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Towards a Systems of Systems Engineering EU Strategic Research Agenda

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Abstract – *This paper presents the work undertaken so far in the formulation of a Strategic Research Agenda (SRA) for research in Systems of Systems Engineering in the EU. The T-AREA-SoS project is introduced to provide a context, together with a section on Drivers for Change which the SRA needs to take into account. The strategy and process for the generation of the SRA is described, followed by details of outputs to date and the potential benefits it is believed would accrue from the implementation of the SRA.*

Keywords: Systems of Systems, Systems of System Engineering, strategic research agenda, global drivers, strategic research agenda process, strategic research agenda themes.

1 Introduction

The T-AREA-SoS (Trans-Atlantic Research and Education Agenda in Systems of Systems) is a Support Action (project 287593); one of its objectives is to develop and deliver to the European Commission a Strategic Research Agenda (SRA) in Systems of Systems Engineering (SoSE) that is of mutual interest to the European Union and the United States of America. This is done with the intention of creating opportunities for international collaboration in the emerging and essential discipline of Systems of Systems Engineering (SoSE). T-AREA-SoS is part of a wider initiative (ICT-2011.3.3) with an objective to increase the competitiveness of European industry and enable Europe to master and shape future developments in ICT (Information and Communication Technologies) so that the future demands of its society and economy will be met. Competitiveness means, in this context, that Europe will be global leaders in SoSE, which will lead to greater Return on Investment (ROI) for European industry, greater innovation within the technical systems community in government, industry, and academia, and long-term economic sustainability of, and through, engineering of large complex systems. There were three other projects launched under ICT-2011.3.3 in the area of SoSE; these are DANSE [www.danse-ip.eu], COMPASS [www.compass-research.eu/], and ROAD2SoS [www.road2sos-project.eu].

While there are number of deliverables in the Support Action, this paper concentrates on the work undertaken to date to create a SRA that will create the environment for the development of concrete research initiatives to enhance existing research programmes and identify key research priorities and challenges to support the European Commission in its planning of Horizon 2020 (the next major multi-year EU investment in research and technology). It will underpin future exploitation opportunities by academia and industry in a range of commercial and industrial sectors of priority to the EU.

The T-AREA-SoS project has taken an essentially top-down approach to the identification of research priorities. Although it looked across domains, it has had a particular focus on transport, manufacture, energy and IT domains, whilst ensuring that the significant advances in SoSE within the defence community is appropriately acknowledged.

The project partners in T-AREA-SoS are Loughborough University (UK), Bournemouth University (UK), Purdue University (US) and the University of Texas at San Antonio (US). However, in line with the nature of support actions, the project has engaged a significant number of commercial, government, academic, and not-for-profit organizations in the formulation of the research agenda that is presented in this paper.

2 Drivers for Change

This section discusses drivers instigated by changes to society and/or the environment that the SRA needs to take into account. These global drivers are extant and interconnected; research into SoS must generally address these in parallel and in some cases deal with conflicting requirements. In researching SoS(E) it will be important to consider how the global drivers should be properly accommodated in new approaches to design, operation, and disposal of systems in the context of SoS. As such, these drivers are a specific consideration in the generation of the

SRA. Firstly; the authors consider an historical perspective of complex, highly interconnected societies and their vulnerabilities to environmental changes. Secondly; a description of seven major global drivers is presented.

2.1 Historical Perspective

In [1], it has been argued that, when faced with widespread change in economic and/or environmental conditions (including biological), the social complexity of a society may cause that society to collapse; i.e. significant social complexity makes a society less resilient. Tainter [1] examined a number of significant civilisations (such as Romans, Mayans, etc) and concluded that they collapsed because of their societal sophistication; arguing that when stress comes, such societies have become too inflexible to respond. In effect, they become a huge, interlocking network of roles, responsibilities and functions, not readily amenable to change [2, 3]. The very essence of SoS development has been increasingly sophisticated, interconnected agglomerations of systems, which may, nonetheless, be subject to different control mechanisms [4] and varying levels of rigidity. European societies are complex and layered, and they rely increasingly on complex SoS for every aspect of sustenance and sustainment. The global challenges, identified below, are the sources of future change to society and/or the environment to which Europe must be resilient.

