers and practitioners conceptualise and understand a SoS problem space. It enables practitioners and engineers to establish a holistic understanding of SoS involved and their situations of development states and technical statuses, and capture and manage important engineering artefacts.

2 SoS engineering overviews

Efforts by the systems engineering (SE) community to identify and address many engineering issues and challenges associated with SoS started two decades ago. Maier (1996) discussed architecting principles for SoS. Levis and Wagenhals (2000) explored the relations between SE process and applications of US DoD C4ISR architecture framework. Combining architecture frameworks (such as C4ISR architecture framework) or enterprise architecture initiatives (for example, TAGOF or Zachman framework) with IT strategic planning, Carlock and Fenton (2001) presented the enterprise systems engineering (ESE) as a SoS engineering (SoSE) solution to engineer whole business and systems as a whole for information-intensive organisations. Based on Handy’s principles of a ‘new-federalism’, Sage and Cuppan (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 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 and Cuppan (2001), Calvano and John (2004) and Martin (2004) 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 systems or projects.

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 (2011, 2014) team have continuously worked on theory and developments of SoSE methodologies since 2003. Chen and Clothier (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’. A shifting of thinking from systems development to systematic SoS evolution management is suggested. SoS management study (Sauser et al., 2008) reveals and explores the SoS philosophy and paradox in SoSE and management. After publishing the US DoD SE guide for SoS (DoD, 2008), Dahmann et al. (2008, 2010) and Dahmann (2014) continued their efforts in defining SoS processes and models, and studying challenges and requirements of artefacts management for SoSE. Understandings of SoSE requirements were further developed by Gorod’s et al. (2008) efforts on SoSE management framework.

Despite the various efforts made in the methodology development, SoSE remains a challenging task for practitioners, as shown in the Pain Points Survey conducted by INCOSE SoS Working group in 2011 (Dahmann, 2014). This situation is not a surprise because SoSE itself is still in its embryonic stages of development (Keating, 2011) without clear definitions in its scopes, processes and objectives, and with confusion in the
SoS thinking

SoS thinking, nature, operation characteristics, boundaries, relationships and evolution or lifecycles.

Many existing SoS concepts and principles are based on the consideration of a single SoS [evident by the definition of SoS, Maier’s architecting principles and Adams’ (2011) Systems principles]. Similarly, many SoS studies tended to be focused on the consideration of a single SoS or its specific issues (Mansouri et al., 2009; Guariniello and DeLaurentis, 2013). However, they can be proved to be insufficient or difficult to apply to a situation where either there are too many interdependent systems or multiple inter-related SoS co-exist in a SoS problem space. There is no existing engineering process model that could adequately reflect and explain clearly the engineering practice or situations for such complex SoS problem spaces. 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. In defence organisations, ad hoc identification (including no identification) or improper conceptualisation of complex SoS is one of main causes of problematic development of architectures and failures of engineering practice involving multiple SoS.

Engineering efforts or factors, from planning decisions, design products, engineering practice to development outcomes, all have direct impact on SoS. For multiple interdependent SoS, these activities should be effectively coordinated and conducted in a coherent and integrated manner. There are, however, certain common challenges issues for all SoS activities, which have direct impact on effectiveness of SoS activities and SoSE practice. These challenges or issues include: high complexity; SoS variety; and different features and requirements in formation and development; relationships between various SoS; architecture/model management, engineering artefacts management; and evaluation and assessments of SoS. Without a clear understanding and effective solutions to these challenges and issues, SoSE approaches may still have difficulties to deliver their promises and possibly fail, due to unaddressed confusion and complexity.

3 SoS thinking

Systems Thinking (Richmond, 1993) or soft systems methodology (SSM) (Checkland, 1999) offers a powerful perspective, a specialised language, and a set of tools that people can use to understand and address complex problems of various systems in the modern world. As the level of complexity increases (mainly due to increased numbers of nonlinear interdependencies between relevant systems or SoS), SoS problems or a SoS problem space can become ‘messy’ (Armson, 2011) [or muddled in one’s mind, also called as messy situations or ‘wicked problems’ (Kovacic and Sousa-Poza, 2013)]. One of the main symptoms of ‘wicked problems’, which is also often observed in a SoS problem space, is ‘everything seems to connect to or entangle with others’ in various forms of interdependencies or interrelationships. Is it possible to avoid dealing with a messy collection of systems or SoS, or prevent SoS problems turning into messy situations or ‘wicked problems’?

Drawing upon systems thinking, the SoSE community have developed methods and approaches to address some SoS issues (Cook, 2001; Martin, 2004; Foo, 2009; Kovacic
and Sousa-Poza, 2013; Jaradat, 2015). However, some fundamental questions remain to be considered, when facing multiple interrelated SoS in a SoS problem space. It is not a wise choice to directly deal with the complexity of a SoS problem space as a whole. A number of factors contribute to the high complexity of military SoS, including diversity, interdependency, context, development states and technical statuses of SoS, and the variety of SoS activities and stakeholders. This multi-dimensional complexity requires the systems thinking to help establish an adequate understanding of a SoS problem space, which can present coherent worldviews of multiple interdependent SoS throughout their lifecycles.

