Systems of systems engineering: prospects and challenges for the emerging field

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Abstract: System of systems engineering (SoSE) is a field that remains in the embryonic stages of development. The work presented in this volume provides a methodological approach, grounded in foundations of systems theory, to perform SoSE. However, further development of the field must be predicated on understanding critical distinctions emerging and bring focus to the challenges and prospects for further development. The purpose of this paper is to develop a perspective of the state of the SoSE field and identify challenges for future evolution. To achieve this purpose, the paper is organised to explore four primary areas. First, the literature is reviewed to provide an account of the current state of the field. Second, an organising framework is presented to structure understanding of field development. Third, a set of challenges to forward movement of the field is offered. Fourth, the paper concludes with reflections on the SoSE methodology presented in this volume and implications for further development of the SoSE field.

Keywords: system of systems; SOS; system of systems engineering; SOSE.


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1 Introduction

At first glance, the field of system of systems engineering (SoSE) appears to defy logical organisation. There have been different descriptions, articulations, and suggestions of what constitutes a system of systems, and what SoSE is (Keating et al., 2003; Keating, 2005; Sousa-Poza et al., 2009; Gorod et al., 2008a). While these deliberations and debates are healthy in the early stages of a developing field, they can be limiting to the longer term maturation of the field. Sousa-Poza et al. (2009) pointed to a major divergence in SoSE between hard system solution based perspectives and those leaning toward a ‘soft system’ inquiry orientation. Drawing on Keating (2005) and extending earlier work, we summarising divergence in the developing SoSE field:

- agreement of what constitutes a system of systems, although progress is being made, is still a subject of contention and lacks broad acceptance
- there is not a widely accepted definition of SoSE, even though this term has been extensively used in peripheral literature
- the underlying philosophical, methodological, or standard practices have not been rigorously addressed or driven advancements in the field
- research continues to be fragmented and field development seems to be primarily application oriented
- the relationship and differentiation of SoSE to related fields [i.e., systems engineering (SE)] is tenuous, and although high level contrasting distinctions have been made, the deep differential separations have not been adequately established
- applications of SoSE continue to emerge, without sound reference to the theoretical underpinnings that ground and provide for generalisable (transportable) approaches
- overemphasis on information technology (interoperability) while, at best, relegating other (human, social, organisational, political, policy) holistic problem dimensions to the background and at worst excluding them completely.

We feel comfortable in postulating that SoSE development is critical to effectively address the complex problem domain presently faced by the engineering community. This domain is characterised by:

1. proliferation of information intensive systems and technologies that have not necessarily been developed for the integrated SoS missions they are being conscripted to perform
2. multiple stakeholders with potentially incompatible worldviews and divergent objectives, often politically driven
3. scarce and dynamically shifting resources that create a source of uncertainty and potential instabilities in mission support
4. constantly shifting conditions and emergent understanding of problems and context that make stable requirements life cycle driven approaches unrealistic
technology advancements that outpace the capabilities, and potential compatibility, of infrastructures necessary to support their development, integration, maintenance, and evolution. 

urgency in demands for responsive action and solution development to alleviate mission shortfalls. 

the abdication of long term thinking in response to immediate perceived operational needs – rendering traditional forms of long range planning virtually innocuous. 

increasing complexities and uncertainties that bring to question the ability of traditional systematic approaches, based in assumptions of stability, to effectively deal with SoS problems.

Unfortunately, these characteristics are not likely to subside in the near future and can be expected to escalate in severity. This landscape represents a challenge to the emerging field of SoSE, requiring a ‘step function’ shift from previous traditional approaches focused on engineering monolithic systems in stable environments. Attempts at simple linear extrapolation of knowledge from singular existing fields (i.e., SE) will not be sufficient, and might more likely retard development of SoSE.

In this paper our purpose is to examine the current state of the SoSE field and suggest challenges and implications for development. To support this purpose we have organised the paper into four primary sections. First, we provide an overview of existing literature and perspectives in the SoSE field. Unfortunately, while instructive on the variety of perspectives and field developments, the examination substantiates the fragmented nature of the SoSE field. Second, a framework is developed to bring structure to the developing SoSE field. The emphasis of this framework is to provide a high level viewpoint of the field that captures central issues in field development and their implications for more integrated maturation of SoSE. Third, the challenges for moving the SoSE field forward are explored. The suggestion is that failure to adequately address these challenges will slow progression of the field and potentially render the field innocuous. The paper closes with some concluding thoughts on the SoSE field and the methodology which was the primary subject of this volume.

2 The literature for SoSE

SoSE is a relatively new field of study as compared to other engineering disciplines and is often viewed as a mere extension of SE, a relatively young discipline itself. The literature for SoSE is fragmented as the field continues to develop and establish some common perspectives. However, this fragmentation has been the case in the past (Keating et al., 2003; Keating, 2005) and continues to characterise the present state (Sousa-Poza et al., 2009) of SoSE. In this section we illuminate the current state of this fragmented literature and the implications of this fragmentation for moving the field forward.

In development of the literature in SoSE we focus on achieving three primary objectives. First, we identify themes that currently exist in the SoSE literature. Our intent is to show that there is some level of convergence in the literature. Second, we examine
three emerging perspectives of SoSE; military, academic, and enterprise. This offers a starting point from which fragmentation can be better understood and frames some particular challenges that must be considered as the field continues to develop. Third, we further articulate areas of continued divergence in development of SoSE. This discussion sharpens the nature of the distinctions and their implications for further development of the SoSE field.