2.2 Global Drivers

The SRA concerns the prioritization of research themes that will support business and government in developing commercial strength or societal improvement through better design for, and management of systems of systems. The global drivers identified below can be considered as societal aspirations or environmental constraints that such design and management must accommodate; either as an immediate concern or as potential future concerns for long-term (or enduring) SoS. They do not drive SoS development themselves, but rather influence (sometimes strongly) the SoS development strategies and approaches. Focusing on the EU, the following key global drivers for the SRA can be identified.

Population Demographics: Growth and aging factors within the EU are driving an intense demand for concerted action to address the inevitable societal imbalances that will result. As one example among many, consider the use of autonomous agents to manage the burden of care of a increased elderly population. Many SoS are involved through the interoperation of systems within government agencies, private and/or not-for-profit organisations, semi-autonomous systems and associated information systems.

Food Security: The rise in global population will drive a concomitant increased demand for foodstuffs. However, food security for the next 50 years is achievable, as long as global population growth is contained, global warming is addressed, and the problems of food provision, distribution and utilisation are addressed [5, 6]. This implies a many dependencies, needing improved management of SoS to improve yield, exploit additional croplands, reduce waste, and distribute food more effectively.

Energy Security: Irrespective of the state of reserves for carbon-based fossil energy supplies (oil, gas, coal), the dependence of Europe on supplies from elsewhere, coupled with the drive by many countries towards low-carbon energy supply to mitigate global warming from greenhouse gases mean that the EU27 must contemplate significant changes in generation, storage and distribution. SoSE capabilities will be essential in the provision of energy security to the EU.

Resource Utilization and re-utilization: The traditional view that the world's lithographic resources (such as iron, titanium, uranium, etc) are limited, and that inevitably they will run out is challenged by a more recent, extended perspective that includes notions of recycling and re-use, as well as the growth of technologies enabling miniaturisation, dematerialisation and substitution of diminishing resources [7]. However, while it is evident that re-use, recycling and reductions in landfill are eminently desirable outcomes, they demand an economic landscape in which recycling etc. is successful and profitable.

Emissions and Global Climate: The rise in average temperature will have severe consequences affecting all the drivers identified in this section as well as the ecological effects on natural habitats, food chains and ultimately biodiversity [8]. Within the EU, considerable effort is being spent on climate change initiatives, such as the Climate Change Programme (ECCP), the Emissions Trading scheme (ETS), legislation regarding the minimum renewables content in energy supplies, the promulgation of insulation and energy-efficiency targets and support for the development of carbon capture and storage (CCS) [9].

Community Security and Safety: SoS are both a source of additional security risk and the means through which such risks may be reduced. The European Cyber Crime Centre (EC3) estimates that the cost of cyber-crime to victims is of the order of €290Bn worldwide. This centre, established 1st January 2013, is predicated on the theory that cyber-crime is more effectively tackled at a pan-European level (or indeed, international level) than on the basis of individual nation states. Indeed, many of the threats to security (terrorism, social identity, organized crime – including trafficking and cyber-crime, public health crises, and large scale environmental crises) are essentially borderless. SoS responses that are not constrained by national borders are required. These will require appropriate SoS modelling and engineering and, as such, will be important drivers for the SRA.

Transportation: It is a given that transportation is fundamental to the global economy and to society as a whole, and it is also a fact that transportation contributes significantly to emissions. Therefore there is a requirement for all regions to attend to the twin problems of both improving and integrating their transportation capabilities and their utilisation, and to reducing their emissions in so doing. This amounts to the following needs:

- Improving the transportation networks in all domains (air, land, sea) and increasing the level of intelligence within them.
- Improving the integration of these networks, and smoothing the usage of them mainly by better implementation of IT resources.
- Moving to non-carbon energy sources to power transport.
- Shrinkage, minimisation, miniaturisation and dematerialisation of goods (as far as possible).

This is a complex set of needs. The European Commission has adopted a comprehensive Roadmap for Transport [10], the goals of which can be described as 'stretch targets', which will address most of the needs above.

Clearly the information needs of all the drivers above constitute SoS challenges which should be incorporated within the SRA.

