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Systems of Systems Engineering: A research Imperative

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I. ABSTRACT

Systems of Systems Engineering constitutes a major challenge for the 21st Century and research into this topic has become an imperative. The Support Action, T-AREA-SoS has been initiated by the European Commission to develop a research agenda in Systems of Systems (SoS) that will inform future investment in this area. Through an extensive consultation and review, a number of SoS capability gaps have been identified. Through structuring and subsequent consultation, these have been developed into twelve research themes the detailed areas of which are mapped to the three SoS characteristics of control, evolution, and emergent behaviour. A framework is presented through which researchers can develop a research campaign in SoS.

II. INTRODUCTION

The concept of systems of systems (SoS), largely confined to the IT and defence communities, has become widespread across many domains and is now a topic of significant research interest. The European Commission has initiated four projects specifically addressing the SoS topic under FP7 (ICT-2011.3.3), two of which (T-AREA-SoS [1] and ROAD2SOS [2]) seek to define a future research agenda that will strengthen European capabilities in the engineering of such complex systems. As will become apparent in the descriptions that follow, the term engineering requires a broad interpretation in the SoS context, because factors associated with information management, human and organisational behaviours, management and governance (to name but a few) also have a significant impact on the performance and quality of SoS. Jamshidi [3] [4] has defined a SoS as follows:

"A SoS is an integration of a finite number of constituent systems which are independent and operatable, and which are networked together for a period of time to achieve a certain higher goal."

This implies that engineering of SoS is not concerned with the intricacies of the individual systems from which the SoS is constructed, but with engineering the interfaces between these systems. Nevertheless, one of the risks in SoS is that the interaction of such intricacies between systems may not be adequately understood and, therefore, not accounted for in the architecture so that unexpected behaviour can occur. It is also problematic that the interfaces are not only concerned with data, but will generally include higher levels of abstraction in which human and organizational interaction occurs. Strictly, the interfaces are not simply concerned with exchange of data or information, but with the resulting interoperation between the systems, through which new capabilities are realised.

NCOIC [5] has defined an interoperability spectrum which shares nine specific interoperability layers between the three broad categories of Network Transport, Information Services, and People, Processes and Applications. At the higher layers of this spectrum, the risk of ambiguity and uncertainty in the communication and, therefore, the risk to the interoperable behaviour between the component systems increases. Furthermore, the simplicity and rapidity with which systems may be networked is creating complex interactions that are imperfectly understood or even unplanned, posing challenges for technical and more general enterprise governance. The study of engineering SoS is not so much a matter of interest and choice, as an imperative to cope with increasingly complex socio-technical systems that are developing with and without centrally co-ordinated design.

This paper begins with a more detailed description of the characteristics of SoS and some contrasts between traditional systems engineering and systems of systems engineering. It will then describe in rather general terms the problem of researching SoS Engineering (SoSE). Through a process of gap analysis and stakeholder engagement, gaps in SoSE knowledge have been identified in the T-AREA-SoS Support Action [1] and from these a set of prioritised research themes has been generated. The relationship of these themes to the high level characteristics of SoS are described which will enable the reader to identify the critical research questions associated with SoS in the domain of interest.

III. SYSTEMS OF SYSTEMS CHARACTERISTICS

It is generally accepted that a SoS exhibits a majority of the five characteristics described by Maier [6]:

- Operational independence of component systems – that if the SoS were disassembled into its component systems, they would be able to operate usefully independently.
- Managerial independence of component systems – that the component systems maintain a continuing operational existence independent of the SoS (i.e. they do, actually, operate independently)
- Emergence - the purposes of the SoS emerge only through the collective actions of the systems participants (i.e. the SoS can achieve outcomes that none of the component systems can achieve acting individually)
- Evolution – the SoS evolves over time (i.e. component systems leave and join the SoS over time; it is not constructed as a single entity)
- Geographical distribution – the component systems are distributed spatially (and possibly temporally), therefore focus is on transport of information between the component systems

