European
Commission

Directions in Systems of Systems Engineering

Report from the Workshop on Synergies among Projects and Directions in Advanced Systems Engineering

held on 04th and 05th July 2012 in Brussels, Belgium

July 2012

Communications Networks, Content and Technology Directorate-General
Unit A3-DG CONNECT
http://cordis.europa.eu/fp7/ict/embedded-systems-engineering/home en.html

Disclaimer: The views expressed here are those of the workshop participants and do not necessarily represent the official view of the European Commission on the subject.

Executive Summary

As the embedded world meets the internet world there is an increasing number of interacting systems with strong connectivity utilised in both society and in industry. The growing overall complexity of systems has triggered a paradigm shift and the need to enhance the classical view of Complex System Engineering towards System of systems (SoS) Engineering. System-of-Systems describes the large scale integration of many independent self-contained systems to satisfy global needs or multi-system requests.

Type	System	System of Systems
Man Made “ICT Powered”	Car, Road	Product range, Integrated Traffic System
	Aeroplane	Airport, Air Traffic Control System
	Train	Station, Signalling, Rail Network
	Wind Turbine, PV, fossil	Smart Grid
	Building	Town, Shopping Mall
	Computer	Distributed IT System
Biological	Animal, Plant	Herd, Forest
Sociological	Family, Club, School, Local Church	Town, Nation, Education System, Religion
Environmental	Weather, river	The Eco-System
Organisational	Company	Supply Chain, Global Enterprise, the Stock Market
Political	Town Council	National Government, EU, UN

Table 1 Types of System of Systems

Examples of system of systems that are found in everyday life are highlighted in Table 1. These range from the “ICT Powered” system of systems to those found in biology, sociological, environmental, organisational and political structures. The EU itself is a very good example of a system of systems. The inherent managerial and operational independence of constituent systems and influences of commercial and social environments within a system of systems introduces major complications that result in the need for a paradigm shift in thinking. Rather than controlling systems the aim in system of systems engineering is to find means of influencing systems towards agreed goals. It should be highlighted that a fundamental challenge for development of the ICT Powered system of systems (shown in yellow) are the many varied interactions and influences that arise from other domains such as those shown in blue in the table.

All of the conventional "knowns" that an engineer relies upon for system development, e.g. fixed requirements and system models, development processes, etc. no longer hold true for system of systems requiring engineers to fundamentally re-think how they are going to develop and maintain the system. Thus there is a paradigm shift required to develop approaches for systems with incomplete models and dynamically evolving/changing requirements. As many of the systems require high availability or have safety implications, i.e. are mixed criticality systems, certification becomes a major hurdle.

The workshop identified key challenges that need to be addressed in the area:

Technological - a need for a common language for multidisciplinary applications, for system modelling and control, validation and verification approaches, visualisation approaches, data mining and data reduction techniques, a means of dealing with emergent behaviour and work to support future standardisation.

Economic - demonstration of business benefits to engage with stakeholders (industry, public, citizen) e.g. by modelling, further establishing platforms for SoS and once implemented, means of guaranteeing QoS and availability.

Societal – achievement of social user acceptance addressing concerns over data security and integrity, and provision of guarantees of safety for mixed criticality systems that allow certification according to standards.

Education – to provide engineers with suitable multidisciplinary training in the area of system of systems.

Overall it was felt that there is a pressing need for examples of and business models for SoS with the aim of developing a framework that can be used on multiple applications.

To build a European Eco System that supports the development of system of systems the following recommendations are made:

1) Develop methods, architecture platforms and theory for SoS applied to a small number of case studies and then identify the commonalities across the case studies
2) Develop multi-scale, hierarchical modelling, simulation, validation capability to provide decision support tools for industry to assess the potential benefits of SoS
3) Identify and build the constituency and stakeholders in SoS
4) Develop an appropriate research and innovation roadmap including use cases that elaborate the added value of the SoS approach.

It is advocated that these key needs are supported under the 2013 workprogramme and in Horizon2020. In particular, a CSA should work on the last two items (constituency building and roadmapping activities). Finally, a long term research dimension for SoS is also required targeting underlying theoretical work.