3 Strategies Adopted for SRA Generation

With reference to a technology strategy, the push-pull approach [9] is widely accepted; this means that the strategic course is constructed partly by the *push* of scientific and technological innovation (which opens certain possibilities) and the *pull* of industrial (or other societal) needs. This is largely the approach that has been adopted by T-AREA-SoS. The engagements during the first year of the support action were mostly with researchers and innovators who are familiar with the Systems of Systems concept and current socio-technical research that supports it. This led to an initial agenda that was constructed from the state of the art in current SoS research and the projections of experts in terms of needs and possibilities. As the agenda was further developed, the pull part was introduced through further interaction with European industry and appropriate consideration of the social and environmental factors that must be a part of the overall agenda.

It is important to note that it is only in very rare cases that an organization or group of organizations can set out to develop a SoS from scratch; more generally, a SoS evolves over time through the inclusion of additional systems and retirement (or other loss) of legacy systems. Other changes may occur through new means of interactions between component systems that lead to new opportunities for interoperation [11, 12]. This has an important implication for the pull part of the strategy development. Very often, for industry, the strategic drivers in SoSE are concerned with being able to carry out current operations more effectively or with less risk of negative emergent behaviour.

3.1 Process

The generation of the SRA has been iterative. An expert community (established as part of the T-AREA-SoS action) drives the industrial as well as academic requirements through which research initiatives have been generated.

The *push* mentioned previously has been shaped by a number of documents created as part of T-AREA-SoS and includes the T-AREA-SoS State of the Art Report (TAREA-PU-WP2-D-LU-9, www.tareasos.eu) and the T-AREA-SoS Gap Analysis Report (TAREA-RE-WP3-R-BU-10, www.tareasos.eu). The SRA has had the following inputs to date:

- Contribution of case studies from SoS experts (T-AREA-SoS State of the Art Report)
- Literature review (T-AREA-SoS State of the Art Report)
- T-AREA-SoS Gap Analysis
- T-AREA-SoS Expert Workshop (Brussels, 4 April 2012)
- INCOSE International Symposium 2012 Panel Session (Rome, 9 – 13 July 2012)
- IEEE International Conference on SoSE Panel Session (Genoa, 19 – 20 July 2012)
- T-AREA-SoS US-EU Exchange Workshop (Arlington, Virginia, 5 – 7 November 2012)
- T-AREA-SoS EU Exchange Workshop (28 January – 1 February 2013)

After the desk research had been undertaken the development of the SRA entered a transitional phase with elements of both *push* and *pull*. The T-AREA-SoS Expert Workshop in Brussels 2012 (which represented the launch of the expert community) appraised the initial findings from the T-AREA-SoS State of the Art Report and 'themes' started to emerge for key areas for research in SoS. The generation of an SRA has undergone the following stages:

Stage 1: The first expert workshop identified fourteen key areas for SoSE research. These were ranked using a single transferable voting system among the experts and through reflection on the outcomes. Essentially, this followed a process similar to the mini-Delphi technique to prioritise the themes [13]

Stage 2: The research areas were further shaped via the expert panel sessions at two summer 2012 conferences. It could be argued that the INCOSE International Symposium and the IEEE International conference on Systems of Systems Engineering constitute representative samples of the systems engineering community that can provide guidance on research in the area of SoS. Panel sessions were held at both these international events during which the emerging agenda was presented in the form of themes and the views of participants sought in terms of priority. Both sessions attracted 40-50 people and included a panel that was constituted from members of current European Research projects in SoS and a project officer from the European Commission with responsibility in this area. It could, however, be argued that SoS generally has a wider set of technical stakeholders than systems engineers and that the software community and the cyber-physical community were under-represented in these solicitation exercises.

Stage 3: A formal gap analysis (TAREA-RE-WP3-R-BU-10, www.tareasos.eu) was undertaken on the research areas acknowledged, to identify specific challenges, opportunities and innovation gaps that need to be addressed.

Stage 4: The innovation gaps were presented at the T-AREA-SoS US Exchange Workshop in November 2012 where they were further developed, refined, validated and checked for completeness. From this workshop emerged the 'themes' for research areas.

Stage 5: Development of the themes into actual research priorities at the EU Exchange Workshop in January 2013.

