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Economic and Societal Significance of the Systems of Systems Research Agenda

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Abstract—**The large-scale Systems of Systems (SoS) are there to improve the provision of societal services. These are driven by global drivers such as population growth, aging, food security, energy security and climate change. However, a considerable number of SoS projects resulted in failures, causing detrimental economic impact. This paper presents a set of preliminary results from an European Commission (EC) funded project called T-AREA-SoS (Trans-Atlantic Research and Education Agenda on Systems of Systems). The primary purpose of T-AREA-SoS is to provide input to EC's €80 billion Horizon 2020 research programme in formulating a Strategic Research Agenda for Systems of Systems Engineering (SoSE) that spans American and European activities. An initial set of prioritised SoSE research elements derived from an online survey are discussed from an economic and societal stance using examples from heterogeneous sectors such as transport, energy and manufacturing.**

Keywords-Systems of Systems; Research Agenda; T-AREA-SoS; Economic; Societal; Heterogeneity.

I. Introduction

The developments since late 1990s in areas such as Systems Engineering and Complex Systems has led to an emerging interdisciplinary area called Systems of Systems Engineering (SoSE) [1][2]. Traditional Systems Engineering focuses on building the right system whereas Systems of Systems Engineering (SoSE) focuses on selecting the right combination of systems and their interactions to satisfy a set of frequently changing requirements [3]. SoSE deals with a range of complex issues across a range of heterogeneous application domains. The emergence of SoSE is largely driven by societal needs including public services such as health, transport, water, energy, smart spaces, food security, etc.

A SoS is an integration of independently operatable constituent systems that are networked together to achieve a global higher goal [4]. There are significant differences between monolithic complex systems (e.g. an aircraft) and Systems of Systems (e.g. an Airport). An Airport is an example of an SoS, as it combines aircrafts baggage-handling, traffic control management, check-in, retail, maintenance, customs, border control and passenger care systems to ensure that passengers can get from one destination to another [3]. Systems of Systems are characterised by Maier [5] as being composed of many heterogeneous systems that are geographically distributed, independently managed and/or operated, evolve over time, and exhibit emergent behaviour. Additional criteria have been introduced by DeLaurentis [6] to include: inter-disciplinarily, heterogeneity of the systems involved, and networks of systems. Systems of Systems also come in four types; directed, acknowledged, collaborative and virtual [7]. For example, the constituent systems 'voluntarily' collaborate in an agnostic way to achieve an agreed-upon central purpose in a 'collaborative' SoS.

This paper is about the economic and societal significance of an initial set of SoSE survey results supported by examples from heterogeneous sectors. This paper begins with introducing the T-AREA-SoS project; discusses the SoSE research themes generated through stakeholder engagement from an economic and societal stance; and concludes with the preliminary results of an online survey that resulted in a set of prioritised research elements.

II. Economic and Societal Significance

The 2012 Global Information Technology report [8] predicted that by 2020, connected devices will potentially explode to 50 billion, outnumbering connected people by a ratio of six to one. Figure 1 shows a forecast of complex systems interactions by 2020. It shows that by then both the structure of the systems and functionalities will be more complex than they are at the present.

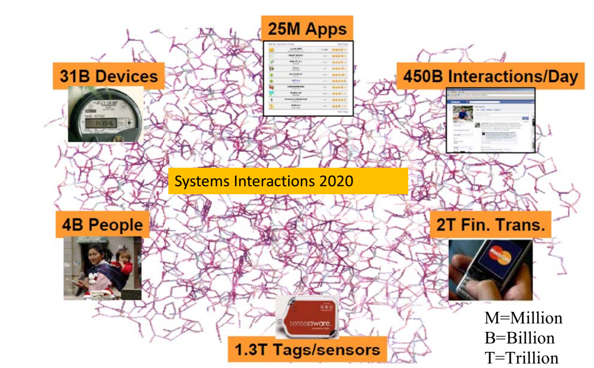

Figure 1. Systems Interactions 2020; 16.5 Billion Intelligent Devices by 2015 and 31 Billion Intelligent Devices by 2020 [9]

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The modern societal world and all industry sectors will increasingly depend on large-scale complex Systems of Systems (SoS) due to an increasingly connected society and industry [10].

