Workshop on Systems of Systems Engineering and Control

Report from the Workshop on Systems and Systems Engineering and Control

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Communications Networks, Content and Technology Directorate-General
Unit A3-DG CONNECT
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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 Systems of Systems (SoS) Engineering. Systems of Systems describes the large scale integration of many independent self-contained systems to satisfy global needs or multi-system requests.[1]

Fig.1 Typcial System of Systems

An example of this is the integration of transport systems (See Fig. 1) to provide fast and efficient movement of passengers and freight.

Developing Systems of Systems presents many technical, organisation, political and sociological challenges. To tackle these challenges the European Commission has funded a cluster of projects creating a Systems of Systems of research projects (See

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[1] Typical characteristics of a Systems of Systems as described by Maier are:
- 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)

Fig. 2). Here there is a combination of support actions addressing roadmapping and generation of strategic research agendas in the area, Integrated Projects tackling development methodologies and modelling frameworks for SoS, and a number of STREP projects researching, optimal control design, distributed autonomous management, critical system certification and self-learning approaches. Further two integrated projects work on adaptability and evolution in SoS engineering as well as on modelling for advanced SoS.

The projects interact via clustering and through the exchange platform provided by CPSoS and related CyPhERS Support Actions. The current status and outcomes from these projects is described in this report along with two underpinning projects, WiBRATE and PROXIMA as well as the key issues relevant for SoS engineering as they came out from the workshop discussions.

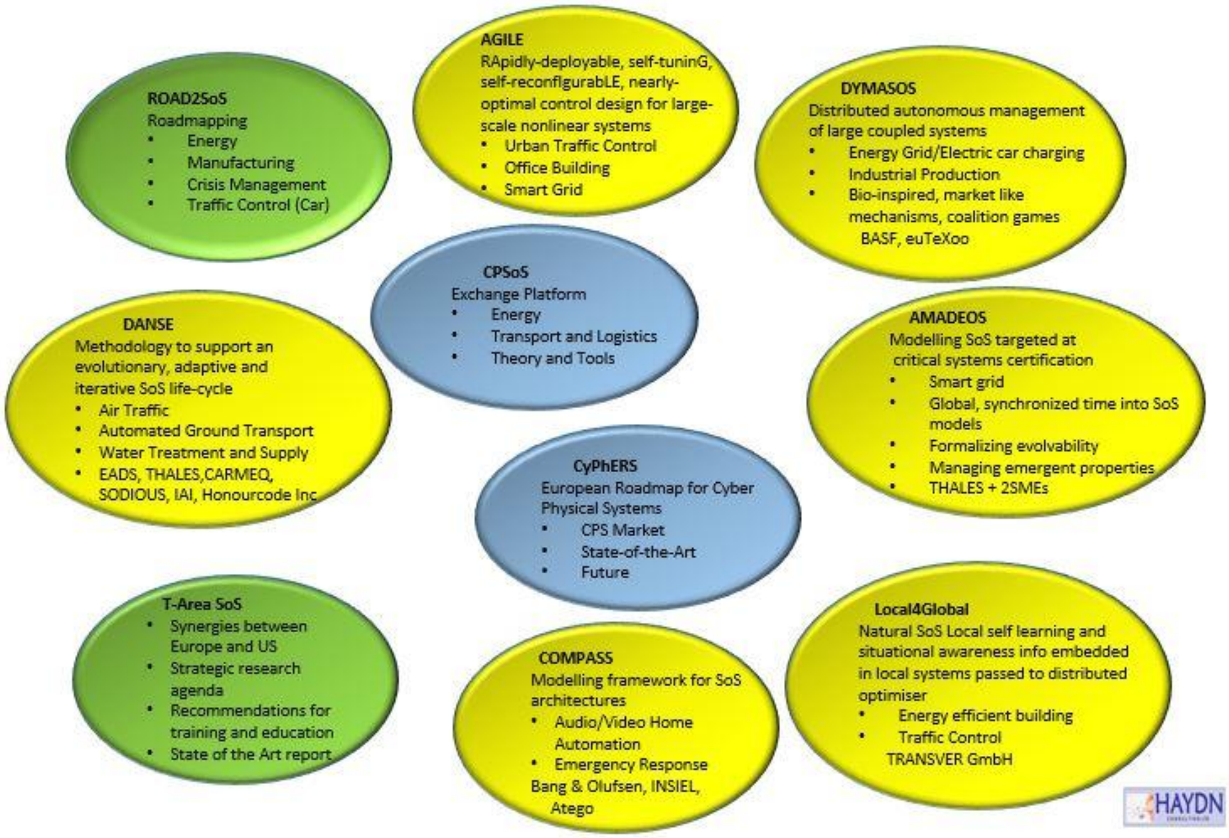

Fig. 2 EU Funded Systems of Systems Projects

Key **socio-economic issues** for SoS engineering

- There is an organisational revolution currently underway which is being enabled by ICT. To understand the needs of SoS it is necessary to spend more time in the problem space.