The first two characteristics are concerned with control, where this term has a broad interpretation ranging from rigid control by one systems of another to simply influence of one system over another. Emergence is specifically concerned with the interaction between systems and is determined by the nature of the relationships between co-operating systems but, more particularly, by the complex interaction of many relationships. It may be the outcome of deliberate design (intended emergent behaviour) or of unpredicted interoperation (unintentional emergent behaviour). Evolution is at the heart of many of the difficulties with SoS; changes in the SoS structure, either to the relationships or through the introduction, replacement, or retirement of component systems creates new emergent behaviours. Unlike the traditional lifecycle view of a system (i.e. concept, design, build, deploy, retire), there are rarely 'clean sheet' opportunities for concept and design, but new systems must be introduced into extant SoS structures. Indeed, [4] combines the work of [7] and [8] to identify the difference between systems engineering and SoS engineering in ten typical aspects of systems engineering. The differences can be simply summarised by saying that SoSE must deal with much greater uncertainty during almost every aspect of development.

Recognising the need for different management approaches for different SoS, Dahmann and Baldwin have identified four types of SoS. The distinguishing feature between these types is the nature of control in the SoS. The four types are [7]:

- Directed - The SoS is centrally controlled. In essence, whilst the component systems maintain an ability to operate independently, their normal operational mode is subordinated to the central managed purpose
- Acknowledged - The SoS has a designated manager. The constituent systems retain their independent ownership, objectives, funding, and development and sustainment approaches. Changes in the systems are based on cooperative agreements between the SoS and the component systems
- Collaborative - The component systems interact more or less voluntarily to fulfil agreed central purposes. This will usually require some level of agreement on standards for co-operation
- Virtual - The SoS does not have a central manager or a centrally agreed purpose. Large-scale behaviour emerges, which may or may not be desirable. This type of SoS relies on relatively invisible mechanisms to maintain it. In this case, individual systems may participate only to achieve their own purposes, rather than a collaborative one.

These types are rooted in an acquisition paradigm, but appear to be applicable to the operational environment as well. It can be noted that SoS themselves may contain many interlocking smaller SoS and that more than one of the types described above can be present simultaneously in any SoS under consideration.

IV. T-AREA-SOS

The Trans-Atlantic Research and Education Agenda in Systems of Systems (T-AREA-SoS) is a support action sponsored by the EU, the purposes of which are to develop a strategic agenda for European SoS research that also identifies the opportunities for co-operative research with the US. The project began in September 2011 and has used extensive stakeholder engagement to prioritise research themes as an input to future funding decisions by the EC. The themes identified below have been generated within this programme; the approach taken and supporting outputs are available on https://www.tareasos.eu/. The motivation for the project and the challenges to be addressed are described in detail in [9].

V. THE PROBLEM WITH SOSE RESEARCH

Before deriving the important research themes for SoSE, it is worthwhile considering the difficulties with this area of research from an intuitive perspective. The problems with the research are, of course, the same as the problems with developing and operating SoS; they are implied by the characteristics described above. The first, and foremost, difficulty is one of complexity. A SoS is often complicated, in the sense of being composed of many component systems with a multiplicity of interactions; establishing the most significant interactions is difficult, which means that any abstraction to create a model is problematic. A SoS usually behaves as an open system [10] and interacts with its environment. The significance of individual interactions is context dependent and may change when environmental changes take place. The behaviours of SoS must be considered holistically, even though their causes may be due to phenomena operating at a very detailed level. This introduces problems of scale and challenges the reductionist approach that is common in many engineering endeavours.

The evolutionary characteristic implies a uniqueness of the SoS state at any particular time, making generalisation of experiments unreliable. To paraphrase Heraclitus: *No man ever steps in the same river twice, for it's not the same river and he's not the same man*. One may, of course, determine that the performance of the SoS due to certain parameters is better or worse than the SoS at some previous condition, but this does not guarantee that new, detrimental emergent behaviours will not appear in the future. In dynamic SoS, with new systems and relationships joining or leaving, definition of the unit of analysis becomes problematical and comparison with previous states unreliable. Much research into SoS has been conducted through case study approaches. This is a methodologically sound approach, but it does not permit generalisation of results but rather a highly bounded validity [11].