When applying the systems thinking [especially critical thinking (Richmond, 1993) and the inquiring/learning cycle of SSM (Checkland, 1999)] to a SoS problem space, an important and specific thinking strategy is proposed as SoS thinking to view and examine fundamental issues of SoS in multiple dimensions, which in particular can effectively facilitate:

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

In order to achieve an understanding of complex SoS problems and the requirements for SoSE, SoS thinking seeks to apply both critical thinking strategies and methods to address those SoS challenges and considerations through specifically exploring the following thinking perspectives in a multidimensional and 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 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: SoS design in a SoS problem space, if conducted, can be very complicated, with a combination of multiple design tasks for multiple SoS undertaken by different stakeholders at different stages of development. These design tasks produce various defined and required outcomes and design products for different aspects for each SoS as a whole, along with development state transitions of those interdependent or relevant 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, as discussed in the following sections, offers a particular viewpoint to a SoS problem space through a specific complexity lens. The rest of the paper discusses in detail:

- How SoS thinking can be applied in military domains, with a number of concepts, models, methods and metrics associated with those perspectives.
- How SoS problems and issues can be analysed and synthesised.
- How military SoS can be conceptualised and approached through using SoS thinking. SoS thinking is however not intended to replace those relevant engineering disciplines or architectural approaches, instead can be used as an enabler for SoS development activities.

The seven perspectives of SoS thinking are general and not specific for military SoS. However, the focus of this paper (from Section 4 to Section 10) is the development and application of these perspectives to military SoS.

4 SoS problems space and engineering factors

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 outcomes resultant from two main factors. One is the compositional factor that is related to either a conceptualisation exercise 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.

### Table 1  SCOTS matrix

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

It has been unclear 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 and manage the conditions of operation and technical status, a
new SoS thinking is introduced, called as SoS Characterisation of Operation and Technical Status (SCOTS). The SCOTS is considered for each SoS identified, rather than for any collection of systems or a SoS problem space. It can be benchmarked at four levels as shown in Table 1, according to their features in four important aspects. Interoperability [characterised by LISI model (C4ISR AWG, 1998), that is, Levels of Information Systems Interoperability] is only one of many aspects that show the quality features and technical statuses of SoS. These four levels are characterisations of technical conditions or statuses of SoS at a given point of time. Engineering efforts and resultant impacts are also indicatively characterised to a certain extent by the SCOTS matrix. The descriptions of and discussions on SCOTS matrix, its applications and relevance to other SoS features (such flexibility or resilience) cannot be detailed here due to the length limit of the paper.

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, on the other hand, can indicate levels of efforts made in the engineering factor and quality of outcomes, that is, SoS performance and quality (or how well it performs or operates), delivered by the efforts. In other words, they reflect the outcomes generated by four main tasks contributing the engineering factor, that is, planning, design, development and management. The engineering factor will have ongoing impact to the performance of SoS throughout its lifecycle. As discussed in the later sections, it is the engineering factor that not only determines 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. The SCOTS level 3 presents an ‘ideal’ case of SoS operation, in particular in the aspects of emergent behaviours and cooperation uncertainty. It could be achieved only if the SoS is adequately designed, delivered and maintained as discussed in Sections 7, 8 and 9.

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 forms, 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 sufficient and 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.

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 through programs or projects.
Case 3 where there are multiple domains of case 2 that overlap or are interrelated in an organisation or crossing organisations.

SoSE issues and challenges are very different in these three cases. For cases 2 and 3, there are some important issues and aspects that are not clearly and adequately addressed by exiting SoS concepts or approaches. They include inter-relationships between SoS, integration of multiple SoS, context dependency, development states, technical statuses, integration management and architecture management crossing SoS, as explored in the following sections.

Due to increasing requirements in integration and interoperability, systems and SoS in cases 2 or 3 and their interdependencies or relationships could become messy, that is, conceptually and contextually unmanageable, if they are not properly specified, engineered and managed. A messy collection of systems is a failure of engineering and management that an organisation should avoid. To prevent such multiple SoS problems becoming messy, a critical task is to effectively conceptualise a SoS problem space, namely, to purposefully and meaningfully identify or define multiple related and interdependent SoS, and systematically and effectively deal with their complicated relationships.

5 SoS categorisation and identification

Ad hoc identification of SoS or no identification in a SoS problem space is problematic and often causes confusions, problems and difficulties in architecture and engineering practice. The rationale suggested by SoS thinking to identify SoS is based on the following considerations:

- there is a need (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)
- a SoS should be identified with its constituents in accordance to the SoS definition and can be assessed to a certain extent 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 composition, formation, development and lifecycle of SoS in a specific domain
- SoS identification should be made consistently within an organisation if possible.