- Humans are intimately involved at many levels within a SoS. How humans interact and influence the SoS in terms of decision making, authority and degree of autonomy needs to be addressed.
- Enablers for development of SoS are interoperability, affordability, incentives and standardisation
- Organisational challenges need to be considered including development of new business models while also addressing concerns such as the need for privacy and confidentiality.

Key **technical issues** for SoS engineering

- The benefits of creating a SoS come from orchestration of the overall system but the problem is that we are not working from a blank sheet of paper – engineers thus need to build on what is available already
- There are many trade-offs and constituent systems needed to commit to additional obligations, constraints and complexity to be part of an SoS
- There is a need for modelling, simulation and optimisation tools that can deal with different model abstractions (there may be little or no information available about a constituent system). Other needs are for predicting dynamic interactions, economic modelling, market driven optimisation and approaches to handling of big data.
- Safety-critical applications require an approach for validation and verification of SoS, dealing with emergence and providing security

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Introduction and Scope of Meeting

This report summarises a workshop organised by Steinbeis-Europa-Zentrum on behalf of the European Commission to identify scientific, technological and socio-economic challenges, enablers and the scientific impact for research in the area of Systems of Systems. This was achieved via means of a series of invited presentations from on-going and recently established projects and other key stakeholders in the field. The meeting was introduced by Dr. Meike Reiman of Steinbeis-Europa-Zentrum explaining the purpose of the workshop.

Introduction (Dr Werner Steinhögl, European Commission)

Werner Steinhögl of the European Commission gave an example of a biological SoS (a beehive). It was highlighted that the field of SoS is not yet well defined but foundations are being developed. Thus far the lessons learnt are that designing a SoS is a challenge and there is a need to work on methods. Applications are also important when developing and integrating SoS technologies and there is a need for industrial use cases to drive research and roadmaps for research and innovation collaborative projects. The view of Cyber-Physical Systems (CPS) and SoS within H2020 was outlined. Here there are a number of layers from components at the centre, to systems at a higher level, to systems of systems when systems are interconnected. The human is seen as being at the outer level but could also be involved at other levels.

It was highlighted that SoS is still to be funded under the area of CPS but at a different layer. There is a desire to de-verticalise technology solutions cutting across barriers between application sectors including mass consumer markets. The Commission wants to bring together actors along the value chain from component suppliers to the system integrator to the end user. The aim is to create new ICT platforms in both vertical markets and core markets by matching between the needs of customers and future technology services of CPS.

There are several funding opportunities for this in the LEIT-ICT scheme of Horizon2020:

- ICT-4 Customised and low power computing
- ICT-30 Internet of Things
- ICT-1 Smart Cyber-Physical Systems
- FoF-1,8,9 ICT for Factories of the Future

What is new in Horizon 2020 is the idea of connecting innovators across value chains moving towards platforms and ecosystems. To bootstrap this the Commission is funding European Networks of Embedded Systems Design Centres.

A fundamental question is "where are the future markets?". There is interest in success stories and what made these activities successful. There is also a need to understand the main barriers to industrial implementation. The two key questions are:

- What are the suitable strategies for technology transfer and how should public authorities invest?
- What is required from industry to make SoS deployment happen and what is the role of SMEs and mid-cap companies?

Key Notes

The meeting was introduced by two keynote presentations to set the scene giving both academic and industry visions for research and innovation potential and business opportunities.

SoS Challenges, Research Priorities and Technology Transfer (including T-AREA-SoS Results: Strategic Research Agenda) (Michael Henshaw, University of Loughborough, UK)

The definition of Systems of Systems Engineering (SoSE) and the link to CPS was outlined highlighting that SoS is more about the organisation of technologies. This raises the question of "how do systems work together collaboratively?". It was also noted that there are different types of SoS and the same set of principles cannot be used for all. There are 4 main types of SoS: Directed (with one controlling system), Acknowledged, Collaborative and Virtual.

Concerns are arising from the increasing use of embedded software and there is a need for a direct and real-time interface between the virtual and physical worlds. It was argued that CPS are a special type of SoS. The key difference is that a CPS interconnectivity is restricted to cyberspace. A radio communication example between two people was given. For this example the question for CPS developers is "how do I improve the radio and Human Machine Interface?". From a SoS engineering perspective there may be different radios and the need for a radio may not be necessary at all if it is possible to shout load enough. Here improvements are made regardless of technology.