The operational and managerial independence characteristics create problems for the researcher who is located within the SoS. These may imply practical difficulties in terms of access to needed research information. Many SoS are part of a commercial endeavour (even in the case of component systems that provide public services) so that a consistent depth of information across the SoS may be difficult to achieve in practice.

Notwithstanding these intuitive difficulties with researching SoSE, it is clear that much may be done to improve the current state of knowledge of SoS. Better understanding of SoS will reduce risk (e.g. safety and security) in complex SoS and enable optimisation of the behaviours against important societal objectives (e.g. holistic approached to reducing carbon emissions). Improved knowledge of SoS will support the development of more sophisticated and better tools and techniques for design and development of SoS, or at any rate their component systems. It will also lead to a better understanding of how to operate SoS so that decision making may be improved during both short- and long-term operation. In the next section, the derivation and analysis of knowledge gaps is described. These were an important step along the way to a prioritised list of research themes.

VI. SOSE GAP ANALYSIS

Derivation of gaps used inputs from a variety of sources. These included literature review, expert workshops, and case study analysis. Eleven case studies were used from the ICT, Manufacturing, Civil Engineering, Defence, and Transport domains. These all concerned large SoS (e.g. emergency response, Air Traffic Systems), which mostly proved to be exemplars of particular inadequacies. Full details of the case studies and other sources are given in [12]. Within the defence community capability analysis is routinely undertaken [13] as a means of long term acquisition planning. Capability is the ability to do something; it is not a synonym for a system function or system purpose [14]. Therefore, a capability gap is an inability to do something that is desired due to some deficiency. Through the various sources noted above a total of forty-nine problem areas were identified and a set of draft priorities derived. These problem areas were expressed as capabilities; i.e. a problem represented the absence of a capability that was desired. As described in [13], capabilities can be structured as a hierarchy in which high level capabilities may be realised through the combination of lower level capabilities. Analysis of the problem areas and mapping parent/child relationships revealed a structure of four capability levels, as shown schematically in Figure 1. The complete mapping is available in [12], but the first two levels are shown in TABLE I. It is interesting, but not very surprising, to see that the level 1 capabilities map to four of the [6] characteristics, but group as Control, Evolution, and Emergence. The twelve gaps at level 2 formed a set of capabilities that could be analyzed further by academic, industrial, and government experts in SoSE. This analysis was carried out in extended workshops (in the US and Europe) that began to expand the capability needs into specific research questions the answers to which would provide industrial and societal benefits. These are the twelve themes of the T-AREA-SoS strategic research agenda in SoSE.

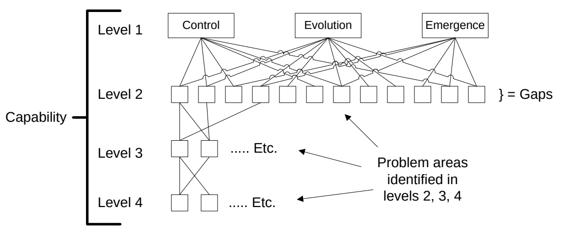

Figure 1: schematic hierarchy of capabilities from which gaps are identified. Lower level capabilities combine to three level 1 capabilities based on Maier Characteristics [12]

TABLE I: LEVEL 1 AND 2 CAPABILITIES FROM GAP ANALYSIS, FROM [12]

Ref.	Capability
1-01	Engineering for emergence
1-02	SoS Control
1-03	SoS Lifecycle(s) management
Ref	**Capability**
2-01	Agility through reconfiguration in dynamic SoS
2-02	Verification & Validation for dynamic SoS
2-03	Prediction and analysis of emergent behaviour
2-04	SoS Measurement
2-05	Integration of corporate and engineering governance for enterprise SoS
2-06	Evolution and migration of legacy systems
2-07	Modelling & Simulation for SoS
2-08	Dynamic composition of SoS
2-09	Prototyping SoS
2-10	Secure SoS implementations
2-11	Economic resilience
2-12	Assuredly safe SoS implementations