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Introduction and Scope of Meeting

This report summarises a workshop organised by the European Commission to identify scientific, technological and socio-economic challenges, European strengths, stakeholders and priorities for research in the area of system of systems. The workshop was organised over two days, the first day concentrating on scientific and technical challenges via means of a series of invited presentations from on-going projects and other key stakeholders in the field. The second day concentrated on roadmapping and constituency building in preparation for H2020. An aim was to identify how a CSA under WP2013 could support the area of system of systems.

Following an introduction to the meeting from Alkis Konstantellos, highlighting plans for WP 2013 and H2020, Max Lemke gave on overview of the system of systems area. This included the drivers for system of systems as the embedded world meets the internet world and the future vision towards autonomous driving, smart spaces, smart electricity grid, networked sensor applications, in-car infotainment and smart phone applications. These new applications present challenges in design to deal with emergent behaviour with the need to balance cooperation and autonomy. There was a need for a generic approach to SoS and to move beyond best effort approaches to satisfy non-functional properties. New computing paradigms are required for multi-core and heterogeneous systems to produce mixed criticality (safety and time critical) systems. Cognitive control and learning simulation capabilities are required to deal with emergent behaviour and new visualisation techniques are needed for interacting and cooperation with complex data. There are also critical security and safety requirements for dependable systems.

A brief overview of the funded IPs, and roadmapping activities under T-Area and Road2SoS was given as well as the IDC study on SoS. Funding opportunities under Challenge 3 were noted. Two IPs are being called for in Advanced Computing and Control Systems addressing mixed criticalities for embedded systems that meet the Internet, and a number of STREPS will be funded in the area of analysing, modelling and controlling the behaviour of system of systems. The aim is to fund a number of case studies (not full systems) in the area of distributed energy and grids, multisite industrial production and automated transportation that can be used to demonstrate generic approaches, concepts and identify open research issues. There are also opportunities under the ARTEMIS Call 2012 addressing closer to market applications with six Innovation Pilot Programmes in critical systems, smart environments, energy systems automation, and the intelligent built environment. Under Horizon 2020 "Creating industrial leadership and competitive frameworks" research & innovation activities on "A new generation of components and systems engineering of advanced and smart embedded components and systems" are under consideration.

Session I (Chair: Werner Steinhoegl)

A series of invited presentations were given from on-going projects addressing the System of systems area project goals, early results and future challenges.

COMPASS Comprehensive Modelling for Advanced System of systems (Prof. John Fitzgerald, UK)

COMPASS is addressing model-based techniques for developing and maintaining System of systems (SoS). The approach is to develop appropriate tools and pragmatic methods for modelling system based on augmenting SysML with CML supported by proof and model checking tools.

Challenges

- Complexity caused by the heterogeneity and independence of the constituent systems, and the difficulty of communication between their diverse stakeholders
- Developers lack models and tools to help make trade-off decisions during design and evolution leading to sub-optimal design and rework during integration and in service.

Research

- Developing a modelling framework for SoS architectures
- Providing a sound, formal semantic foundation to support analysis of global SoS properties.
- Building an open, extendible tools platform with integrated prototype plug-ins for model construction, simulation, test automation, static analysis by model-checking, and proof, and links to an established architectural modelling language.
- Evaluating technical practice and advanced methods through substantial case studies

Applications

- Emergency Management – combining Information systems of fire, police and hospital services
- Audio/Video/Home Automation (to respect digital rights with interacting systems)
- Looking at other applications Smart Cities and Energy Grid driven by Industrial Interest Group

Early Results Work has been concentrated on defining case studies and the CML definitions. It had been identified that exclusive definitions are not helpful and there was a need to use approaches that were appropriate to a specific problem considering the dimensions of system of systems. Breadth across a variety of disciplines was required rather than depth in one and there was need to speak the same language. Challenges were in modelling and analysis, abstraction, distribution time mobility, composability reasoning for verification and feature interaction integration. The heterogeneity of systems, stakeholders and need to take into account social, political and economic models was highlighted. Documented experience of SoS example applications is crucial.

DANSE Designing for Adaptation and evolutionN in System of systems Engineering (Prof. Bernhard Josko, DE)

DANSE is developing approaches for SoS engineering considering the evolving, adaptive and iterative life cycle.