2.1 Common themes in SoSE

Despite a body of literature that is fragmented, there are some common themes that appear to mark the landscape for SoSE. The term system of systems has been applied to numerous types of systems. Examples include global earth observation system-of-systems (GEOSS) (Fritz et al., 2008; Herold et al., 2008; Martin, 2008), software-intensive system of systems (SISoS) (Lane and Boehm, 2008), reduction of carbon emissions system of systems (Agusdinata and Dittmar, 2007), modelling and simulation for system of systems (DeLaurentis, 2008; Mittal et al., 2009; Osmundson and Huynh, 2005), information management and net-centric system of systems (Kotov, 1997; Bass, 2005; Gorod et al., 2007), communication structures (Kotov, 1997), imagery and data mining system of systems (Christiansen, 2005; Gheorghe and Vamanu, 2008), space exploration system of systems (DeLaurentis et al., 2006), and maritime transportation system of systems (MTSoS) (Mansouri et al., 2009). Although the term system of systems has been used with significant breadth, there is little that would provide a litmus test to identify what can truly be titled ‘system of systems’ with any level of certainty. In effect, SoSE has not established a sufficient identity that can adequately distinguish in form and substance against other (related) fields such as SE. This may be due to the ‘newness’ of the field, but might also be due to potentially incompatible worldviews concerning the nature, purpose, and trajectory of SoSE.

However, irrespective of having disagreements on what system of systems is, many researchers and practitioners continue to publish work under the system-of-systems umbrella. Work being done demonstrates opportunities for how useful SoSE can be now and in the future in dealing with multidisciplinary problem domains across a variety of applications. Although within those domains the common threads in the SoSE literature exist at a very high level, beyond which consolidation and agreement is currently a fleeting prospect.

Maier (1998) has been frequently cited (DeLaurentis, 2008; Gorod et al., 2008a; Keating, 2009) for the proposed distinction of SoS from traditional systems captured by: operational independence of the elements, managerial independence of the elements, evolutionary development, emergent behaviour, and geographical distribution. These elements, along with some additional recognised elements, are pervasive in the literature for SoSE and are amplified below.

- **Operational independence of the elements** – decomposition of a SoS into constituent systems would not render the constituent system inoperable. Instead, each constituent system has the ability to operate independent of other constituents.

- **Managerial independence of the elements** – constituent systems that make up system of systems can be separately acquired and integrated with the managerial function of the constituent systems remaining independent of the SoS.
Evolutionary development – once a system of systems is enacted, changes have to be made to the SoS as more knowledge is acquired and circumstances shift. Thus, functions can be added, removed, or updated until the SoS effort is no-longer necessary. The SoS continuously evolves. This is in contrast to traditional systems, where all phases of design, from conceptual design through system retirement are ‘front’ loaded.

Emergent behaviour – Keating (2009) suggests this attribute exists in all SoS efforts with roots found in classical systems theory, where properties (patterns, capabilities, structure, behaviours, performance) develop from the interaction of system elements over time. These properties and events cannot be predicted or understood from the properties of single elements in the system of systems.

Geographical distribution – Eisner (1993) early on suggested that systems of systems are large geographically distributed assemblages. The notion of geographical distribution has continued to be a point of consensus in the SoSE literature.

Interoperability – interoperability is “the ability of two or more systems or components to exchange information and to use the information that has been exchanged” [IEEE 610.12., (1990), p.42]. Although this seems trivial, manmade systems are typically designed in isolation, not as systems of systems. SoS only inter-operate constituent systems after deployment and after new patterns have emerged, especially in system acquisition (Boardman et al., 2006).

Complementarity – complementarity provides multiple perspectives of any given system (Keating et al., 2004). While each perspective is neither correct nor incorrect, the “Multiple views and perspectives are essential, particularly in the formative stages for a system of systems effort, to ensure a robust approach and design. Failure to include multiple perspectives can be limiting to the eventual system of system solution that is generated” [Keating, (2005), p.3] which can lead to a Type III error (Mosteller, 1948; Mitroff and Featheringham, 1974) of solving the wrong problem precisely. Each system should complement the other systems within the SoS arrangement.

Holism – this is a philosophical concept that is opposed to atomism. An atomist idea presents the belief that any whole system can be broken down or analysed into separate parts and the relationships individually indentified. However, the holistic view maintains that the whole is the primary and often greater than the sum of its parts. “Holism suggests that we cannot understand a complex system through reduction to the component or entity level” [Keating et al., (2008), p.27] even though by nature of analysis we reduce a complex SoS problem in order to understand it more fully. To understand the concepts presented in SoS, we should be able to holistically understand, develop, and deploy SoS efforts in order to fully appreciate their purposes.

Even though the SoSE field lacks maturity, we conclude that some of the more common accepted assumptions include:
• a higher level of interaction amongst constituent systems
• SoS efforts have to produce a service, behaviour, or performance that cannot be produced by single systems
• SoS systems can operate independently of the SoS to achieve a purpose separate from the purpose of the SoS
• a SoS is made of multiple complex systems which are working towards a common goal or mission
• intended and unintended consequences can emerge as a result of the interaction of multiple complex systems working together in a SoS.

There appears to be some convergence around the characteristics of a system of systems and general ‘properties’ attributable to a system of systems. However, we conclude that the field of SoSE continues to struggle with fragmentation and multiple perspectives. Three perspectives, military, academic, and enterprise, are examined as exemplary of this fragmentation of the SoSE field.

2.2 Three emerging perspectives on SoSE

In review of the literature on SoSE, we found that perspectives appeared to emerge around three dominant schools of thought depicted in Figure 1.