VII. RESEARCH THEMES AND KEY QUESTIONS

It is possible to partition the emergent research themes in many ways; however, to maintain consistency with the discussion above, they are grouped as follows:

- Research themes that address understanding of SoS
  - Theoretical Foundations
  - Characterisation of SoS
  - Emergent Behaviours
- Approaches, methods and techniques
  - Multi-level modelling
  - Architectures/architecting
  - Prototyping
  - Evaluation of SoS
  - Trade-off
  - Humans & Organisations
- Tools and implementation
  - Measurement & metrics
  - Security
  - Energy efficient SoS

Naturally, there is cross-over between the themes and the groupings are not rigid, but it is helpful to consider each in turn.

As a discipline, SoSE lacks an agreed theoretical foundation. It might be argued that the underpinning theories of SoS reside in a range of more traditional disciplines that need to be brought together in some way. However, to begin with there must be some agreement about a conceptual model of SoS that should be consistent with the characterisation and accommodate the concept of emergent behaviours. Greater understanding of SoS from a theoretical perspective will lead to the development of better approaches for the predication and management of emergence.

Horizontal and vertical integration of models to consistently and accurately model SoS behaviours will create insight into the nature of SoS and also lead to more reliable simulation and modelling of SoS phenomena. Enterprise Architecture is, de facto, the tool of the SoS Engineer, but there is a need to extend architecting to achieve more formalised and quantitative application of architecture to this problem space. Prototyping is an important element in the development of new systems, and evaluation should be interpreted as verification and validation of SoS. The research challenges of this latter concern, not only the technical and philosophical questions of validation, but also the cost implications. The challenges are associated with the impossibility of testing every condition of the SoS. Trade-off to achieve high level (SoS) objectives more reliably and also includes a sociological challenge of reducing the tendency towards local optimisation of the component systems of a SoS, rather than overall optimisation.

As noted above, the role of humans at both the organisational and individual level is impossible to predict with certainty, but research is needed into the incentivization of appropriate high level behaviours.

According to Lord Kelvin: *If you cannot measure it, you cannot improve it*[1]. Given that control is one of the main concerns with SoS, then research into what to measure and how in a SoS is an underpinning requirement that supports many of the other themes. Security and energy efficiency are rather specific challenges that are prioritized due to their impact on the public, business, and government organisations.

The themes can also be mapped to the Maier characteristics of a SoS [6]. Through this means the issues which create the research imperative are exposed. These are shown in TABLE II.

VIII. THE RESEARCH IMPERATIVE

TABLE II maps the relationship of the research themes to the three characteristics of Control, Evolution, and Emergence. This may be used by research planners to create research campaigns that will illuminate the topics of SoS and SoSE and to understand the linkages between various parts of the problem space. The body of the table identifies the key research questions or topics to be resolved. The relationships between the various aspects of the problem space indicate that a research campaign is required to address various aspects simultaneously and other parts at an appropriate time to build up the European capability in SoSE.

IX. CONCLUSION

The nature of SoS and the difficulty of conducting research into SoS/SoSE have been described. Through analysis of expert input, a set of twelve themes have been identified and then bounded, in order to initiate new research projects that will collectively enable a better understanding of SoS and SoSE. The relationships between research topics are expressed in TABLE II. This can also be viewed as a framework for planning a research endeavour in SoS/SoSE.

It has been argued that the introduction of SoS and the inexorable expansion of SoS mean that SoSE research is not a matter of choice, but an imperative to ensure that globally resources are used in a more sustainable manner, safety and security of individuals and organisations are more certain, and European competitiveness is maintained and expanded. A strategic research agenda in SoS should now be pursued in accordance with the themes identified in this paper.