Challenges

- Maintain stability whilst achieving typically changing overarching objectives
- Manage unexpected emergent behaviour, which may cause substantial loss of service, (partial) shutdown or safety risks
- Increase overall system state awareness to support stakeholder optimisation decisions

Research

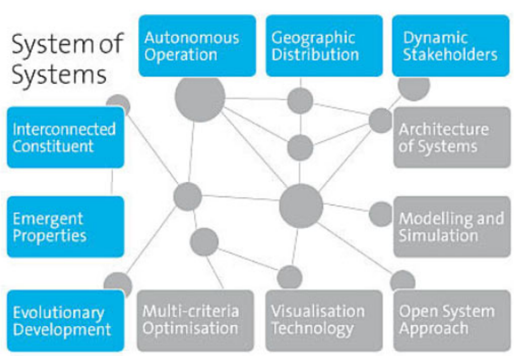
- Methodology to support an evolutionary, adaptive and iterative SoS life-cycle
- Contracts as semantic-sound model for SoS interoperations
- Development of approaches for SoS architecture - continuous and non-disruptive system component integration
- Supportive tools for SoS analysis, simulation and optimisation
    - Exploitation and dissemination of SoS

Applications

- Validation of new SoS approaches by real-life test cases:
    - Emergency First Responders
    - Air Traffic Management, Autonomous Ground Transport, Integrated Water Treatment and Supply

Early Results A key problem is that it is not possible to have a complete view of the overall system state. It is thus difficult to represent what the SoS should do, what it can do and what the SoS actually does. Quite often there are conflicting goals, e.g. traffic management, where all cars want to go the same routes for speed. Reaction times for emergency services depend on the time of day, etc. System behaviour is not predictable because the constituent systems have their own goals and the overall system has partial observability and authority. These systems may have tens of thousands of leaf systems. A challenge is to aggregate subsystems in an appropriate way eliminating unwanted behaviours by construction.

ROAD2SOS (Christian Albrecht, DE)



System of Systems Characteristics and Research Needs (Courtesy ROAD2SOS)

ROAD2SOS is a Support Action producing roadmaps and identifying future research strategies for system of systems engineering coordinated by Steinbeis-Europa-Zentrum with 7 partners from 4 European countries (France, Germany, Spain and UK).

Early Results The project is defining roadmaps for the domains of distributed energy generation and smart grids, integrated multi-site industrial production, emergency and crisis management, and multi-modal traffic control. The aim is to identify priorities for research and development, economic and social barriers, enabling technologies, and drivers. Identifying these is expected to highlight cross-domain similarities as well as domain-specific particularities. Cross-domain challenges identified so far are in providing efficient real-time handling of large amounts of data and interoperability amongst heterogeneous devices. A lack of IT education among decision makers has been identified and gaining stakeholders for SoS implementation is challenging due to the non-centric, non-hierarchical, multi-actor nature of SoS. Among the most promising benefits expected from a SoS approach are entirely new business models and the expected market participation of smaller economic units. In all the domains examined, SoS approaches promise more efficient use of resources, delivering a scale and scope of capacity and services otherwise unattainable. In the examined domains, various SoS concepts have been found to exist but vocabulary is domain specific and SoS architectures are expected also to be domain specific. Roadmapping workshops and case studies are being performed over coming months.

T-AREA-SoS Trans-Atlantic Research and Education Agenda on System of systems (Prof. Mike Henshaw, UK)

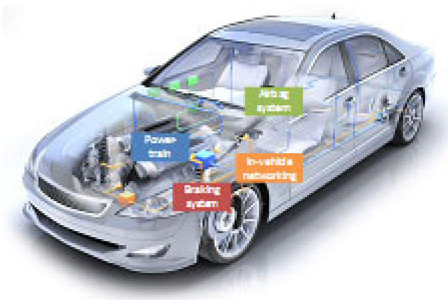
T-AREA-SoS is a Support Action between two institutions in Europe and two institutions in the USA (Purdue and University of Texas San Antonio). Aims are to:

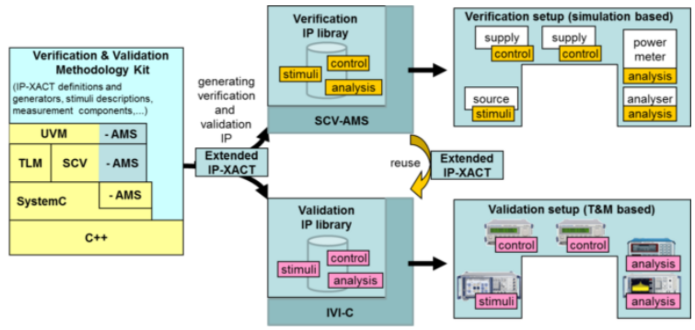
- Create a strategic research agenda in SoS engineering
- Create research themes in SoS engineering that target priority sectors for societal need
- Identify the state-of-the-art and an analysis of gaps in research in SoS
- Create an Expert Community drawn from industry, Government, NGOs, academia, and end users to transfer cross-sector knowledge about SoS
- Identify the skills required for both system developers and system users, and make recommendations on training and education for their development to support research initiatives
- Foster and promote a common language and expression of the concepts of SoS that will enable communication and cross-fertilisation of systems knowledge, tools, and techniques

Early Results A state-of-the-art report has been produced identifying the top 6 areas for research. It has been noted that different types of SoS have different characteristics and so the importance of features vary. There is a need for sociologist and legal expertise. Metrics are also needed to identify incentives for commercial consideration to explain the benefits of putting systems together. A Web based thesaurus has been proposed to help define a common language.

VERDI Verification for Heterogeneous Reliable Design and Integration (Karsten Einwich)

VERDI is a project investigating a unified system level verification methodology for heterogeneous SoS so that IP can be used across and inside companies. The project is defining a path from verification IP to validation IP. Industrial partners are Continental, Infineon and NXP.





System of Systems within Analogue/Mixed Signal Electronics for Automotive (Courtesy VERDI)

Challenge

- SoS requires interaction and interoperability between the analogue/mixed-signal (AMS), digital electronics, software and other physical domains involving different design disciplines such as system design, verification and prototype validation.

Goal

- Create integral system verification and validation methodology to improve design efficiency and quality by linking simulation-based, "pre-tape-out" system analysis and verification with system validation and analysis of the physical prototype using measurement equipment

Early Results Work is concentrated on an engine management system and signal processing sensor. There is tight integration between the electronics and mechanical components. A challenge comes from different companies and cultures working together using different terminology. Increasing safety requirements and regulations are driving the importance of verification. Full verification is impossible today. Challenges are decomposing the specification so that different communities can talk to each other. The aim is to reuse what is developed in the lab in the final product.

Invited Presentations

Following the summaries from the existing funded projects a number of invited presentations were given by key actors in the area SoS & Complex Systems.

Prof. Herman Kopetz (University of Vienna, AT)

The concept of autonomous Problem Solving Systems (PSS) was introduced. PSS are independent being under different management control with the ability to reject demands if there is no incentive. A chain of trust needs to be built. It was highlighted that it is much easier to define a state than define the process that gets to that state. Challenges are how to specify goal states and guarantee that a transition to a goal state occurs within a given time. Another challenge is to design the incentive structure. Emergent properties occur due to positive or negative feedback, non-linearity and time lags caused by interaction. There is a need to consider the macro and micro levels that lead to emergence. New concepts, theory and design rules are needed to express abstract and concrete problems. Security is a big issue. Approaches to achieve integrity by self-observation to react to normal failures are required.