A. Economic Importance

The need for a research agenda to deal with SoS challenges can be illustrated through preventing well-known SoS failures which in return can lead to positive economic growth. The economic impacts of a catastrophic SoS failures effects the ability of the economy to operate. This is usually assessed in terms of the extent to which that ability to produce goods and services has been impaired by the failure e.g. losses of electric power, physical damage to roads, buildings, and infrastructure systems [11]. These failures are in different sectors, and encompass SoS characteristics but the financial and social effects are clear. For example the 2010 Icelandic volcanic ash cloud transformed Northern Europe into a no-fly zone and airlines were expected to lose over $200 million a day in revenue, according to a "conservative estimate" from the International Air Transport Association [12]. This had a catastrophic cascading effect that spread to land, rail and sea transport systems that were unable to cope. Another example is the USA Gulf of Mexico oil spill caused by an explosion and fire on a drilling rig leading to the death of eleven people [13].

A further major failure example can be given within the context of financial markets e.g. the "Flash Crash" of May 6th 2010. Cliff and Northrop [14] investigated the global financial markets from an ultra-large-scale systems perspective and conclude that there is an "urgent need to develop major national strategic modelling and predictive simulation capabilities, comparable to national-scale meteorological monitoring and modelling capabilities". Other recent examples of SoS failures include the Hurricane Sandy in New York [15]; Google hack attack in US (Operation Aurora) [16]; power failure in India [17] to name but a few. These failures will result in losses in economic activity i.e. Gross Domestic Product (GDP).

The theoretical and empirical research has identified that those factors such as support for research and development; investment in human capital; active financial markets; and public investment in infrastructure (transport and ICT in particular) appears to have a positive impact on growth [18]. Other initiatives that are relevant to SoS and will influence positive growth and jobs strategy include climate change and its implications for sustainable development [19]; technology roadmaps for smart grids [20]; and Europe's competitiveness in the global economy [21]. The SoS strategic research agenda considers such examples not just as SoS but as sociotechnical ecosystems. Therefore, the implementation of the strategic research agenda will prevent SoS failures and result in positive growth.

The impact of the SoS failures from heterogeneous sectors are discussed and mapped onto the research themes and elements in later sections.

B. Societal Importance and Global Drivers

The large-scale SoS are also driven by global drivers. The examples provided below are mainly from the EU but exhibit issues for the rest of the world.

Population demographics, especially growth and aging – for the EU, the estimate is that the current population of around 500 million will rise to a peak of 526 million in 2040, and then decrease to 517 in 2060 [22]. These changes and the aging population, if not addressed in the intervening years, represent a major disruption to civil society, affecting most aspects of it, from families to industry and to infrastructures.

Food security – the EU is in economic balance with respect to food; however most imports are cereals and other basics and exports are of processed foodstuffs. Consequently, there are security issues. Cropland increases are possible in several parts of the world, but this is minimal in the EU. Instead, the increases must come from improvements in crop genomes and husbandry techniques, and from assurance of foodstuffs from the rest of the world [23][24].

Energy security – investments in renewable sources of electrical energy and a smart supply grid in EU are likely to increase cost from about 10% of GDP in 2005 to about 15% in 2050 – a 50% increase, which will be noticed by all consumers [20][25]. Furthermore, the target will require a major shift (with associated investment) to low-carbon vehicles, durable energy-consuming goods, energy-efficient manufacturing methods and processes, and so on. There will be a consequential shift in in the nature and numbers of jobs within manufacturing, services, construction, transport and agricultural sectors of the economy.

Resource utilisation and re-utilisation: there is still a need for further action at both EU levels and internationally to create a more incentivised environment for business partnerships and processes to flourish, and to ensure that current approaches to design, manufacture and disposal of new products and systems or SoS include the consideration of reuse and recycling.

Emissions and global climate – as the sequence of reports from the Intergovernmental Panel on Climate Change (IPCC) [26] emphasise, anthropogenic effects on the natural environment and on global climate are significant, and the prognosis is catastrophic unless remedial action takes place. One could foresee that interconnected SoS would be needed to produce a solution more quickly over time, since these could provide pervasive channels in parallel for the communication and instantiation of the necessary changes. Another vivid example of SoS approach for climate change is Global Earth Observation System of Systems (GEOSS) [27]. It represents 10-Year implementation plan reference document of GEOSS which states the importance of the Earth observation and the challenges to enhance human and societal welfare. This implementation plan, for the period 2005 to 2015, provides a basis for Global Earth Observation (GEO) to construct GEOSS. The plan defines a vision statement for GEOSS, its purpose and scope, and the expected benefits. Prior to its formal establishment, the Ad Hoc GEO (established at the First Earth Observation Summit in July 2003) met as a planning body to develop the GEOSS 10-Year implementation plan [27].