The fundamental problem with SoS is that from a single system community's perspective for it to be a part of the SoS there are needs for additional obligations, constraints and complexities. It is rare that participating in a SoS is seen as a net gain from the viewpoint of single system stakeholders. The need for business experts and sociologists was highlighted. Drivers behind future SoS were increasing population and food security.

The results of the T-AREA-SoS Support Action were presented. This project performed by two institutions in Europe and two institutions in the USA (Purdue and University of Texas San Antonio) had the objective to create a strategic research agenda in SoS engineering that highlighted key research themes. The project had also identified the state-of-the-art and gaps in research. A SoS expert community had been brought together to support this. The project also identified the skills required for system developers and system users, and has made recommendations on training and education. The themes identified within the SRA are:

- Theme 1: Characterisation and Description of SoS
- Theme 2: Theoretical Foundations
- Theme 3: Emergence
- Theme 4: Multi-level Modelling
- Theme 5: Measurement and Metrics
- Theme 6: Evaluation of SoS
- Theme 7: Definition & Evolution of SoS Architecture
- Theme 8: Prototyping SoS
- Theme 9: Trade-off
- Theme 10: Security
- Theme 11: Human Aspects
- Theme 12: Energy-efficient SoS

A comment from the audience made at the end of the presentation was that, although sociologists have a role to play in SoS, as ICT engineers there is a need to concentrate on systems with significant ICT and solve the issues in this domain.

Industry View- Innovation Potential and the Business Opportunities (Alf Isaksson, ABB)

It was argued that "Cyber-Physical Production Systems" may be the next industrial revolution. An overview of ABBs activities was given. ABB has 5 Automation labs and 5 Power labs. The company produces many products for the paper, oil, mining, steel, ship, power grid, powerplant, wind farm and cement mill industries.

It was noted that 20% of the GDP of Europe comes from manufacturing. Industry challenges are in providing 100% available plant supported by predictive maintenance, energy efficient equipment and 100% secure communication lines. For the manufacturer engineering efficiency is key. It was highlighted that there are a number of initiatives going on in Germany, the US, China and the UK.

The industrial revolutions that have occurred were outlined from the advent of steam power, to disassembly lines in slaughterhouses that led to Ford's Assembly line, and the move from relays to programmable controllers. It was noted that there are both technology and organisational revolutions. To date there has been a technical revolution followed by an organisational revolution, followed by a technical revolution. The next wave is "communication everywhere", with smarter devices and knowledge being stored in the cloud. It is thought that this will result in a new organisational revolution.

In Germany the Future Vision Industry 4.0 has advocated the need for new business models, engineering and commissioning, providing services, operation and maintenance. ABB has already produced a tablet based system that locates where the engineer is and when the device is pointed at an asset service information is provided. Internally the company has defined "Cloudification levels". A key interest is in availability of data. The ability to put data in the cloud allows access from all departments.

The biggest research need at present is to identify the right questions. It takes time for new technologies to influence industry and typically it takes around 10 years for a new generation of technology to get through to the process industry. Although the industry has moved towards working on the same platforms, individual companies do not want to be open in order to lock end users into a single supplier.

Testimonials for Running Projects: Results and Success Stories

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

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.

Fig. 2 Overview of DANSE (Courtesy DANSE)

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 a 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

It was highlighted that there were many challenges resulting from different drivers for stakeholders, unexpected emergent behaviour and insufficient awareness of system state. The approach being adopted was to use contract based formal methods to create systems that were "correct by evolution". The work had been investigating models of SoS behaviour, looking at aspects of dynamicity, goals, capabilities, authority, coordination, use of resources, communication, awareness (trusted information), and observation. The relationships between dynamicity and the Maier Criteria had been mapped. A snapshot of the methodology was presented which uses VDM, system behaviour modelling, architecture optimisation and dynamic analysis. This had been investigated for an emergency response system combining the fire, police and ambulance services. A key aspect was design exploration.