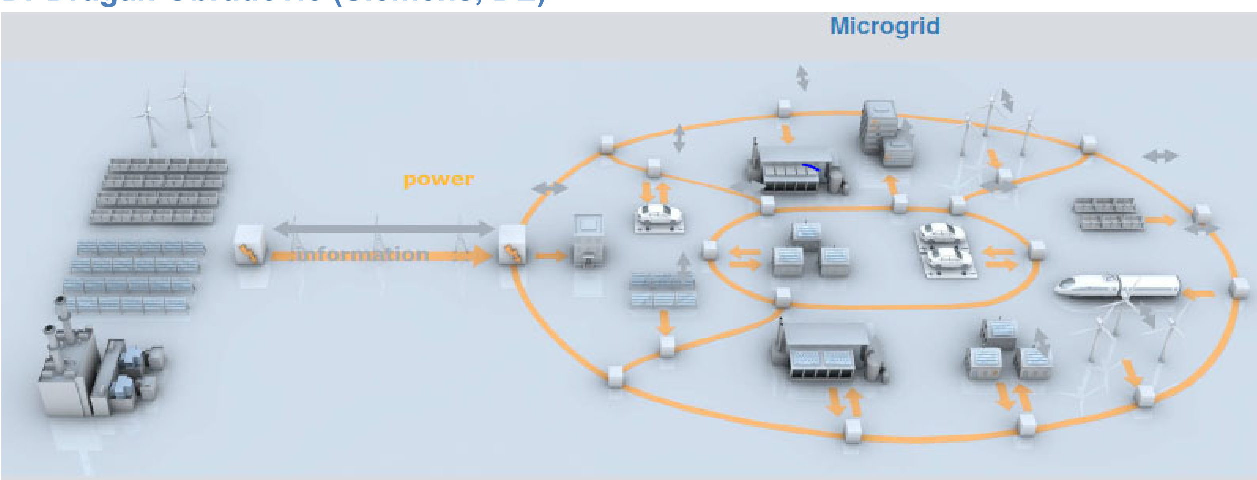
Prof. Göran Andersson (ETH Zurich, CH)

The importance of SoS for power and energy systems with large elements of wind and photo voltaic renewable sources was highlighted. There are also opportunities in the joint operation of infrastructure, e.g. electricity, gas and district heating systems. Many projects in the US have a focus on increasing reliability. This is usually not an issue in Europe. There is a need for models and methods for capturing the fluctuating nature of wind and PV power. Integrated models are required of complete energy systems combining energy producing and storage systems across different countries.

Dr Jean-Luc Garnier (Thales, FR)

A number of applications were highlighted including military, air traffic management, rail signalling, space satellites for earth observation and crisis management. A challenge is to demonstrate how SoS engineering approaches can improve engineering of complex systems. There is a need to compromise Maier's criteria (discussed later) to exploit system of systems. The concept of using products and flexible paradigms to deal with loose coupling was introduced. Support is needed for multi-lifecycle management and to cope with changing dynamics as systems are inserted and removed. Modelling is also required to estimate the feasibility and behaviour of proposed system of systems. "Urbanisation" is required to define common rules and principles that the constituent systems must follow in a SoS.

Dr Dragan Obradovic (Siemens, DE)



Smart Grid (Courtesy Siemens)

A number of applications were highlighted in industry, energy smart grid, city infrastructures and healthcare. The question of "what is a system of systems?" was raised. Several theories are available but a hierarchical approach is required. Game theory may well be promising approach. Controllability and observability are challenges. Safety and availability of infrastructure is paramount. The issues of selling and buying energy on demand for systems with wind farms and large scale storage were highlighted. For fast processes the delays in the system become important. The increasing use of open standards, e.g. OLE for Process Control (in distributed automation systems is seen as beneficial.

Prof. Markos Papageorgiou (TU Crete)

It was highlighted that a considerable amount of work had been performed since the 1970s on large-scale systems, decentralised and hierarchical (multilevel) approaches, complex systems, artificial life, multi-agent systems and autonomic systems which are relevant to, and could be exploited for, SoS. Several transportation problems were highlighted including efficient urban and motorway traffic control, bottleneck congestion control and coordination of multi-modal transportation. Opportunities for SoS exist in future vehicle automation systems. A means of predicting emerging global traffic flow behaviour (from bottom up) and subsystem design (from top down) is needed. A question is whether a global theory exists for all applications. Insights from successful applications may contribute towards a theory.

Prof. Kim Larsen (Aalborg, DK)

"ICT powered" system of systems were highlighted including intelligent building, agriculture, smart grid and biological systems. Key challenges arise from collaboration in distributed subsystems and use of decentralised control. It was noted that large scale systems and multi-scale systems are data intensive. Dynamic behavioural models and stochastic models are required to deal with adaptive components that can join and leave the system. Game theory offers an approach to establish equilibrium. Tools and algorithms are required for distributed and multicore implementations.

Christian Sonntag (TU Dortmund)

The chemical processing and manufacturing industries were highlighted. A challenge is to provide tool integration and design support when different control components are provided by different companies. Autonomy is something that is usually avoided in these applications as failures can be catastrophic. It was highlighted that the geographic distribution in these applications may not strictly meet Maier's criteria. The future trend is towards more integration for factories of the future. Tool vendors need to develop tools to support this and control engineering techniques such as dynamic models and model based methods have a role to play.