Figure 1 Three diverging perspectives of SoSE (see online version for colours)

First there is the military perspective, driven primarily from an emerging perspective within the US Department of Defence. This perspective is dominated from a set of constructs focused on ‘interoperability’ of technological command and control (individual) systems. These individual systems require integration of separate ‘technology’ systems in support of a ‘system of systems’ mission.
A second emerging school is based in the academic perspective. Although this appears to be the weakest of the emerging perspectives, we thought it was important to include since it represents potential for more rigorous and grounded development along philosophical and theoretical lines.

The third emerging perspective is what we have deemed the enterprise perspective. This perspective takes a more robust view of SoSE, taking into account the notion of the enterprise as a system of systems that exists beyond the purely technological view.

Our concern is not to judge a particular perspective as right or wrong. On the contrary, the different perspectives are put forward to show the potential sources of divergence in the development of the SoSE field. Each perspective brings a logic which provides its own internal validation to the community which produces and consumes the perspective. However, our major premise is that the unexamined intersection of the multiple perspectives emerging within the SoSE field are a source of divergence and will continue to hinder coherent development of the field.

2.2.1 The military perspective of SoSE

At this point in SoSE development, we accept that there is not an accepted definition of SoSE. However, the development of SoSE appears to be most closely, and perhaps inextricably linked, to the military community. In addition, the military perspective appears to somewhat dictate the past discourse in SoSE. The military discourse appears to be dominated by four primary themes:

1 Emphasis of ‘technology’ as primary. This appears in the overriding emphasis of the technological aspects of the problem domain of concern to military developers. The concern with the system of systems role in military domains is focused clearly on supporting command and control through the integrated use of technology to achieve system of systems missions. If addressed at all, other dimensions of systems of systems (human, social, political, etc.) receive minimal emphasis.

2 Interoperability of technology as a central objective. In support of the technical emphasis, the military concern is with ensuring that ‘all’ technical (sub)systems in a system of systems are interoperable. That is they can effectively pass data and information across multiple ‘independent’ subsystems to provide integration for command and control. Therefore, a system of systems is an integrated network of technological subsystems that work together to support achievement of the military command and control functions.

3 Extrapolated from SE. The military version of SoSE finds its basis in more traditional thinking about SE. This relates to an emphasis on requirements, traceability, and the ‘architecture’ paradigm.

4 Heavy emphasis on acquisition. The military perspective is biased toward the processes and considerations for acquiring equipment (technical) that must operate together (interoperability). This acquisition emphasis permeates the military driven SoSE perspective.

The military dominated perspective complicates development of the SoSE field. In recent US Department of Defence publications (DoD, 2006, 2008), the non-uniformity of SoSE perspectives was acknowledged by recognition of notions such as:
1. no difference between SE for systems and system of systems
2. the only difference is no one in control of a system of systems
3. nothing being new in system of systems, any system that has subsystems is a system of systems, and this has been done since the inception of SE.

The US military has emerged as a leader in promoting system of systems and the perspective has been dominant in the discourse and development of the field. Their continued efforts are expressed (DoD, 2006) and reinforced in an updated version of the Systems Engineering Guide for Systems of Systems (DoD, 2008). In titling the updated version of the guide, the perspective suggesting SoSE as the extension of SE perspective is evident (Chen and Clothier, 2003). To capsule the military perspective, we provide some definitions associated with the military perspective of SoS and SoSE;

“SoS systems engineering deals with planning, analyzing, organizing, and integrating the capabilities of a mix of existing and new systems into a SoS capability greater than the sum of the capabilities of the constituent parts.” [DoD, (2008), p.4]

“The overall objective for developing a system of systems is to satisfy capabilities that can only be met with a mix of multiple, autonomous, and interacting systems.” [DoD, (2006), p.5]

“Systems of systems should be treated and managed as a system in their own right, and should therefore be subject to the same systems engineering processes and best practices as applied to individual systems.” [DoD, (2008), p.5]

“A set or arrangement of interdependent systems that are related or connected to provide a given capability. The loss of any part of the system will significantly degrade the performance or capabilities of the whole. The development of a SoS solution will involve trade space between the systems as well as within an individual system performance.” [DoD, (2006), p.83]

The military-centric view of SoSE seems to be focused on an extrapolation from SE. In Table 1, the thrust of the military perspective of SE in relationship to SoSE is provided. This is not a ‘criticism’ of the military perspective. On the contrary, it is intended to suggest the need to ‘open’ the dialog to other perspectives to mature the SoSE field. We conclude that the military perspective of SoSE is an extrapolation of traditional SE, simply taking a different emphasis.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Traditional SE</th>
<th>SoSE</th>
</tr>
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<tbody>
<tr>
<td>Purpose</td>
<td>Development of a single system to meet stakeholder requirements and defined performance</td>
<td>Evolving new system of systems capability by leveraging synergies of legacy systems and emerging capabilities</td>
</tr>
<tr>
<td>Systems architecture</td>
<td>Established early in the life cycle; expectation set remains relatively stable</td>
<td>Dynamic adaptation as emergent needs change</td>
</tr>
<tr>
<td>System interoperability</td>
<td>Interface requirements are defined and implemented for the integration of components in the system</td>
<td>Component systems can operate independently of SoS in a useful manner; protocols and standards are essential to enable interoperable systems</td>
</tr>
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Source: Adapted from Valerdi et al. (2007)
Table 1  Emphasis areas in SE and SoSE (continued)