Stage 6: Presentation of the research priorities to the expert community to obtain feedback on the order of priority.

Stage 7: Validation of the research priorities at a virtual workshop.

Stage 8: Presentation of the SRA to the European Commission.

4 Outputs

The SRA themes developed through stages 1 to 5 (above) are described below. These constitute the themes of the SRA.

Theoretical Foundations for SoS: It is acknowledged that there is a distinct lack of an underpinning theoretical foundation for SoS, and to some extent Systems Engineering. From the perspective of academics, the need for a firm theoretical foundation to SoS is driven by the need for recognition within universities. However, more importantly, there is a need to understand at a fundamental level the nature of emergence as a scientific phenomenon arising from highly complex interactions. It is only through such understanding that new methods of predicting emergence (either at design or during operation) can be developed. It is acknowledged that as an integration level topic, SoSE is likely to draw on the theories of other disciplines and therein lies the challenge of how to sensibly integrate theories that may come from wholly different philosophical perspectives.

Characterisation and Description of SoS: There are a substantial number of definitions of SoS [14, 15, 18] and more recently classifications of types of SoS have also been proposed [4]. The characteristics given by [4, 11] are generally accepted, but stakeholders require more detailed characterisation and, if possible, mathematical descriptions of SoS. Such characterisation is needed to underpin measurement (see below) and to guide the management and governance strategies for operating SoS. To be clear, it is not suggested that the characterisation published by Maier [7] is incorrect, but that the time is ripe for more detailed means of describing and, hence, classifying SoS. A question that is sometimes asked is 'what is the difference between Systems Engineering and Systems of Systems Engineering?' Through more definitive characterisation and classification of SoS, it will be possible for organisations to identify more confidently the skills and techniques that they need to develop and operate SoS.

Predicting, Management of Emergence: This concerns the basic challenge of SoS; particular problems arise because of increased uncertainty in SoS situations. This particular theme overlaps significantly with the other themes which may address aspects of it. The focus for this theme is the need to understand at a more fundamental level the causes of emergence and to determine the research directions most likely to improve the ability to predict emergence and enhance resilience in advance of deployment of individual systems within the SoS. Indeed, a particular area of interest to industry concerns the management of legacy systems in the sense of new emergent properties.

Measurement and Metrics: Whether or not one subscribes to the '*you can't control what you can't measure*' view expressed by [16] and many others, it is clear that there is a fundamental deficit in understanding what and how to measure SoS. This has much to do with the distributed ownership and/or operation of individual systems within the overall SoS, but definition of appropriate metrics and the economic methods through which they may be reliably measured is an area highlighted as significantly important to stakeholders.

Multi-Level Modeling: This theme includes two main aspects: firstly, multi-level in the sense of scale-free modelling, which would lead to more general theories for SoS; secondly combining multiple and heterogeneous models within the same simulation or predictive technique. In the latter case, there are significant challenges associated with integrating models that may have different fidelity, different types of parameterisation, or different philosophical approaches. Model integration must also be considered from the vertical, as well as the horizontal, perspective. That is to say the construction of hierarchies of models that remain consistent with each other.

Evaluation of SoS: Traditional techniques for verification and validation are well established and understood at the single systems level, but are no longer applicable at the SoS level. This is mainly because of the impossibility of testing every possible state of the SoS. It is suggested that rather than trying to impose traditional Systems Engineering approaches for verification and validation (V&V), an entirely new paradigm may be needed. This may impact design codes and concepts of certification in some domains.

Human and Organizational Aspects: Another major challenge associated with the distributed ownership and/or operation of individual systems within the overall SoS [7] is concerned with governance, control and lifecycle matters. It is noted that in many of the SoS failures (e.g. communication between blue light services in the London 7/7 bombing [17]) occur due to human/ organizational aspects or a combination of these and technological inadequacies. The organizational and human aspects of SoS are therefore significant areas of concern.

Trade-Off: Trade-off is a fundamental part of Systems Engineering and it could be argued that trade-off at the SoS level follows the same approach. However, the formulation of the trade-off problem and the resolution among a range of stakeholders (systems owners) in the SoS poses problems which will require the generation of new knowledge in this area.