Peter Marwedel (TU Dortmund)

The need for education in system of systems was highlighted. An issue is that it is extremely difficult for a single university to teach the subject. Students demand practical work which is challenging to provide, due to the complexity and cost of systems of systems. Support for continuing education, e.g. in the form of summer schools, would be a goal but is lacking after the end of the ArtistDesign NoE.

Fatihcan Atay (Max Planck Institute)

It was highlighted that anticipation and prediction are key elements of complex systems and there is a need for efficient mathematical models that provide abstractions. Here there are a number of approaches already available such as network theory, dynamical systems theory, self-organising graphs, and game theory. There is also a need for data reduction techniques and modelling techniques for when only partial information is available.

Summary of Key Points, Session I

The increasing connectivity between systems is providing many opportunities to create new system of systems functionalities to provide business and social benefits. A question is what is defining about "system of systems" that makes them different from a conventional complex system. This is highlighted in Table 2 below which indicates the differences between the classic way of developing systems which engineers currently use and the challenges introduced by the new area of system of systems.

Characteristic	Old - Classic	New - System of Systems
Scope of System	Fixed (known)	Not known
Specification	Fixed	Changing
Control	Central	Distributed
Evolution	Version controlled	Uncoordinated
Testing	Test phases	Continuous
Faults	Exceptional	Normal
Technology	Given and fixed	Uncertain
Emergence	Controller	Accidental
System development	Process model	Undefined

Table 2 Differences between Current and New System of Systems (H. Kopetz)

Engineers are used to having a good model of the system with fixed requirements, a clear understanding of system interactions and well-controlled development cycles/development processes to support this (e.g. the V-model of development). For system of systems development none of these elements are available requiring engineers to fundamentally re-think how they are going to develop and maintain the system. Thus there is a paradigm shift required in thinking to support development with no good system model and dynamically evolving/changing requirements. As many of the systems require high availability or have safety implications, i.e. are mixed criticality systems certification becomes a major hurdle.

The workshop highlighted that a theory is required for development of system of systems (or potentially a number of theories dependent on the type of system of systems). From a modelling point of view it is thought that the techniques are already available to model a SoS but a challenge is to put structure into rules and theories at the micro and macro levels. A complication has been the adoption of Maier's criteria as the fundamental definition of a system of systems attributes. These state five typical characteristics for a system of systems:

- Geographic distribution
- Operational independence of the elements
- Managerial independence of the elements
- Evolutionary development: An SoS evolves over time, developing its capabilities as the constituent systems are changed, added or removed
- Emergent behaviour: The SoS itself offers additional services above and beyond the capabilities of the constituent systems (but it can also exhibit unexpected and potentially damaging behaviours)

In general, system of systems are composed from a number of geographically distributed, independent agents that have grown up over time with their own goals that are connected/coordinated to provide services and added value. The independence and geographical distribution introduces technical, management and societal challenges when trying to manage the system as a whole. A key point is that the Maier characteristics are the typical characteristics of a system of system. Not all of the characteristics necessarily need to be present. Interpretation of the characteristics also needs to be considered carefully particularly with respect to geographical distribution as this means different things to different people. It was highlighted that connectivity and sharing of knowledge are also key characteristics of a SoS but these are not mentioned by Maier. These are necessary to drive a SoS towards goals. The key defining complications of system of systems arise from managerial and operational independence. The key problem is how to make large systems more manageable. A number of application areas were highlighted by speakers as shown in Table 3.

Application	
Water management	treatment, reservoir management, flow control, pumping, and sewage treatment
Traffic control	flow control, signalling, automated highways, driver information, navigation
Emergency response	coordination of ambulance, medical treatment, medical information, disaster management
Air traffic control	routing, radar detection, transponder information, satellite tracking, avionics and communications
Smart Grid	more intelligence in distribution network (fossil, wind, PV, storage)
Railways	signalling, operation across borders, maximising capacity
Satellites	coordination of satellites for imaging/provision of services
Distributed control systems	
Automotive systems	increased integration of mixed signal electronics with mechanical components
Automation	factories and manufacturing
Process Control	large chemical plants

Table 3 Summary of Examples of System of Systems Highlighted During Meeting

These present different degrees of geographical separation from large scale separation to a range of applications that can be considered to be more "local" distributed systems. A key need highlighted by the participants was the need for documented experience of exemplars and the table above presents potential case study areas. Key points made by speakers are summarised in Table 4.