Given the diversity of SoS and SoS issues, it is unrealistic to think or believe that different SoS and their complicated engineering issues could be effectively addressed by the same architecture approach or the same engineering practice. The awareness of SoS diversity leads the consideration of SoS classification that can potentially bring benefits to the engineering practice. A good classification can offer a basis to consider different
SoS thinking

and appropriate concepts, methods, metrics and solutions for different SoS. Such a practice can encourage and enable engineering activities to treat their engineering issues differently according to natures and features of different SoS.

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 infrastructures 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 (CONOPS) documents, or presented as a mission thread or in an operational view of architecture.

In addition to the considerations of SoS identification rationale, the categorisation introduced in such a manner has its specific significance in two folds. First, it can enable SoS activities and engineering practice to be focused on specific SoS, to avoid facing an unmanageable ‘super’ SoS or a messy collection of systems. One of the main outcomes or effects resultant from the SoS identification is the ‘complexity reduction’ from the whole SoS problem space to a subspace associated with a specific SoS, as further discussed in Section 5. Secondly, it can ensure that responsibilities of various stakeholders in development and management can be adequately considered and specified against specific SoS identified. All these categories can span multiple levels of scale if needed. 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 information systems or applications to a force wide information network.

Such categorisation of SoS helps stakeholders (from both the defence and industry) understand the nature and features 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 changes and improvements in relevant processes of force
and capability planning and development, towards a holistic and joint engineering practice for military SoS problem spaces.

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. 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.

Apart from lacking clear guidance on SoS conceptualisation, many engineering or architectural approaches in the current practice do not make distinctions between SoS in different categories, and thus lack specific considerations for their different features in development and management. In the current practice, moreover, SoS in some categories are often not even considered or identified. Consequently, their design and development requirements (including architectures) and lifecycle management are not adequately addressed.

SoS thinking specifically suggests architecture developers be aware of and consider:

- the SoS development may need to deal with multiple SoS
- for each SoS (not in the category of O_SoS) there may be multiple potential operational views that are SoS as well by themselves and should be shared with different constituent systems or SoS
- how designs or architectures of different SoS are related
- who should be responsible for design of these SoS, in particular O_SoS and U_SoS and when, as discussed in Section 9.

Without an awareness of existence of multiple SoS, or due to missing identifications of some SoS concerned, or a mistake in the first step of the conceptualisation, engineering or architecture activities conducted in parallel often encounter development conflicts, gaps or holes, and incoherent or uncoordinated developments of relevant architectures.

The categorisation of military SoS makes consistent identifications of SoS possible and can provide a foundation for defence to consider how to achieve effective military SoS governance (Keating and Katina, 2014; Jaradat, 2015) and how to more effectively develop and manage SoS in different categories. A good practice in SoS conceptualisation and identification also offers a good basis to further consider and address other more complicated SoS development issues as discussed in the following sections.

6 SoS interdependencies

Each SoS has its own web of interdependencies to other relevant SoS in a SoS problem space. These interdependencies and relationships are important issues for a SoS in its development and management and have significant impact on its effectiveness and performance in operation. A SoS of interest may have relationships with other SoS in three different ways if only considering the SoS definition, as illustrated in Figure 1 (for the purpose of a uniform treatment, interdependencies between a system and a SoS are modelled in the same manner as between SoS):
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- internally, it may have a number of constituent systems or SoS that are either fully or partially aggregated with others into the SoS (note these constituent SoS 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.

Not all of these relationships and interdependencies are well considered and adequately handled either in traditional SE or by relevant disciplines. In particular for relationships that cross different SoS, they are neither main design issues of individual constituent systems when they were designed nor required as formal outcomes of SoS design, according to the current practice guidance. Lateral SoS (or systems) are those which may interact with the SoS of interests and have some impact and constraints to operations, but are totally controlled and managed by other agencies. However, this lateral SoS may also contribute to or be part of the same higher SoS along as the SoS of interest.

In a SoS problem space, any relationship links two systems/SoS with semantic meanings. The complex relationships between military SoS in different categories imply specific development requirements and integration needs. These relationships can be captured through categorisation-based reference models as indicatively illustrated in Figure 2. They appear in various forms involving SoS in different categories, as indicated by arrow lines from (or to) a SoS in one category to (or from) other SoS in either the same category or different ones. The relationship, ‘Part-of’ (in Figure 1), can also be described by some domain specific terms, such as ‘Deployed-to’ or ‘Contribute-to’ if two SoS belong to different categories. For instances, an I_SoS (e.g., a combat information system) can ‘be deployed’ to (or installed as a constituent of) a P_SoS (e.g., an amphibious warship); a P_SoS (such as a submarine) can also contribute to (or be a constituent of) a C_SoS (such as an ISR capability); and several SoS in other categories can be jointly deployed to an O-SoS (as constituents). It is the operation context or requirements that determine which SoS in these categories and which relationships are involved and should be addressed accordingly as required.