Community security and safety – the critical infrastructure for the lifestyle, health, transport, feeding and security of the citizenry of Europe is dependent on information technology that can be attacked from anywhere in the world is a pointer to the need for co-ordinated action. If one adds in the effects of extreme weather (which recognises no borders), it is clear that pan-EU safety and security SoS are essential. It is evident that the delivery of security at personal and infrastructural levels and social cohesion must go hand in hand, and that this must be delivered through a multitude of co-ordinated channels by a plenitude of organisations, and given their necessarily distributed yet connected and integrated nature, SoS technology will evidently be important.

Transportation – there is a requirement for all regions of the EU to attend to the twin problems of both improving and integrating their transportation networks and their utilisation, and to reducing their emissions in so doing. This results in a complex set of needs including improvements to the transportation networks and increasing the level of intelligence within them; moving to non-carbon energy sources to power transport; and shrinkage, minimisation, miniaturisation and dematerialisation of goods (as far as possible).

Globalisation of economic and social activity – it is to the credit of the EU that is has taken a leading role both in creating the benefits of globalisation (for example in the Kyoto and Doha agreements) and in mitigation of its potential local negative effects (for example in the European Structural Fund and the European Globalisation Fund). Nevertheless, these globalisation changes will continue, and may be more pervasive than in the example above, so there will still be a strong need for a smooth approach to change which could be created by government economic, regulatory and incentivisation actions to create level playing fields and by business to exploit the opportunities so created. Both of these activities will be assisted greatly by SoS technology, again because of the need to take a comprehensive approach rather than an issue-by-issue one.

Although the global drivers refer specifically to the EU, they will have different impacts in other parts of the world. The same drivers will be in action; however, the effects will be different. The Authors reduced the considerations just to the EU for the reasons of space. The next section introduces the T-AREA-SoS project and provides an overview of the prioritised research elements.

III. T-AREA-SoS Strategy

T-AREA-SoS (Trans-Atlantic Research and Education Agenda on Systems of Systems) aims to increase European competitiveness in, and improve the societal impact of, the development and management of large complex systems in a range of sectors through the creation of a commonly agreed EU-US Systems of Systems research agenda [3]. T-AREA-SoS is part of a cluster of four Systems of Systems Engineering projects contributing to the strategic research agenda. The other EU funded collaborative projects are Road2SoS [28], COMPASS [29] and DANSE [30].

A. Methodology used to derive the strategic research agenda

A push-pull approach has been adopted to analyse the research elements of this strategic research agenda. 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. The T-AREA-SoS project assembled a large team of subject matter experts who provided input into the identification of the priority research themes. These were developed over the course of 19 months that included 4 multi-day workshops [31]. These included two workshops in Brussels, a workshop in the US, a workshop in the UK, a panel session at INCOSE 2012 (Italy) [32], a plenary session at the IEEE Systems of Systems Engineering conference (Italy) [33], a questionnaire survey of SoS experts and numerous editing activities by the project partners [34] [35].

B. Prelimanary Results

A set of research elements (organised into 12 research themes) are extracted after a rigorous analysis of the workshop that took place at the International Auditorium in Brussels over two and a half days between 30th January and 1st February 2013. The 23 participants of this particular workshop were EU-based experts with research expertise in the area of SoS. The experts were drawn from academic and industrial communities. The agenda for the workshop was based around the research themes that had emerged to date and identification of any missing themes. The finalised 12 themes as a result of the iterative workshops over the course of 19 months are described below:

- *Theoretical foundations* – the basis for analysing and understanding SoS and for predicting their operational behaviour.
- *Characterisation and description of SoS* – finding a way for all disciplines to describe the structure of a SoS and its operational behaviour, both for intended and emergent cases.
- *Multi-level modelling* – creating and joining stand-alone models together, both vertically across levels, and horizontally along a level, to obtain a better understanding of the characteristics of a SoS.
- *Emergence* – identifying, analysing and understanding SoS behaviour that is not expected, then exploiting ‘good’ behaviour and reducing ‘bad’ behaviour.
- *Measurement and metrics* – developing appropriate metrics and associated methods to measure SoS.
- *Evaluation of SoS* – finding ways to combine metrics to assess the performance of a SoS.