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

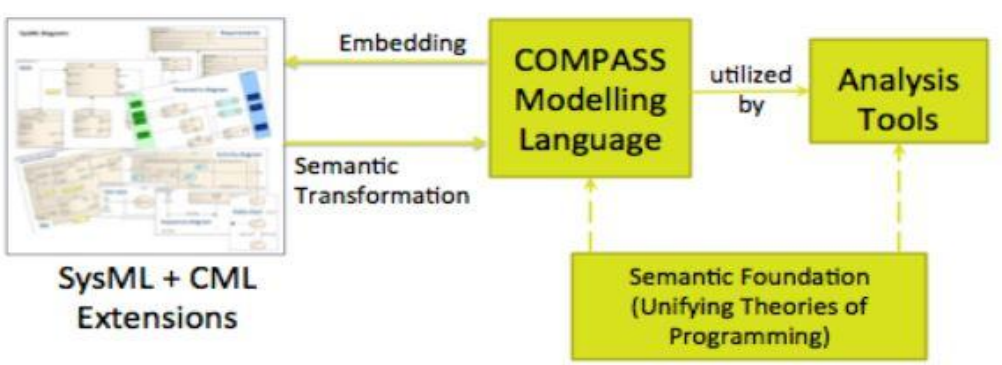

Fig. 3 Overview of COMPASS (Courtesy COMPASS)

COMPASS is addressing model-based techniques for developing and maintaining Systems of Systems (SoS). The approach is to develop appropriate tools and pragmatic methods for modelling systems 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

The project is developing a formal modelling language and tools for SoS. The formal semantics for SoS problems were being considered and an Open tools platform for analysing emergence was being produced. The three main technical foci of the work are collaborative SoS modelling using formal contracts, verification of emergence and semantic heterogeneity. SysML was being used as the basis combined with the CML (Compass Modelling Language) formal modelling language which feeds into automated model checker and proof tools. Guidelines for SoS modelling in SysML had been produced. Analysis of a Bang and Olufsen system using the approach had identified a potential deadlock problem which was later experienced by a customer. In the future there is interest in audio, video and home automation with music following an occupant from room to room. This is challenging as there needs to be interoperability between old and new products. There is also a design need to have one single leader that provides the streaming of data into the house. This requires "Emergent leader election" so that integration of a new device does not affect an existing system. Work is on-going on traffic management and smart grid applications.

ROAD2SOS: A Roadmap for Innovation in SoS

A significant roadmapping activity had been performed in 4 domains. The outcomes from this work and the roadmaps that had been defined were each presented for the 4 domains.

Overview, Main Findings and Innovation Opportunities (Christian Albrecht, DE)

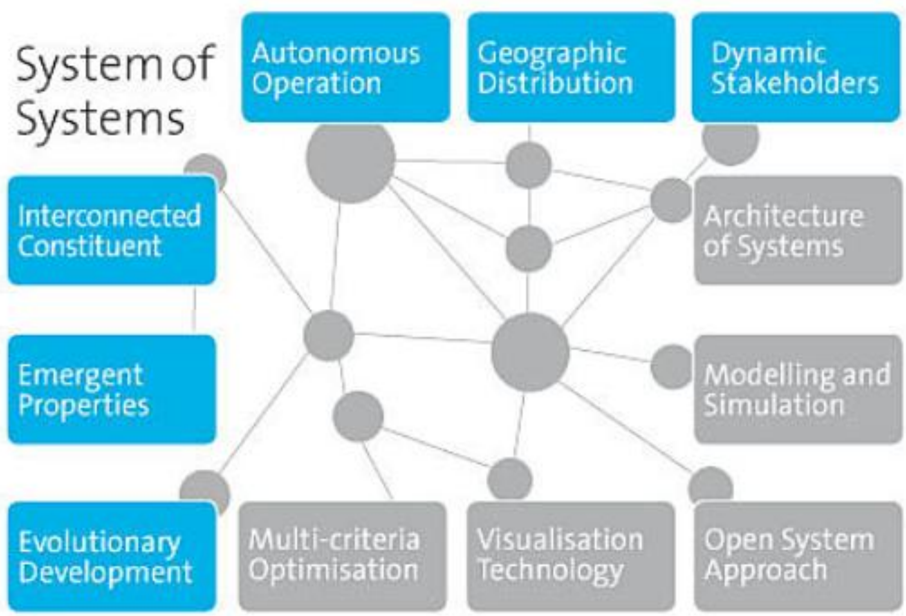

Fig. 4 System of Systems Characteristics and Research Needs (Courtesy ROAD2SOS)

ROAD2SOS is a 27 month Support Action producing roadmaps and identifying future research strategies for systems of systems engineering coordinated by Steinbeis-Europa-Zentrum with 7 partners from 4 European countries (France, Germany, Spain and UK).

The project has defined 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 was to identify priorities for research and development, economic and social barriers, enabling technologies, and drivers. This has been achieved through a series of Roadmapping workshops and consultation with experts. The four roadmaps have been created with a bottom up emphasis.