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Traditional SE</th>
<th>SoSE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System ‘ilities’</strong></td>
<td>Reliability, maintainability, and availability are typical concerns</td>
<td>Enhanced emphasis on ‘ilities’ such as flexibility, adaptability, and composability</td>
</tr>
<tr>
<td><strong>Acquisition and management</strong></td>
<td>Centralised acquisition and management of the system</td>
<td>Component systems separately acquired and continue to be managed and operated as independent systems</td>
</tr>
<tr>
<td><strong>Needs anticipation</strong></td>
<td>Concept phase activity to determine system needs</td>
<td>Intense concept phase analysis followed by continuous anticipation, aided by ongoing experimentation</td>
</tr>
<tr>
<td><strong>Related cost</strong></td>
<td>Single or homogenous stakeholder group with stable cost/funding profile and similar measures of success</td>
<td>Multiple heterogeneous stakeholder groups with unstable cost/funding profile and measures of success</td>
</tr>
</tbody>
</table>

Source: Adapted from Valerdi et al. (2007)

The military embrace of SoSE is not likely to subside in the near future. As systems become more complex in technological sophistication, the need to integrate them technologically will continue to dominate the military perspective discourse. This is not necessarily bad or good. However, it can drown out more novel and wide ranging discourse on the developing field of SoSE.

2.2.2 The academic perspective of SoSE

The academic perspective offers a very different and more expansive look at the nature and development of the SoSE field. The suggestion of the academic nature of SoSE development is held in three primary elements of the perspective:

1. **Search for theoretical and conceptual differentiation.** For a field to mature it must establish an identity that provides a marked uniqueness from other fields. Confusion exists when these distinctions are not made. A primary thrust from the academic perspective is to establish these distinctions. Unfortunately, the calls for these distinctions have been near absent. Works such as Keating (2005), Gorod et al. (2008b), and Sousa-Poza et al. (2008) demonstrate this struggle for field identity and distinctions.

2. **Exploration of phenomena as central.** In contrast to other SoSE perspectives, the academic perspective is interested in taking a more cerebral approach to development. This is in stark contrast to the military perspective, which shows little patience for theoretically grounding of SoSE practices, instead focusing on ‘real world’ technical applications. In theoretical work, the emphasis is on investigation, inquiry, and seeking to understand SoSE phenomena whose origins and explanation are in question. In such works as Keating (2005), Gorod et al. (2008b), and Sousa-Poza et al. (2009) this academic quest is evident.

3. **Grounding in systems theory.** The academic perspective appears to appreciate and attempts to ground itself in systems theory. The principles, laws, and concepts of systems theory (Skyttner, 2001) and the host of seminal systems authors (Beer, 1979,
1981; Checkland, 1993; Mitroff, 1998; Midgley, 2003) provide a basis for a deeper academic development of SoSE and linkage to a sound theoretical body of knowledge. This perspective is largely being lost in the SoSE field development.

The academic perspective of SoSE is captured in several of the definitions that have emerged. For instance, Keating et al. (2003) suggested that SoSE is

“The design, deployment, operation, and transformation of metasystems that must function as an integrated complex system to produce desirable results. These metasystems are themselves comprised of multiple autonomous embedded complex systems that can be diverse in technology, context, operation, geography, and conceptual frame” (p. 36).

This definition lies in stark contrast to those suggested by the military perspective, bringing in notions of autonomy, meta-systems, and complexity. This perspective finds its roots deeply embedded in the systems theory and cybernetics literature. The academic conundrum is further suggested as a split in SoSE development between perspectives rooted in a technical perspective (e.g., SE) or inquiry perspective (e.g., systems thinking) as the driving emphasis (Sousa-Poza et al., 2009). Further suggesting the distinction of the more cerebral academic perspective from that rooted in industry/government applications, Gorod et al. (2008a) identify a separate lineage to SoSE ‘academic’ development in contrast to the technical (practice oriented) development. The more robust nature of SoSE development of the academic perspective is evidenced by reference to such diverse concepts as multidisciplinary development (Sousa-Poza et al., 2009) and paradox (Gorod et al., 2008a; Keating, 2008; Simpson and Dagli, 2008). We anticipate that the academic perspective will continue to advance as an essential part of the SoSE field evolution, despite the overwhelming emphasis on the ‘practical’ SoSE applications sought by government and industry practitioners.

2.2.3 The enterprise perspective of SoSE

The enterprise perspective of system of systems provides an important set of insights into distinctions in the emerging field of SoSE. It is noteworthy that the enterprise perspective drops ‘engineering’ for the emphasis on system of systems. This distinction is important as it places distance between disciplines rooted in SE and the enterprise applications of system of systems. In effect, there is a widening of the system of systems (engineering) paradigm from the enterprise perspective. Several of the central tenets for the enterprise perspective include:

1  Expanse beyond technical considerations. The enterprise emphasis in many instances embraces movement of SoSE beyond the narrow focus of technology. Instead, the enterprise perspective includes areas as diverse as strategy and social components (Rouse, 2006; Rebovich et al., 2009). This expansion of SoSE is critical to an emerging field that could easily be bounded to a technology centric disposition.

2  De-emphasis of engineering. It is not by accident that the enterprise perspective appears to de-emphasise engineering in SoSE. SoS presents a broader reach and also permits inclusion of ‘non-engineering’ applications such as enterprises (Rebovich, 2009) and the different types of problems which can be addressed beyond a technology solution orientation.
3 Dominance of architecture. The notion of architecture at the system of systems level is central to the enterprise perspective. System architecture has been a dominant theme in SE (Maier and Rechtin, 1999; Maier, 1998) and has certainly found roots in emerging research in SoSE (Valerdi et al., 2008) and particularly in the enterprise architecture paradigm (Carlock and Fenton, 2001; Morganwalp and Sage, 2002; Rhodes et al., 2009).