- *Energy-efficient SoS* – providing the knowledge, methods and tools to enable the builders, operators and users of Smart Grids to optimise their work.
- *Trade-off* – developing ways to enable decision-makers to create different SoS versions for a given purpose, and then to choose the 'best' one.
- *Prototyping SoS* – addressing the issues involved in attempting to prototype a SoS.
- *Definition and evolution of SoS Architecture* – extending and elaborating the Systems Engineering approach to the SoS environment.
- *Security* – ensuring that the physical, ethical and cyber aspects of safety and security of the SoS, its people, its end-users, and its social and physical environment are properly addressed.
- *Human aspects* – ensuring human aspects such as culture, knowledge, roles and experience are included in SoS design and operation.

A set of research elements for each theme described above is generated through comprehensive analysis of the workshop results in Brussels. An extract of research elements for the "multi-level modelling" and "emergence" themes are shown in Table 1. The whole list consists of 78 research elements.

TABLE I. AN EXAMPLE RESEARH THEME AND ELEMENTS

Research Theme	Research Element
Multi-level Modelling *Creating and joining stand-alone models together, both vertically across levels, and horizontally along a level, to obtain a better understanding of the characteristics of a SoS.*	Specifying interfaces between models in sematic and temporal terms - vertical and horizontal integration (issues of heterogeneity).
	How to build a single set of compatible models for a given purpose (including the integration of models of black boxes).
	Development of methodologies for the model-based SoS approach and the development of skills for architecting and for interpreting of architectures.
	The development of processes for model building and evolution from purpose through conceptualisation to the final detailed model which is applied.
	Elaboration of tools and methods for the visualisation of 'big data'.
Emergence *Identifying, analysing and understanding SoS behaviour that is not expected, then exploiting 'good' behaviour and reducing 'bad' behaviour.*	Development of a scientific understanding of how and why emergence occurs (causes of emergence)
	Development & compilation of a toolkit and strategies to deal with positive and negative emergent behaviour (e.g. prediction of emergence, prevention through design and operation, amelioration of negative emergent behaviour, and exploitation of desirable emergent behaviour)
	Enhancement of modelling and visualisation methodologies and techniques for emergence prediction and assessment of consequences
	Compilation of a catalogue of real-life cases providing examples of emergence
	Identification of competences required to deal with emergence and the encapsulation of these in training and educational programmes

The research elements that emerged through the workshops and activities of T-AREA-SoS are mapped across the 12 themes. These are then presented to the expert community to prioritise. Each expert was asked to indicate their 10 most important research element from the whole list of 78 and rank them accordingly ('1' being the most important and '10' the least important research element). These voting scores provided an assessment of the experts' judgements regarding relative importance of the research elements. A ranking system using a form of Single Transferable Vote (STV) was adopted to minimise 'wasted' votes. Approximately 100 participants were targeted and 38 responses were obtained to date. This is still an on-going activity and the results are likely to change. The 10 most important SoSE research elements for the SoS community are shown in Table 2. This priority listing is expected to enable the European Commission to identify and target the SoSE elements where research is most needed and therefore to initiate future funding opportunities.

TABLE II. PRIORITISED SOSE RESEARCH ELEMENTS

Rank	Research Question	Research Theme
1	Generation of generally agreed framework for SoS theories.	Theoretical foundations
2	Identification of fundamental principles for SoS.	Theoretical foundations
3	Elucidate a coherent characterisation of SoS, boundary of SoS, goal of SoS, etc.	Characterisation and description of SoS
4	Establishing common terms and definitions for characterising SoS and SoSE.	Characterisation and description of SoS
5	Establish the paradigm (conceptualisation) for SoS and hence SoSE.	Theoretical foundations
6	Development of scientific understanding of how and why emergence occurs (causes of emergence).	Emergence
7	Development of methods for SoS evaluation over time periods and in different contexts.	Evaluation of SoS
8	Construction of models to aid the development of the theories.	Theoretical foundations
9	Development of methodologies for the model-based SoS approach and the development of skills for architecting and interpreting of architectures.	Multi-level modelling
10	How do you create an SoS enterprise architecture incorporating Views such as security, cost, human factors etc.?	Human aspects

Table 2 show the 10 ranked research elements that the participants considered significant for the SoS community. These are discussed next from an economic and societal stance.