Figure 1  Generic relationships between SoS (see online version for colours)
The number of these relationships between various SoS in those categories contributes directly to the SoS complexity. It increases dramatically as the numbers of constituent systems and relevant SoS in all categories increase, and could cause problems and difficulties for development if relationships are not specified and managed in an adequate manner similar to the models in Figure 2. Thus, understanding and managing these SoS relationships becomes a critical area of military SoS analysis and engineering. Systems dependencies or SoS interdependencies can be modelled and analysed for different purposes (Guariniello and DeLaurentis, 2013). The interdependency perspective of SoS thinking is mainly focused on interdependency identification and specifications for engineering and integration management purpose.

Based on the identifications of SoS in a given problem space, each SoS has a sub-space that is captured by its web of SoS interdependencies or relationships, through using Figures 1 and 2. This context provides not only a clear and holistic view on how a SoS is related to others, but also effective measures to control and manage complexity for development and management. It means the engineering complexity for a specific SoS can be contextualised and effectively controlled in a sub-space, rather than mixed up with others in the whole SoS problem space. The correspondences of interdependencies identified in different relationship webs of relevant SoS can help stakeholders effectively establish both awareness and agreements on design and development requirements for potential cooperation and integration.

These relationships can be defined and further explored through domain knowledge and relevant engineering and management rules. Semantic meanings of these interdependencies (e.g., ‘Deployed-to’ or ‘Contribute-to’) implicitly indicate needs of architecture considerations and integration solutions. In an engineering practice, definitions and specifications of these relationships can be used to help identify and
confirm potential integration requirements in different aspects, from structures, functions, information to cooperation within or across SoS. Relationships between SoS also come with certain engineering statuses and conditions, such as availability of systems/SoS, and conditions and progresses of development/integration, which may change over time due to engineering progresses and management decisions. These interdependency or relationship descriptions thus need to be captured, explored and addressed in systems requirements, architectures, interface specifications and design, configuration charts, or even doctrines or operational manuals. Thus, they need to be adequately captured and maintained as important engineering artefacts. Engineering and management concerns and issues associated with these relationships and their implementation are yet to be formally examined by relevant disciplines or practice. Adequate methods, metrics and solutions or tools should be introduced to deal with SoS interdependencies and relationships and manage interdependency-related engineering artefacts since they have great impact on the behaviours and performance, or technical statuses, of a SoS.

Positive emergent behaviours and joint effects are goals for any SoS and resultant from interactions and cooperation associated with SoS relationships and interdependencies. Some of these emergent behaviours are predictable, whereas others may only become apparent in operation. To make them more predictable, achievable and effective, certain planning and design efforts are required to enable or facilitate their implementation and realisation. Conversely, negative or undesirable emergent behaviours or uncertainties need to be identified, analysed, or mitigated through effective design or remedial actions as required.

After identifications of main SoS in different categories and their interdependencies in a given domain, the SoS problem space is effectively conceptualised for engineering and management purposes. Semantics captured with the interdependencies and relationships between SoS also invites relevant stakeholders to consider their specific aspects or worldviews to these SoS, including management, technical, personnel, financial and legal. Through these interdependencies and identified relationships, stakeholders can more effectively communicate about issues concerned in context, and appreciate, assess and manage outcomes, risks, options and challenges.

7 SoS development states

SoS have very different lifecycles from traditional systems and more complicated lifecycle management issues. Each SoS, if identified, is in one of development states at a given point of time. From an engineering management viewpoint, these development states can be characterised as follows:

- **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. 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 3.

- **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.

SoS identification is a conceptualisation activity. A SoS identified can be in any state of development. The envisaged SoS means that the SoS is either a new arrangement of existing systems or a future SoS (since some constituents are to be delivered). 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 such a case, the SoS development could be similar to a complex system development in terms of development control. 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 3, due to features of their formations, conditions of its constituents and decisions from the engineering factor. As indicated in Figure 3, there are three typical state transition paths where the SCOTS levels indicated are what the transition paths can ensure for resultant SoS. How well a SoS can operate as a whole after going through these different transition paths or under impacts of different engineering efforts is further discussed in Section 8.

A development state transition of SoS occurs when certain development milestones are achieved or key management decisions are made. The transitions from the envisaged or the planned directly to the realised mean that the SoS skipped the design and development processes for the SoS as a whole. This situation occurs if all constituent systems exist and are brought together without additional engineering efforts made in design and integration. This includes the case where a collection of existing systems or SoS is newly identified as a SoS, for which the realisation already occurred. Such a SoS is most likely to be at either the SCOTS level 1 or even the SCOTS level 0 unless constituent systems were previously well-designed as adaptive systems technically and functionally or open and flexible enough for future interactions and cooperation with others. Due to reality and requirements of concurrent development of its constituents, evolutionary or incremental SoS development may result in partial state transitions. This
practice 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.