While we might certainly entertain other framing perspectives for SoSE, the selected perspectives were purposefully chosen to illustrate three important points. First, the field of SoSE is emerging, and as such the dialogs are also emerging and are beginning to ‘cluster’ around more dominant focal perspectives. This is essential to prevent SoSE from developing in a singular monolithic fashion. Second, and unfortunately, the emerging dialogs are developing in near mutually exclusive and independent directions. This may limit the integrated development of the field as a result of the splintering of paradigms to the extent that they are no longer recognisable to one another. Of higher concern and consequence is the lost potential for insights that might accrue from cross-dialogs between the perspectives. Third, the thought must be engaged that the underlying worldviews, upon which the different perspectives find their basis, may be irreconcilably incompatible. Given an inability to reconcile worldviews that underpin the perspectives, SoSE is likely to evolve into a fragmented set of clustered focal areas. This would certainly result in a field never to mature to a point of sustainability, instead relegated to a temporary faddish passing as the next big idea comes along.

2.2.4 Continuing divergence in the emerging SoSE field

In this section, we discuss problems that face SoS and have contributed to ambiguities related to the definition of SoS. While military, academia, and private enterprises point to the potential need and use of SoSE, the literature reveals that the SoSE field is diverse but divergent. We present the following as continuing divergences within SoS perspectives as first denoted by Keating (2005), and amplified here:

- beyond some high level agreement, there is not considerable broad acceptance of what constitutes a SoS
- although SoSE is a term that has been used, it has not received broad acceptance in definition or underlying perspectives related to philosophy, methodology, or standards
- research in SoS and SoSE has been fragmented, with a range of efforts and applications, with little research development targeted to underpinnings of base knowledge
- irrespective of contrast to SE, distinctiveness of SoSE in relationship to associated domains has not been clearly established
- current endeavours that are assumed to be from the system of systems arena do not adequately indentify or qualify reasons for such claims
- in some sense, SoSE has been supplanted by SoS in popularity, further reducing the development emphasis for SoSE
• lack of rigorous development of the conceptual and theoretical basis of SoSE necessary for claims of identity for the field, sustainability of development, and ultimately viability

• ethical considerations in SoSE are not a consideration, even in the face of system of systems that require scrutiny in the political/policy domains beyond technical engineering considerations.

These divergences might be explained due to SoSE still being a developing field and also emphasis on technical aspects of systems knowledge. This has relegated development to a technical focus, minimising emphasis on tacit core knowledge foundations like philosophy, methodology, and axiology. As was the case in Keating (2005), we find it essential to mention that SoSE development is still sorely lacking in philosophical, methodological, axiological, axiomatic, and theoretical levels to complement the applications, methods, tools, and techniques developing.

3 Bringing structure to the developing SoSE field

Development of the SoSE field can, and has, proceeded on many fronts, including the academic, military, and enterprise directions already noted. However, we propose a particular framework to better organise, integrate, and understand the research, development, and activities engaged under SoSE. The framework takes a holistic view to simultaneously move a field forward along several fundamental dimensions. Based on previous work for emerging knowledge (Keating, 2005; Keating et al., 2003, 2010), Figure 2 depicts the holistic relationships for integrated knowledge development.

Figure 2 Interrelated areas of development for the SoSE field (see online version for colours)

A synopsis of the levels of focus for each of the interrelated levels is provided:

• Philosophy – research directed at developing a theoretically consistent articulation of the paradigm(s) for SoSE. The emerging system of beliefs providing grounding for theoretical development is the primary contribution of this area.
- **Theory** – research focused on explaining phenomena related to SoSE and development of explanatory models and testable conceptual frameworks. The range of theoretical developments advances understanding of the field and encourages diversity in thinking.

- **Axiological** – research that establishes the underlying value, value judgment frameworks, and belief propositions that are fundamental to understanding the variety of perspectives for the SoSE field.

- **Axiomatic** – investigation into the emerging principles, concepts, and laws that define the field and constitute the ‘taken for granted’ knowledge upon which the field rests. This also includes integration of knowledge from other informing and related fields/disciplines.

- **Methodological** – research undertaken to develop the theoretically informed frameworks that provide high level guidance for design, analysis, deployment, and evolution of SoSE efforts.

- **Method** – research focused on development of the specific models, technologies, standards, and tools for SoSE. In effect, this is the development of the toolsets and implementing capabilities for practitioners in the SoSE field.

- **Application** – advancement of the practice of SoSE through deployment of science-based technologies and methods.

In the following sections, we develop the current issues in field development across each of these areas. While this development is certainly not intended to be exhaustive, it does represent the nature of developmental issues across each of the areas.

### 3.1 Philosophical development view

Philosophy establishes the world view which ultimately drives decision, action, and interpretation to consistency. Worldview has been presented as “….a system of coordinates or a frame of reference in which everything presented to us by our diverse experiences can be placed” [Aerts et al., (1994), p.9]. This world view is what Checkland (1999) refers to as weltanschauung, the image or model of the world that provides meaning. Philosophical underpinnings (epistemological and ontological) provide the foundation for any field that informs the dominant perspective of the field from an internally consistent reference point. SoSE does not currently have a consistent worldview and will be challenged to establish this consistency in the future.