IV. DISCUSSIONS

The two themes: (1) characteristics and description of SoS and (2) theoretical foundations, are fundamental to understanding and describing SoS. These themes do not exhibit a direct economic and societal impact; however, provide the underpinning knowledge for the other research themes. They do not have a direct route to SoS delivery and evaluation as opposed to themes such as multi-level modelling, emergence and evaluation of SoS. The themes and research elements that have a direct economic and societal impart are discussed below. These are supported by examples from heterogeneous sectors.

Multi-level modelling – in the case of emergency situations such as the Hurricane Sandy in New York [15] and power failure in North America and India [17], there is a need to model to maintain the supply chain. Due to the inherent scale and complexity in SoS, modelling will require a combination of models and notations from different disciplines, with different purposes, and with different level of fidelity. It is highly unlikely that a single model/notation or single modelling/notational approach will adequately capture all the necessary behaviours of SoS [34]. The analysis of the evolution of peak load demand in Smart Grids and hence the modelling estimations for future needs in the electricity sector are important [20]. Model-Based Systems Engineering approaches such as UML and SysML [36] that have been used successfully in traditional Systems Engineering would need to be extended for SoS. Initiatives such the EC FP7 funded COMPASS project [29] suggests a way forward.

Emergence – a scientific understanding of emergence and development of toolkit and strategies to deal with positive and negative emergent behaviours will support the management of crisis like the Icelandic volcanic ash cloud. With this example alone, the global airline industry would not have lost more than £130m a day because of the disruption caused by the volcanic ash cloud that has brought Britain's air transport network to a halt [12].

Measurement and metrics – the challenge for SoS is both defining the appropriate metrics and devising the means through which they can be accurately measured in a timely manner. The impact is both economical and societal. For example, FiReControl in the UK, a large-scale SoS that commenced in 2004 and was expected to be complete by October 2009, was cancelled in 2010 after £245 million has been spent on the project [37]. There were numerous problems with the project, which was undetected or detected too late, caused by lack of techniques and metrics to measure the quality of the SoS, as well as effective estimation and management of cost. The key need in measurement and metrics is to be able to measure the behaviours of the SoS itself, rather than its components. It is about how one characterises and resources likely required future behaviour and what is desirable and what is not in specific contexts.

Evaluation of SoS – the distinct characteristics of SoS need to be taken into consideration as these characteristics impact their evaluation. SoS designers need to accept that it is unrealistic to test and SoS fully before deployment. A more appropriate way to test a SoS is using an evidence-based approach to addressing risk [38]. Dahmann *et al.* [38] identifies issues critical to success of each increment of SoS development, as well as places where changes in the increment might adversely impact user missions, and then focuses pre-deployment evaluation on them.

Human aspects – the majority of large-scale SoS are simply too complex for humans to handle. For example, although many reasons contributed to the failure of the NPfIT project [39], one of the most salient reasons was that the project was structurally and functionally too complex for the developers and the organisations to manage. The National Project for Information Technology (NPfIT) in the UK was the world's largest single civilian IT system ever attempted [39]. NPfIT was designed to link all parts of England's National Health Service. Due to its scale and complexity, it was impossible for anybody to visualise the whole NPfIT system in a single frame of vision and this led to poor requirements engineering and systems specification, and eventually the failure of the project. In 2010, the UK government cancelled NPfIT at a cost of £12.7 billion [39].

V. Conclusion

The twelve themes derived as a result of the iterative workshops, and an initial set of SoSE elements prioritised using an online survey, are discussed from an economic and societal stance. These outputs form the basis of a strategic research agenda and use examples from heterogeneous sectors such as transport, energy and manufacturing. Such examples are considered not just as SoS but as sociotechnical ecosystems. The implementation of this research agenda will minimise SoS failures and result in positive growth. The global drivers such as population growth and food security will impact areas such as energy, extra housing, health, education, jobs, etc. The proposed research agenda and hence SoSE aims to sustain a developed and civilised society.

The prioritised research elements may change as a result of further inputs from the expert community and future iterations. A finalised set of results will be presented to the European Commission to provide input into shaping EC's €80 billion Horizon 2020 research programme.

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