**Figure 3** Development state transitions throughout SoS lifecycles (see online version for colours)

SoS in different categories may have different state transition conditions and paths in practice. The SoS development state management is a new task yet to be appreciated and recognised by many relevant stakeholders and disciplines or an issue for SoS governance (Keating and Katina, 2014; Jaradat, 2015) to consider. Effective identification of SoS makes the development state management possible and be directly conducted against identified SoS. Individual development projects or traditional SE practice is usually focused on systems development management, which are unable to adequately cover and address issues of state transitions and management of SoS in different categories, such as O_SoS or U_SoS. More studies and methods are required to explore features and requirements of the SoS state management for SoS in different categories (Chen, 2016).

Systematic SoS development state management crossing SoS is necessary for success of concurrent developments, acquisitions and evolutions across multiple relevant military SoS.

An important feature for military SoS is that a realised SoS does not have to be in operation all the time or all its constituents are not required to ‘physically stay together’ as a whole, especially for O_SoS. Once a SoS is realised, however, it remains in that state (or technical conditions) (that is, ready for real operation as required) so long as no significant changes to conditions and statuses of its constituents. The state transitions illustrated in Figure 3 have been drawn, for sake of simplicity, as a one-way process. In reality, due to the need of evolution or evolutionary development, a SoS may need to repeat some development states (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.

O_SoS, for example, has its unique features in development and realisation (Chen, 2016). Operations are planned and studied as either the envisaged or the planned O_SoS in forms of scenarios or CONOPS, to help design and implement real operations. Real operations, namely realised O_SoS, are often delivered on a basis of a planned or designed O_SoS (namely, planned scenarios or CONOPS). In practice, O_SoS design and realisation involves usually an iterative process from planning to realisation (as a reference O_SoS), in order to complete and improve some aspects of operation design, in particular in human-related aspects, such as command and control (C2) processes, cooperation and interoperability. Military trials, exercises and training conducted to test, experience and improve operations can also be considered as part of design and development process for O_SoS and U_SoS. Generally speaking, these efforts ensure O_SoS or U_SoS, if realised, would operate at the SCOTS level 1 or above. How well force units, capabilities and systems can be integrated and operate with required interoperability is really determined by engineering efforts made for O_SoS in those four aspects in SCOTS matrix and outcomes generated.

For the best interests of military operations, the shorter the realisation process the better, in particular for O_SoS. Is it possible for an O_SoS to be realised at a desired SCOTS level (e.g., the SCOTS level 2) quickly 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:

- fully designing, developing and testing a reference O_SoS to, or close to, its realisation through force generation and training, and making it as close as possible to a potential real operation
- if possible, developing adaptive or pre-designed modular and configurable constituents or components of SoS in other categories with composability, under well-established guidance of SoS integration, such that they could be quickly aggregated and ‘plug-in and play’ to form different O_SoS as needed.

Different from the traditional ‘Vee model’ in SE, the SoS development state transition model explores specific features (or unintentional consequences/situations) of military SoS formation and development and maps different and likely engineering outcomes to SCOTS matrix. As a result, it provides a basis for the consideration of the 1st order assessment, namely, SoS development assessment. For a given SoS of interest, the assessment begins with the identification of SoS and 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, sets the development process requirements or the required state transition path. The 1st order assessment can be continuously carried out throughout development stages, as needed, to ensure relevant development activities to be timely conducted accordingly for various identified SoS in different categories by relevant stakeholders, and required development products/artefacts to be generated in right context.

For each SoS in a SoS problem space, the information on SoS development states, transition paths and all products generated should be recorded and managed as engineering artefacts since they present engineering facts and outcomes that have impacts to other relevant SoS and are important for conducting SoS assessments and integration.
Understanding of SoS development states and their relations to progress and quality of planning, design and development is important for SoS analysis and engineering practice.

8 SoS technical statuses

The technical status is a complementary concept to the SoS development states and 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 aspects defined in SCOTS matrix (Table 1). It is only considered for the realised or the deployed SoS. For SoS in other development states, a targeted SCOTS level can be viewed as the expectation to its operation features or development requirements. As mentioned in Sections 4 and 7, different engineering efforts and outcomes can result in a SoS in different technical statuses, even with the same constituents. After being realised, a SoS may typically appear in the following situations in terms of the ability to function [or similar to the operability (Guariniello and DeLaurentis, 2013)].