The development of a strong philosophical basis is essential to maturation of the SoSE field. Philosophy provides the broad underpinnings that support development of methodologies, technologies, and tools consistent with the SoSE paradigm. Lack of commonality in questions concerning the nature of knowledge (epistemology) and how reality is viewed (ontology) are certain to be a continuing source of problems for development and sustainment of the SoSE field. Sousa-Poza et al. (2009) stipulate that

> “just as traditional systems engineering tools are not sufficient anymore to deal with today’s problems, the hypothetico-deductive method of theory testing common in the dominant discourse will no longer serve the needs of the contemporary research to build theory or address SoS problems … Given that SoS is a nascent discipline the work presented by many researchers in the field is theoretical by nature and in the best case exploratory.” (p.5)
Some may claim empirical work in SoSE but solely under narrow conditions in which the idea of SoS is lost or void of social context (Sousa-Poza et al., 2009). Sauser et al. (2009) suggest developing a philosophical view of SoS explains “why do we have this asynchronicity and how might it be overcome; what is the essence of a system and how can this be leveraged to explain the fundamental distinction between a system that is truly a SoS and one that is ‘merely’ a system (of parts)” (p. 294) and why a shift in thinking may be needed.

The lack of a strong philosophical foundation contributes to continued ambiguities emerging in the SoSE field. This is not to suggest that there can, or should, necessarily be convergence in all aspects of the SoSE philosophical paradigm. However, there should be a continuing dialog on philosophical issues such that the accepted values and premises of the field become more commonplace. At a minimum, the debate should be sharply focused on key philosophical distinctions. At present, the ‘mainstream of SoSE’ is far from engaging the philosophical dialog and debate.

### 3.2 Theoretical development view

The theoretical development for SoSE lacks emphasis and sophistication. It is difficult to speculate why this is the case. Perhaps it is because the pragmatic applied perspective of SoSE has little patience for theoretical expositions. Or perhaps the linkage to SE, held by many engaged in SoSE field development, has been primarily developed from a practitioner’s perspective. This practitioner’s perspective has shown little inclination to explore or develop theory. It would be an understatement for us to write that we lack grounded theories in SoSE. Theoretical treatment of SoSE simply does not have any semblance of maturity or organisation. Well developed theories can be instrumental in furthering and accelerating development of the SoSE field. There is a close coupling between theory and the other interrelated field development areas. The viability of a field often rests with sustainable theoretical guides and less with the derivatives (e.g., tools) that are developed at a lower level of granularity to support applications. Good theoretical foundations provide for field sustainability and viability into the future. Theory provides a basis for testing, evaluation, and increasing validity of propositions. The patience necessary to validate theory takes time. It will remain to be seen whether or not the SoSE field has the patience and temperament to invest in development of the theoretical aspects of the field. It would be unfortunate for the theoretical concentration to be ignored as SoSE matures.

### 3.3 Axiological development view

Axiology is related to the nature of value and value judgements and thus has a strong human-subjective component. On the surface we might argue that SoSE implicitly engages values and value judgements by its very nature. However, beyond implicit and superficial treatment of axiology in SoSE, the field has not begun to effectively address the issues and implications concerning values. For example, systems works such as those of Midgley (2000) and Gibson et al. (2007), discussing the nature of values and boundary judgments, have not made it into the mainstream for consideration in development of the SoSE field. While SoSE has recognised the critical importance of the human element (Keating et al., 2003; Keating, 2005), the development of the axiological component in SoSE is sorely deficient. An emphasis and consideration for axiological development of
SoSE offers significant opportunity for advancement of the field. Human values and value systems are certainly not new to the systems literature (Hebel, 1999; Parra-Luna, 2001), but have thus far eluded significant inclusion into the landscape of the developing SoSE field.

3.4 Axiomatic development view

The development of self-evident truth is necessary for SoS to be fully appreciated. According to Keating (2005), we need to develop SoS with what is accepted as source knowledge which we currently lack. This large responsibility lies primarily with the academic community, which must take the lead in the development and dissemination of source knowledge. The incorporation of existing principles, laws, and concepts from the ‘systems’ world must be coupled with new and emerging knowledge that matures into accepted axiomatic propositions for the SoSE field. The lack of emphasis on development of this conceptual foundation for SoSE highlights the need for rigorous development of axiomatic knowledge to drive consistency in principles, concepts, and laws across all domains of SoS applications. The wide ranging reach of SoS increases both the need and difficulty in developing an axiomatic consistency for the field. However, without this development, the SoSE field will likely be relegated to a fleeting notional concept that burned out only to be replaced by newer ideas in vogue.

3.5 Methodological development view

Keating (2005) suggests that a methodology is concerned with the guiding frameworks that inform engagement of SoSE problems. However, it might be expected that as SoSE continues to mature, the available methodologies to support SoSE will continue to grow. There is not a singular SoSE methodology that dominates the field, nor should there necessarily be, particularly in the early stages of field development. The SoSE methodology presented in this volume exemplifies a methodology, with a corresponding set of assumptions, strengths, and limitations. The universally accepted and applicable SoSE methodology is a fantasy since each methodology has limitations. However, it is important to note that a SoSE methodology, either implicitly or explicitly, draws upon grounding from the philosophic, axiologic, and axiomatic levels. In this sense, the degree of divergence in methodologies for SoSE, present and future, will be rooted in philosophic, axiologic, and axiomatic-based differentials. This is not a criticism of any particular methodology. Instead, we look to the philosophical underpinnings as a potential source of divergence. However, a mark of maturity of a field is found in the acceptance of the philosophical traditions and axiomatic consistency. Unfortunately, in the SoSE literature, there is not an acknowledgement of the philosophical basis for current methodologies and applications. This must be inferred as an afterthought, with philosophical and axiomatic consistency limitations simply not considered as an informing precursor to development or application. However, the methodology developed and applied in this volume breaks from the norm and does account for philosophic and axiomatic grounding.