Speaker	Applications/Key Points
H Kopetz, Vienna	Problem Solving Systems, need new concepts and theories
G Andersson, ETH	Wind and PV, need models and methods for fluctuating systems
J-I Garnier, Thales	Air Traffic/Rail/Space, concept of products, need modelling to assess feasibility and behaviour
D Obradovic, Siemens	Smart grids/wind, game theory may be answer need hierarchical approach
M Papageorgiou, TU Crete	Urban transport, may need different theories for different systems
K Larsen, Aalborg	Micro and macro levels, game theory, dynamic behavioural models
C Sonntag, TU Dortmund	Chemical processing, need tools and vendors to provide tools
P Marwedel, TU Dortmund	Need education for SoS- cannot be done at a single university
F Atay, Max Planck Institute	Mathematics has a range of theories that can be exploited in system of systems engineering for modelling and data reduction

Table 4 Key Points Highlighted in Meeting

Discussion (Chair: Alkis Konstellos)

The discussion session covered how should a system of system be classified and the features (e.g. autonomy, evolution) that makes a SoS different from a complex or ultra large system. It was highlighted that many larger companies, infrastructure operators and governments have an interest in SoS. A question is how small SMEs can contribute to the area as they need to understand how their products will fit in with system of systems. The experience gained from performing use cases was considered to be very important allowing an understanding of what types and levels of modelling are required. It was felt by the group that there was already a large toolkit of approaches that could be utilised, e.g. game theory, dynamic behavioural models, but how to use these tools for SoS is still an issue. It was highlighted that in order for industry to assess the potential business benefits of adopting SoS (which often requires collaboration across multiple companies/industries/organisations) economic and performance modelling is required. The same models can also be used for risk analysis. The question of whether the Commission should support standardisation in the area was raised. Although it is clear that there is much to be gained from definition of a common modelling language/approach that engineers from different disciplines/industries can understand it was felt that it was too early to propose a standard (although existing standards such as ISO-15704 may provide a starting point). A first stage would be to gather the requirements for a modelling language/methodology. There may be some opportunity in the interim to explore systems engineering standards for certifying engineers.

Session II, Structured discussion on approaches/people

It was highlighted that there were many potential lessons to be learnt from large scale IT projects. Successful examples were in military applications, railways (EAEA, TRAK), ESA's capability approach and in air traffic management (SESAR). There were also examples that had tried to address the complexities of system of systems and had encountered difficulties including the US Future Combat System, the Danish rail network, Danish travel card, National Health Service in the UK and the Air Traffic Control system in the US where lessons could be learnt. It was noted that large projects tend to fail when they start from "green field" rather than from integrating existing systems. A difficulty is in defining a clear system architecture and for one company to have a complete knowledge of the providers/builders of the constituent systems. Defining responsibilities and IPR also presents challenges. Mastery of system of systems would drastically reduce the effort and risk of building large systems.

It was noted that there are already projects on smart grid, traffic management, etc. so there was a need to clearly define what funding the area of system of systems would provide beyond existing projects. Here it is thought that funding should address the management of complexity for systems integration of systems with evolving requirements. There is also a need for industry/infrastructure operators/government to get together to lobby to highlight the importance of system of systems. Although it is an important topic car companies on their own, for instance, are unlikely to lobby for system of systems as they are just an element of the overall system and there is no business model for it. It was highlighted that SoS had been identified as a key area on the research priorities for Austria by industry and also by the Department of Transport in the UK. System of systems is difficult to sell/explain to the public at large. The broader community profits from it but there is a need for it to be supported by a public programme such as those supported by the EU.

There is a pressing need for examples and business models with the aim of developing a framework that can be used on multiple applications.