- **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 directly 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 3. 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 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 assessments (as a kind of preparation for or being part of T&E) through looking at both the ability to function (that is, 4 situations) and the way it operates (namely, four SCOTS levels). The assessment made in such a manner can clearly indicate not only how well a SoS operates but also the reasons or causes to the status if combining the information from the 1st order assessment.

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 appropriate information should be captured in these aspects in order to assess the technical status or operability (Guariniello and , 2013). 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 for future development, but is generally too late to provide effective feedback to current 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 in order to get timely feedback for design and development. This is extremely important for situations 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 Section 7, can effectively shape the up-front design requirements for SoS and their constituents, 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 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 et al., 2000) between its constituents and related to their integration and cooperation. 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 3, 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 can possibly change from one situation to another, even sometime without involving formal changes of its development state. 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 efforts are carried out or certain management decisions for more effective cooperation are made, as observed for some O_SoS or U_SoS through training and exercises. Of course, it could also change undesirably if quality and conditions of elements involvements and relationships change or are not maintained. Thus, it is the task of SoSE teams or relevant stakeholders to effectively monitor and manage SoS technical statuses throughout their lifecycles.

9 SoS design relevance and paradigm

SoS design is a key part of the iterative process of SoSE suggested by Dahmann et al. (2008) and DoD (2008), but can become very complicated when dealing with multiple SoS, due to the diversity of and interdependencies between military SoS. Because of different engineering issues associated with various SoS, it remains as a question to be clearly addressed what SoS design is about or how it can be done adequately and effectively for multiple SoS in different categories.

It is important to remember the difference between a large complex system and SoS in design. The design for each SoS, if conducted, is focused on cooperation and integration between its constituents, rather than designing their individual functions and architectures. A SoS can be adequately designed only if the SoS is clearly identified and its constituents have been designed to a certain extent. Considerations of the categorisation, development states and interdependencies between different SoS can provide better definitions or explanations of SoS design activities and their outcomes in a joint manner. As part of the SoSE practice for Defence, design activities for SoS in different categories need to be organised, carried out and coordinated in an integrated design paradigm, as illustrated in Figure 4. SoS design for military SoS is a collaborative and responsive practice, including an iterative process as needed, which involves multiple stakeholders from strategic planners, war-fighters, capability planners, capability analysts and designers of systems and capabilities.

There are two collections of SoS design products (models and architectures) as shown in the centre of Figure 4. One is design products of O_SoS and U_SoS. The other includes design products of C_SoS, P_SoS and I_SoS. There are two main purposes to separate them. First, they are generated in very different processes or activities by different stakeholders. Secondly, the interdependencies between design products in these two collections are important but currently are ignored or poorly handled in the existing engineering and architecture practice. SoS in different categories need to go through different design processes undertaken by different stakeholders. There are many important issues in SoS design, such as specific design aspects and requirements, to be further explored for military SoS in different categories.
In addition to consider the principles for architecting a single SoS (Maier, 1996), it is important to note that different military SoS are designed (as indicated by red arrows in Figure 4) in different processes and contexts of force and capability development with focuses on different aspects. The design products are also used differently (as indicated by yellow arrows). The design of O SoS, for example, is a complicated process involving multiple design activities. It starts from the force level design and is 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, development agreements as references for V&V or tests and evaluations of relevant SoS in other categories. Thus, relevant military SoS should not be designed, developed and evaluated in isolation.

Ultimate goals for defence force and capability development are their successes in operations (O SoS or M SoS). Without right and consistent designs of relevant O SoS, designs of P SoS, C SoS or I SoS generated by acquisition projects, in particular their integration activities, cannot be fully completed and effectively verified or tested in an integrated manner. Integration of these SoS, or joint force integration, must be delivered in context of O SoS (or Mission SoS), and often in a range of operation contexts (or O SoS).

The high complexity and high interdependencies between different designs (or architecture and models) of different SoS make design management and architecture management be a key to success of the whole SoS design practice. Individual development tasks or projects work as parts in this paradigm and make their contributions to the body of knowledge of military SoS design. Design activities for individual SoS in projects or tasks can be significantly benefited from successful SoS design management.
not only in costs and productivity but also more importantly in quality. It is the SoS design management (one of main tasks of SoSE) that can provide adequate solutions for context management, relationship management, development state management and integration management (Chen et al., 2015).

10 Extended CoP for SoSE and SoS activities

The high complexity of SoSE practice and activities, which is hidden in the SoS process model (Dahmann et al., 2008), is now explored from different perspectives. It is the SoS CoP perspective or SoS activities that directly deal with this complexity in practice. The stakeholder community related to and concerning SoS challenges is broad because of their involvements and interests in a range of SoS activities, as shown in Figure 5, dealing with SoS in different categories. In addition to engineers, developers, architects and integrators, other stakeholders [or community of interest (CoI)], such as decision makers, project managers, capability analysts, program/capability managers, and war-fighters, can all potentially use SoS thinking to help effectively and collaboratively approach various SoS issues.