A SoSE methodology is not necessarily better, but only more appropriate given the context and philosophical disposition of that context for application of the methodology. A central challenge for maturing the SoSE field is to advance
methodologies that are ‘accountable’ for their philosophical underpinnings. Thus, the appropriateness, or inappropriateness, for application may be better understood. It is doubtful that SoSE will ever have a ‘universally’ accepted methodology. On the contrary, SoSE methodologies are more likely to be more or less congruent to the circumstances surrounding their application. The notion of not thinking of methodology as right or wrong has been echoed by Valerdi et al. (2007). What has been, and still remains, the case is the recognised need for industry, academia, and government to engage rigorous efforts in development of SoSE methodology (Mittal et al., 2009; Keating et al., 2004).

3.6 Methods view

There is an abundance of tools (Valerdi et al., 2007; Chattopadhyay, 2008; Keating et al., 2009), techniques (Sindiy et al., 2007; Sheard and Mostashari, 2009; Keating et al. 2009), processes (Clark, 2009; Keating et al., 2009), and technologies (Dahmann et al., 2008; Ulyanov, 2008) that can be applied to SoS endeavours. However, the preponderance of these tools, techniques, processes, and technologies have been extrapolated or adapted from other fields for application in a SoSE domain. This is not to criticise these approaches, or to cast doubt on their ability to assist in a SoSE endeavour. On the contrary, while these approaches may offer utility, the fact remains that approaches typically have not been ‘purpose built’ specifically for facilitation of SoSE and this area is severely lacking. This might be expected of a field in the embryonic stages of development. Whether these artefacts have been developed for use in SE or SoSE is a matter of how unique that are in the relation to problem at hand. If a problem is determined to be of the SoS category, this means the methods employed have to be appreciative of the unique nature of the problem, distinct from more traditional systems problems. This will ensure that proper tools, techniques, or processes are employed (Wojcik and Hoffman, 2007). Keating (2005) stipulates that “It is important to note that the determination of ‘appropriateness’ is a function of the other levels [views], the context, and the system of systems problem” (p.4). Concerning methods, Sousa-Poza et al. (2009) add that while “a methodology provides the foundation for the development of robust methods, it is the methods, however, that provide the scholar the necessary basis for a robust defence against criticism” (p.5). This implies the flexibility of method selection to perform within the general framework of a methodology. It is evident that there is much yet to be done concerning the development of specific methods to support SoSE endeavours, but also the implications for selection of SoSE methods consistent with the problem, context, and methodology.

3.7 Applications development view

Since system of systems is an emerging field, there is not a vast array of applications we would hold as exemplary. Most certainly, there are reports that purport to be of SoSE applications, particularly from the dominant military perspective (e.g., Dahmann et al., 2008; Boardman et al., 2006). In addition, there have also been SoSE and SoS development in a variety of fields, including areas as diverse as critical infrastructure (Gheorghe and Vamanu, 2008), space (DeLaurentis et al., 2006), and energy (Agusdinata and DeLaurentis, 2008). However, there is much to be gained
by widening the boundaries of the discourse on SoSE. For many application related works, it is difficult to precisely determine how SoSE is being applied. The applications may range from ‘hard’ SE to variants of general systems theory, cybernetics, and systems thinking. There is also an emerging issue related to applications dropping the engineering from SoSE and simply claim the more general SoS descriptor. For the SoSE field to mature there must be some boundaries that allow specificity for what constitutes a SoSE application. Just as the notion of what constitutes a SoS has started to gain some clarity, so too must the nature of what constitutes a SoSE application gain clarity.

As a start to understanding whether or not an application is truly a SoSE application, we believe that SoSE field development must clarify understanding of how the following areas are considered:

- **problem** – the nature, characteristics, and formulation of what constitutes a SoSE problem for application
- **context** – the unique aspects of the domain within which the SoS and the SoSE problem are embedded, influencing the approach, results interpretation, and expectations
- **worldviews** – the compatible or incompatible perspectives that underpin SoSE application and influence framing of the problem, approach, and interpretation of results
- **approach** – the development of an appropriate (fit to context, worldview, and problem) methodological approach to address the situation.

At this point in development of the SoSE field, there appears to be little emphasis on the nature of problems for which SoSE is applicable. This may stem from the multiple utilities of SoSE, including:

1. a philosophical worldview for understanding the systemic nature of complex systems and the efforts to engineer appropriate responses
2. methodologies to guide and direct efforts for complex system (of systems) problems
3. a language capable of driving thinking, decision, action, and interpretation to different levels
4. an emerging set of tools/methods to assist practitioners in dealing with complex system of systems problems
5. a set of systems-based principles that engage more holistic understanding and action for complex problems.

However, there must be limits to application of SoSE, or at least recognition of the level of SoSE being applied to a problem domain. Surely, every problem is not suitable for SoSE application. However, there is not currently a distinguishing set of features that would permit consistent inclusion, or exclusion, of candidate problems for SoSE application. Resolution of the application question should receive increasing emphasis if SoSE is to remain viable and create an identity that distinguishes it from other related fields.
4 Challenges to advancing the SoSE field

The advancement of SoSE is currently challenged. While we hope that the field begins to develop in a more integrated fashion, it is entirely possible that the roots of fragmentation will make consolidation unlikely. While this is neither bad nor good, it certainly limits the potential of this emerging field. Early in the development of a field, struggles are important to challenge ideas and resist the temptation to accept too early unchallenged assumptions. However, for a field to mature there must be some consolidation and foundations accepted, even as temporary stepping stones for further development of a coherent identity. SoSE is now struggling to find consolidation and an identity that can distinguish it as a field. As a starting point for examining challenges to SoSE, we suggest that SoSE finds applicability for the following circumstances:

- where traditional SE has failed to produce intended results for problems that exist well beyond technical dimensions, to include more holistic dimensions including organisational and managerial, policy and political, and human and social
- where traditional SE approaches cannot be appropriately applied due to the nature of the problem domain having high levels of uncertainty, ambiguity, and emergence
- where low levels of understanding of the problem domain and relationship of constituent system elements influence the approach and resolution expectations for the situation.