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TABLE II: SOSE RESEARCH THEMES AND MAPPING TO THE ADAPTED MAIER [6] CHARACTERISTICS FOR SOS

SoS Theme	Control	Evolution	Emergence
Theoretical Foundations			Theoretical foundations should enable a better understanding of interactions between component systems and hence inform development of prediction techniques.
Characterisation of SoS	Control structures are a fundamental aspect of characterising SoS (i.e. a significant distinguishing feature between different types of SoS).	There are several relevant timescales that characterise SoS. These include lifecycle or life phases (depending on the SoS), rapidity of change and reconfiguration within the SoS; cyclic or chaotic change (i.e. likelihood of repetition and concomitant frequencies) See [15], fig. 6.3.	It is not clear whether emergence can be classified (different types) and hence be a part of the characterisation
Emergent Behaviours	Clear evidence that emergent behaviours result from multiple ownership and management of individual systems. Contract structure within a SoS is a significant influencer on emergence. Distribution and availability of information and knowledge influence emergence.	As yet, there is no formally agreed definitions of SoS states; transition between states would be an influencer on manifestation of emergence. Similarly, emergence may, itself, be the trigger for state change. This is likely to be highly non-linear. At the practical level, individual systems joining, leaving, or being replaced in the SoS change the risk of emergent behaviours and cannot necessarily be predicted in advance.	A fundamental property. An area for theoretical research to understand the nature of emergence within a SoS including emergence in human, process and technical sub-systems..
Multi-level modelling	Incorporation of non-technical aspects in models. Integration of models from different disciplines and philosophical perspectives. Dynamic simulations of 'soft' organizational aspects are required.	Modelling dynamic behaviour along the SoS lifecycle. Models that can reliably handle multiple characteristic timescales that vary by many orders of magnitude.	Challenge of modelling SoS holistically in a way that does not excluded possible emergent behaviours. Horizontal and vertical integration of models to create conceptually consistent models of highly complex systems. Role of simulation in understanding emergence.
Architectures/architecting	Enterprise architecting must account for control by different organisations etc. and interfaces between them.	Development of dynamic (executable) architectures; evolution of architectures with evolving SoS.	Assessment of architectures to determine (quantitatively) the quality of a particular configuration in advance of construction.

SoS Theme	Control	Evolution	Emergence
Prototyping	Influences availability of individual systems to participate in prototypes. Prototyping human behaviour and the variables that influence this.	The integration of new systems into legacy SoS constructs and with legacy systems is a major source of difficulty. This means that prototyping may require participation of extant operational systems - which poses operational and ethical problems. Relevance of prototypes to evolving SoS.	Definition of appropriate prototypes at appropriate stages in systems development to ensure de-risking of negative emergence and adequate demonstration of positive (or designed) emergent behaviours.
Evaluation of SoS	Contract network of SoS is an integral part of validity. Ambiguous responsibilities (e.g. design authority) within SoS enterprise. Evaluation of ownership and hence accountability of systems within an SoS.	Maintaining certification/qualification of SoS as it evolves. Problem of legacy systems being validated against old standards. Dynamic validation of SoS during environmental and/or SoS change	New paradigms of verification and validation for SoS.
Trade-off	Multiple perspectives and priorities lead to local trade-offs or lack of agreement about optimisation objectives.	Prediction of lifecycle behaviours (e.g. whole life costs).	Understanding the potential for new trade-offs along the SoS lifecycle as both desirable and undesirable emergent behaviour is recognised.
Humans & Organisations	Governance, enterprise structures, contracting, incentivization, psychological and sociological behaviours all have a significant impact on the performance and robustness of SoS.	Generating, distributing and maintaining knowledge across multi-organisational enterprise.	Role of humans in resolving unwanted emergent behaviour through innovation and commitment. Unpredictability of individual behaviour, in contrast to statistically likely behaviour.
Measurement & metrics	Combining soft and hard measurements. Availability of information across the enterprise (e.g. protected information in one part of SoS). Achieving consensus on critical metrics for SoS.	Legacy data. Lack of benchmarks for determining effects of change.	Identification of appropriate metrics and affordability of measurement. Traceability of constituent metrics of derived measures Measuring the source and impact of emergence
Security	A problem area concerned with application of the themes above		
Energy efficient SoS	A specific application area requiring application of the themes above.		