Next steps towards constituency building

A call for proposals has been issued with deadline early January. Consortia for this are encouraged to investigate a number of case studies. Energy was considered to be a good application sector. There are plenty of tools and theories already available but it is difficult to know which to apply and how to integrate them. Common tools and methods are needed. A better way of designing would provide a huge saving for European industry. Many large scale projects involve industry consortia. Reductions in the costs of implementing and maintaining systems would justify investing in this area now.

What is the EU identity?

Europe has a unique position in that it is made up from a group of countries being a system of systems itself. There is thus a history of collaboration across organisations and national boundaries. Europe also has great strengths in its engineering industries, automotive, aerospace, power generation, etc. with expertise in traditionally engineered systems taking a whole system approach. There is also great strength in digital and analogue electronics. Europe has a long established culture of competing companies working together in pre-competitive research. Europe is thus well placed to exploit the benefits of system of systems engineering and is ideally placed to implement it across European infrastructure.

Call for case studies

There is a need to define a set of case studies that have characteristics that lead to one or more methodologies that can be addressed as a cluster of projects. A suggestion here is to map out system of systems dimensions, look at the regions that are occupied and perform case studies that give coverage of the space. A challenge is to define the bounds of a system of systems and also deal with the changing view of the system over time. There was a clear need to identify the business benefits that could be gained from system of systems integration and the performance at local and global levels. The experiences and lessons learnt from development of existing large scale systems may provide valuable lessons.

Potential stakeholders in system of systems are likely to be infrastructure operators (e.g. highways and water management), governments and also leading companies that perform large scale systems integration, e.g. Siemens, Rolls-Royce, Airbus. Vestas, etc. Potential applications are:

- Autonomous Driving – to reduce traffic deaths (these have already reduced due to the introduction of automatic braking systems)
- Electromobility – electric cars and the need to provide charging stations
- Road Traffic - congestion reduction
- Rail Networks – capacity maximisation, signalling and operation across borders
- Smart Grid – combining conventional and renewable sources with storage
- Smart Cities – consumption of energy and carbon emissions
- Manufacturing - integrated network of supply chain materials, manufacturing capacity, quality control for prototyping and low volume production
- Intelligent Homes – assisted living, ageing population
- Disaster Planning and Emergency Response

Test cases are needed and leading companies should be engaged with to identify their interests.

Research Challenges

A number of key challenges have been identified with respect to the development of system of systems with relevance for the next 5 years. These can be classified into 4 areas:

Technological

System of systems are inherently multidisciplinary and therefore there is a need for a common language. Systems modelling, validation and verification tools are required for the development of SoS. Visualisation of systems behaviour is very important. The possibilities of emergent behaviour also needs to be considered to ensure that potentially damaging consequences are avoided. Although the development of standards in the area is thought to be to very beneficial the field is still immature and a better approach may be to gather the requirements for system of systems in advance of a standardisation activity.

Economic

There is a need to demonstrate business benefits to allow engagement with industry. Opportunities to establish platforms for SoS are likely to appear. For implemented systems Quality of Service and availability are paramount. The consequential losses and impact on European Citizens incurred from failure of a Smart Grid for instance would be very high.

Political

Social user acceptance is important. Here there are public concerns over data security and integrity from external attack. A noted issue is that system of systems tend to mix criticality. This introduces both security and safety considerations particularly from a legal point of view. There is a need to provide approaches that can lead to certification of system of systems.

Education

There is a lack of engineers with suitable multidisciplinary training in the area of system of systems. Providing suitable education is difficult due to the scale and complexity of system of systems and requires coordinated effort.

European Eco System Needs

To build a European Eco System that supports the development of system of systems there are a number of pressing needs which should be tackled as soon as possible. These are outlined below:

- Develop methods, architecture platforms and theory for SoS applied to a small number of case studies and then identify the commonalities across the case studies
- Develop multi-scale, hierarchical modelling, simulation, validation capability to provide decision support tools for industry to assess the potential benefits of SoS
- Identify and build the constituency and stakeholders in SoS
- Develop an appropriate research and innovation roadmap including use cases that elaborate the added value of the SoS approach.

It is advocated that these key needs are supported under the 2013 workprogramme and in Horizon2020 by instruments such as STREPS and IPs. In particular, a CSA should work on the last two items (constituency building and roadmapping activities). Finally, a long term research dimension is also required for SoS targeting underlying theoretical work amongst others.

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