In light of these considerations, we suggest the following primary challenges for the maturing SoSE field.

- **Treatment as an extension of SE** – A system of systems has been recognised as unique in relationship to a system. Therefore, approaches and thinking based in ‘traditional’ SE extrapolated for application to SoSE should be met with scepticism. Otherwise, there is little utility in a unique field developed for SoSE. Instead, it would be simply another form of SE.

- **Aspiring to rigor in field development** – From a gestalt perspective, while applications purporting to be of the system of systems variety may be completed with rigor, the development of the field itself does not project rigorous development. This is evident by the lack of significant literature concerning the conceptual foundations for SoSE. Instead, emphasis is placed on methods and applications. This imbalance represents a major challenge to holistic and balanced development of the field.

- **Sacrifice of theoretical maturation** – There is a strong basis in systems theory and cybernetics that is largely being bypassed by the developing SoSE field. The systems basis for SoSE holds great promise. Existing laws, concepts, and principles stemming from the rich history of ‘systems’ seems to be largely ignored in development of the SoSE field. Inclusion and expansion of this theoretical body of knowledge will serve to strengthen the foundations of the SoSE field.

- **Explore non-dominant dialogues** – Exclusion of the philosophical, theoretical, axiomatic, and axiological domains misses an opportunity to broaden the emerging SoSE field. These domains are what will provide a more robust foundation and provide for sustainable grounding of the field in something other than methods and applications. Longevity will be a function of holistic development of the SoSE field.
• **Unrealistic separation of system from context** – There seems to be a somewhat tacit acceptance for separation of the system from the context (circumstances, factors, patterns, conditions) within which the system is embedded. This separation is false and limits the inquiry into the system of systems. If systems of systems are truly to be engineered, this engineering must also account for the context within which the system of systems exists.

• **Holistic treatment of the problem space** – There is a propensity to attack SoS problems as first and foremost technical problems that require a technology-based solution. This may be because technical solutions are generally well bounded, less ambiguous, and generate more easily understood solutions. Unfortunately, SoSE problems lie beyond technical solutions. This means that the SoSE problem must be approached holistically, considering the range of technology/technical, organisational/managerial, human/social, and political/policy issues – including their interrelationships. To focus primarily on technical aspects of SoSE problems limits the potential the SoSE field offers.

• **Characteristics and role of the SoSE engineer** – The knowledge, skills, and abilities that distinguish a SoSE engineer are not sufficiently identified. If this engineer is truly ‘different’, the nature of the difference must be understood and incorporated into selection, training/education, and qualification. This is a difficult task, since a SoSE engineer may cross many different disciplines based on the particular problem being faced. The limits to the domains where a SoSE engineer might participate remain unexplored.

While this set of challenges is certainly not complete, it offers a glimpse into areas that are not currently being exploited for maturation of the SoSE field.

5 Conclusions

The emerging field of SoSE is entering into an exciting and challenging time. The fact that SoSE has been slow to develop as a field is no coincidence. From initial struggles with defining the characteristics of a system of systems to the lack of accepted definition(s) for SoSE, the field appears in some disarray. In this paper, we have tried to provide some understanding of the state of the field, some organising constructs as a path forward to begin a more focused development, and several challenges to maturation of the field. This is especially relevant as the future of the field is presently being written.

The methodology and application which has been the subject of this volume is a step forward in the quest to advance the SoSE field. The methodology and application are demonstrative of three important implications for researchers and practitioners engaging in the development of SoSE. First, the methodology presented is *a* methodology, not *the* methodology. A fixation on developing the singular methodology for SoSE is an illusion. As was evidenced in the development, the methodology remained malleable, being fit to the uniqueness of the problem as well as the context within which the problem existed. Second, the methodology was based in explicit system-theoretic foundations. This established the basis for understanding necessary for all following applications of the methodology. The system foundations provide a consistent frame of reference for application. Application decisions, actions, and interpretations find consistency in the
reference point provided by theoretical and philosophical grounding. Third, a SoSE effort such as this application can be as much about inquiry for understanding as about developing a tenable solution. It is short-sighted to engage complex SoS problems with the expectation that a solution will necessarily result. On the contrary, there might simply be the uncovering of another set of problems, or perhaps an identified set of feasible activities to ameliorate some aspects of the situation. To some quarters of the loosely coupled SoSE community this is at the same time troubling, unacceptable, and threatening to a worldview based in a strict problem-solution paradigm.

The advancement of the SoSE field will require concerted efforts of the academic, industrial, and government communities. It is inevitable that SoSE will encounter barriers (as it already has) from some practitioners, researchers, engineers, and the general public whose core work and understanding is based on tradition SE. The culture of traditional SE relies heavily on developing solutions to well bounded technical problems. Unfortunately, the SoSE problem domain is concerned with problems that are uncertain, ambiguous, emergent, and lack definitive boundaries. Therefore, there is a need for new language to drive new thinking, new technologies to support applications, and new applications to demonstrate utility of the SoSE field. If SoSE is to remain viable and mature as a field, we must resist short sighted temptations to unilaterally focus on convenience rather than thoughtful and holistic development.

References