Figure 5 A variety of SoS activities (see online version for colours)

Through applying SoS thinking, stakeholders (not only SoSE teams but also SoS CoI) and other SoS activities can work very differently from the past and with the following features:
• all SoS activities directly deal with various SoS that are consistently identified through a shared conceptualisation practice
• relations between different activities are either determined by or resultant from the interdependencies or interrelationships identified between relevant SoS
• stakeholders are fully aware of their responsibilities in SoS design, development, management and operation
• activities and stakeholders can work more collaboratively and responsively, thanks to the effective identification of relevant SoS and their interdependencies
• a consistent approach and language in defining and communicating about SoS is commonly used by activities and stakeholders
• activities and stakeholders can present, assess and manage work outcomes of SoS activities in shared engineering contexts through using effective artefacts management solutions
• activities and stakeholders can effectively identify, control and manage uncertainties and disagreements to reduce or minimise conflicts, gaps or risks in planning and development (or avoid chaotic development).

In such a practice, SoS activities can not only effectively use these SoS concepts, methods, models and metrics but also help improve SoS designs and effectively generate and manage other engineering artefacts as required. More importantly, based on the commonly shared SoS designs, activities can be more effectively coordinated or conducted in an integrated manner to produce coherent and quality outcomes. The core of SoS CoP is a SoSE practice that needs to cover all development states or stages of lifecycles of SoS in different categories. Based on SoS thinking, SoSE tasks, processes, methods and practice can be designed and tailored accordingly (to be discussed in a separate paper), and tasked to specifically address SoS issues, requirements and complexity of SoS explored in those perspectives.

11 SoS thinking approach

The SoS thinking is a specific application of or an extension to systems thinking and provides an approach to the conceptualisation of SoS problem spaces through adequately identifying SoS and their interdependencies. It can help achieve a clear understanding of complex SoS problems and ensure they will not be handled in messy situations. The seven SoS thinking perspectives outlined in this paper are introduced to tackle common problems and difficult issues in SoSE practice. They can be applied individually to explore specific issues as discussed in the previous sections and also to serve as a set of lenses, as illustrated in Figure 6, through which the high complexity of a SoS problem space can be explored and addressed accordingly. The key difference that SoS thinking brings to a SoSE practice is an ability to enable engineering efforts and management activities to be more clearly and effectively planned, organised and carried out for SoS identified in a SoS problem space.

The SoS thinking perspectives can also be jointly applied as a seven-step process or method, as shown in Figure 7, to help stakeholders and SoS activities effectively
communicate about SoS problems and systematically establish understandings of SoS concerned. At each step, relevant SoS lenses with their metrics or models are used to help explore and analyse relevant issues. Table 2 gives a description of each step, in terms of SoS thinking concepts, metrics or methods used; the questions to be answered; and the expected outcomes. The process can be iterative in parts or as a whole as needed in order to reach and maintain a good and shared understanding of the SoS problems.

**Figure 6** SoS thinking kaleidoscope for SoS complexity (see online version for colours)

![SoS thinking kaleidoscope](image)

**Figure 7** A seven-step SoS thinking approach (see online version for colours)

![SoS thinking approach](image)

The questions listed in Table 2 are important for stakeholders and engineering management but very difficult to answer clearly and coherently without a similar approach as SoS thinking. A summary of direct benefits and differences resulted from applying SoS thinking to a SoS problem space is given in Figure 8.
<table>
<thead>
<tr>
<th>Step</th>
<th>SoS thinking methods</th>
<th>Main questions to answer</th>
<th>Outcomes</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>SoS problem space case analysis</td>
<td>Which case of SoS problem spaces are you facing?</td>
<td>Confirming SoS problems and engineering factors</td>
</tr>
<tr>
<td>S2</td>
<td>SoS identification using SoS categorisation, SCOTS matrix</td>
<td>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?</td>
<td>A SoS list and a set of SoS web contexts, Specification of their targeted SCOTS levels, Specification of stakeholders concerned and their responsibilities</td>
</tr>
<tr>
<td>S3</td>
<td>SoS relationship reference models, Engineering context management schema (or SoS web context)</td>
<td>How are these SoS related each other? How should these relationships between SoS be modelled and managed?</td>
<td>Understanding and specifications of relationships in SoS web contexts, Engineering context management</td>
</tr>
<tr>
<td>S4</td>
<td>SoS development states, State transition paths, SoS design relevance and paradigm, Category-based design guidance</td>
<td>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 to be developed?</td>
<td>Understanding of situations of SoS development, Accesses to models or architecture, Understanding of current problems of development</td>
</tr>
<tr>
<td>S5</td>
<td>SoS technical status analysis, SoS design and development assessments</td>
<td>What technical statuses are they likely to be? What development gaps exist in association with these SoS?</td>
<td>Assessments of design products required and their availability and quality; Notices and requests to relevant stakeholders</td>
</tr>
<tr>
<td>S6</td>
<td>SoS technical status assessments, SoS design and development assessments</td>
<td>What are expectations or development requirements for SoSI though they already exist?</td>
<td>Expectation and specifications on the quality of technical status or the targeted SCOTS level of SoSI</td>
</tr>
<tr>
<td>S7</td>
<td>Category-based design guidance, SoS design relevance and paradigm, Engineering context management schema</td>
<td>Which design products are required and will be generated and for which SoS? Which are main problems or risks facing this activity?</td>
<td>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</td>
</tr>
</tbody>
</table>
This process can effectively lead to much needed systematic conceptualisation and contextualisation in a SoS problem space, and generation of shared and consistent worldviews, with the outcome of effective complexity control and management. It enables a systematic and effective capture of important engineering artefacts for each identified SoS, based on the engineering context schema associated with its interdependency web (Chen et al., 2015). The effective engineering artefacts management can potentially provide useful and meaningful information to support applications of relevant approaches or disciplines for either analytical studies (Guariniello and DeLaurentis, 2013) or engineering management (Keating and Katina, 2014; Jaradat, 2015). The conceptualisation effectiveness to a SoS problem space for an engineering purpose can be examined through answering three main questions:

- how the complexity and context management is handled or controlled
- how interdependencies of systems or SoS are modelled and captured
- how systems/SoS assessments and lifecycle management can be addressed.

**Figure 8** A summary of benefits for SoS activities after using SoS thinking (see online version for colours)

<table>
<thead>
<tr>
<th>Before applying SoS thinking</th>
<th>After applying SoS thinking</th>
</tr>
</thead>
<tbody>
<tr>
<td>-- Limited shared awareness of the SoS problem space;</td>
<td>A shared understanding of the SoS problem space;</td>
</tr>
<tr>
<td>-- Ad hoc identification and consideration of SoS concerned;</td>
<td>Multiple SoS of interest and concern are identified consistently, according to the defined categories;</td>
</tr>
<tr>
<td>-- No effective enabler in context management for effective communications and engineering management;</td>
<td>Key relevant stakeholders can be identified for their responsibilities;</td>
</tr>
<tr>
<td>-- No consideration on diversity of military SoS and their different features in formation, development and management;</td>
<td>Development requirements for different SoS can be specified against their categories;</td>
</tr>
<tr>
<td>-- Ad hoc or inconsistent specifications and management of SoS relationships;</td>
<td>Engineering context can be effectively established and managed for SoS identified and handled consistently across SoS;</td>
</tr>
<tr>
<td>-- No or limited consideration on SoS development states and state transition paths;</td>
<td>Important relationships or interdependencies between SoS can be captured and their development or integration requirements can be specified accordingly;</td>
</tr>
<tr>
<td>-- No consideration on technical status management;</td>
<td>Development states and transition paths of SoS identified can be effectively planned and examined;</td>
</tr>
<tr>
<td>-- No adequate metrics and method for SoS assessments;</td>
<td>SoS assessments can be conducted from both perspectives of development and technical status; and</td>
</tr>
<tr>
<td>-- Difficult to effectively orchestrate SoS activities, and relate and manage relevant outcomes; and</td>
<td>Engineering artefacts management can be supported by an engineering context management schema.</td>
</tr>
<tr>
<td>-- No effective and systematic solution for engineering artefacts management.</td>
<td></td>
</tr>
</tbody>
</table>

Effective conceptualisation is important and has great impact to many engineering and analytical activities, including architecture development. The complexity management and development control and management in an adequately conceptualised SoS problems space will be much more effective than directly dealing with the whole collection of complex systems. Given that there is often limited guidance on conceptualisation and identification of SoS from many architectural approaches and engineering practices, the SoS thinking approach or a similar approach can be considered as a complementary
element or an enabler to help improve their applications in military domains. The systematic conceptualisation and contextualisation can also enable a range of SoS activities to address SoSE issues and requirements in a coherent and coordinated manner, including SoS architecture and artefacts management, and SoS integration assessments and management.

12 Conclusions

This paper introduces SoS thinking as a specific systems thinking approach to effectively dealing with SoS complexity and engineering issues, and discusses SoS thinking applications in military domains. A number of new SoS concepts, methods, models and metrics associated with SoS thinking are also introduced to facilitate conceptualising, contextualising and understanding a complex SoS problem space as a more disciplined and well-guided practice. This study on SoS thinking and the relevant discussions on the new concepts are preliminary. SoS thinking is not limited to the 7 perspectives and can be further developed if other important perspectives are identified and explored. SoSE researchers and practitioners are invited to help improve or further develop both SoS thinking and the approach if more or better methods or models can be introduced or developed.

References