Prototyping of SoS: Although there are many technical challenges associated with SoS, a particular area of important research and development concerns the approaches that could be used to prototype SoS. As mentioned above, the very nature of SoS implies that it is usually necessary to combine new systems with legacy systems and constructs as part of the development process. As noted in the evaluation theme, this poses problems for V&V, however, there are associated challenges concerning the cost of testing (prototyping), access to parts of the SoS, the ethics of testing within operational SoS, and determination of what constitutes a useful prototype. Of course, a prototype can be used at different stages in the development life cycle, and so there are also questions around appropriate timing of prototyping activities within the SoS development.

Definition and Evolution of SoS Architecture: System architectures, enterprise architectures, and architecture frameworks have attracted significant research interest in recent years and are considered to be of fundamental importance in effective management of design for/of systems of systems. Model-based design is seen as a transformative approach for the engineering of SoS that should strongly link the technological aspects to the business considerations of enterprises.

Energy Efficient SoS: There is a general need for greater energy efficiency and SoS are no exception. Particular areas relevant to SoS are SMART GRID, cloud data storage, big data and security.

Security: There is already huge investment and effort in the area of cyber-security, which is in essence a SoS problem. However, the nature of SoS means that security in general is an area of importance; whether it be the physical security of systems within the SoS, or the protection of private or confidential information stored in network systems. Of especial interest within the theme identified in the T-AREA-SoS research agenda is the problem of security threats being essentially borderless and the risks posed by protection in which different nations have different regulatory frameworks. SoS security research is, therefore, a theme of direct and significant priority for the EU.

5 Future Work

As previously mentioned, the generation of the SRA is an on-going process and further stages need to be completed before the SRA is presented to the European Commission. The themes have been decomposed into individual research 'elements': the elements will be prioritized by the expert community prior to a virtual workshop to validate the emergent research priorities.

5.1 Prioritization of the Research Elements

Further analysis of the key research elements within the themes will be undertaken by the T-AREA-SoS team and a list of priorities will be generated. The list will be circulated to the T-AREA-SoS Expert Community, INCOSE Corporate Advisory Board, IEEE SoS Technical Committee, INCOSE SoS Working Group, ROAD2SoS, COMPASS, DANSE, and attendees from the two exchange workshops. The recipients will be asked to identify the elements that they believe are the key research priorities that should be the focus of the SRA. Furthermore, respondents will also be asked to identify any research elements that are missing from the list.

The resultant reordered list of prioritized research elements will then be presented at a virtual workshop. The workshop will validate the findings and identify any missing research needs. This will determine where the expert community believe resources should be targeted for further research to deliver the benefits shown in section 5.2.

5.2 Benefits

It has already been identified that SoS are critical to the delivery of goods and services. One of the difficulties with SoSE is that the business case is less clearly defined than the engineering of individual systems. Nevertheless, the workshops have identified that within each theme, there was potential for a real benefit to industry, and increased competiveness in solving the issues identified. Some of the general benefits as identified by industry were:

- Improved performance
- Reduced costs
- Reduced systems failures
- Improved tools and resources specific to SoS
- Improved reliability

The impact of undertaking research in the themes of *Theoretical Foundations for SoS*, *Predicting*, *Management of Emergence* and *Characterization and Description of SoS* would benefit in providing 'understanding' - a more SoS aware workforce. The impact of undertaking research in the themes of *Prototyping of SoS*, *Definition and Evolution of*

SoS Architecture, *Multi-Level Modelling*, *Evaluation of SoS*, and *Trade-Off* would benefit in improved 'design techniques' that the workforce can use. Lastly, the impact of undertaking research in the themes of *Security*, *Energy Efficient SoS* and *Measurement and Metrics*, will directly impact 'performance and operation of SoS'. A clear indication of the benefits to industry that will accrue from the implementation of the SRA will be described in the final agenda to be delivered to the European Commission in May.

5.3 Limitations

The limitations of the process to generate an SRA have been engaging communities other than the acknowledged communities involved in SoS such as the cyber physical systems and software engineering.

6 Conclusion

The process adopted by the T-AREA-SoS team and the extensive stakeholder engagement has generated an SRA in SoSE that will inform the future funding decisions of the EU.

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