The work has been specific to the theme areas but it is hoped that some themes are transferable to other domains. The project is nearly complete and is currently wrapping up the recommendations. The project has identified two sets of overall priority themes.

Priority Theme 1
The first is to allow better and faster decisions on a greater variety of sources. These themes include: real-time systems, real-time communication, improved forecasting, better analytics, measurement and metrics for SoS, co-ordinated planning, decision making and action of many entities, closer interaction among system actors, collaboration platforms, autonomous real-time decision making, improved algorithms for automated reasoning, artificial intelligence, awareness, safe autonomous systems, increased information and data exchange, efficient handling of big data, distributed computing, improved smart sensors, sensor data fusion and big-data-based decisions.

Concerns were that it is estimated that there will be 1000 sensors per person in the world by 2016 which could lead to a complexity trap through information overload.

Priority Theme 2
The second priority theme is concerned with the design, operation, monitoring and control of (very large) scale distributed systems. This needs to consider handling/management of a large number of stakeholders, governance, handling /management for increased complexity, deal with/embrace heterogeneity of constituent systems, interoperability of heterogeneous systems, multi-protocol integration, HMI, understanding emergence, modelling and simulation tools for SoS, prototyping of SoS, architectural patterns, increased adaptability and flexibility of systems, dependability reliability, engineering for resilience and SoS certification.

The potential barriers that have been identified are: business models have yet to emerge, the need for high upfront investment, unclear economic benefits, unclear risk benefit ratio, absence of demonstration, concerns regarding stability, concerns regarding security and privacy, concerns about intellectual property and social acceptance of pervasive IT systems.

It is advocated that some demonstration in the application domains is needed.

Presentation of Domain-Specific Roadmaps (Meike Reiman, Philippe Liatard, Dolores Ordóñez, Urula Rauschecker)

Traffic Domain

It was highlighted that existing systems are not sufficiently interconnected to ensure optimal usage of infrastructure. In order to allow optimised usability, more efficient and convenient transportation and the use of safety automated vehicles, there is a need for standard system interfaces, open systems, miniaturised sensors, and networking and communications standards. There is also a need for collaborative information systems between transport modes, self-configuration and car-car/car-infrastructure connectivity. This will require consideration of maintenance cost of distributed, heterogeneous architectures, business models for new services, public acceptance and also political and organisational support as the costs will be high to install the communication and infrastructure needed. This communication will need to be secured.

A number of recommendations for future research have been made. These are for higher interoperability supported by real-time systems with real-time communications. There is a need for improvements in smart sensors and data fusion to handle the data produced. There is also a requirement for autonomous software and self-calibration capabilities. Additionally, recommendations need to be developed for future implementations in cities that will lead to the concept of Smart Cities.

Emergency and Crisis Management Domain

It was noted that emergency and crisis management is performed differently in different countries and even from region to region. There is a need for interactive sensor networks to assess risk information and allow real-time decision making. There are needs for increased surveillance which will present information and communication challenges. The benefits are seen as smarter information management before, during and after an emergency to act more quickly. Interactive sensor networks can also be used to assess risk parameters.

The domain needs are for interoperability and coordination supported by faster speed communications. These need to have built in resilience. Human and sociological aspects are key factors. There is a need for integrated autonomy, higher interoperability, real-time systems, decision making approaches and a means for modelling applications.

The barriers to adoption are an unclear economic benefit and lack of business model. There are also concerns about security and a lack of skilled personnel that can exploit the technology.

The key challenges for emergency responders is in the use of new technologies and employing new techniques for decision making. There is a need for higher interoperability between equipment and for research on real-time systems. Improvements in smart sensors are seen as key but it is also necessary to handle Big Data through improved algorithms and have supporting modelling and simulation tools. There is a need to increase the investment in technology research and this fits in with activities in Smart Cities and buildings. There is a need to consider provenance of data to make proper usage of social media, e.g. twitter input from the public.

Sociological issues also need to be considered such as how new technologies can be used to influence or change existing procedures adopted in emergency response scenarios and also to deal with potential conflict if there are competing aims.

Production Domain

It was highlighted that there are various suppliers on a buyers' market and there was a high effort to join production networks. The term Systems of Systems is not used in the production domain but multi-site industrial production is commonplace.

The main trends and drivers are for flexibility and agility, management of complexity, efficient information exchange and optimisation. To support this there is a need for communication standards, interfaces, protocols, analytics and models. There is also a need for management of big data. Key issues in the industry are improvements in product specification, manufacturing execution and control, tracking production and process control. Although there is a trend for increased automation and use of IT, factory managers still want "control" of the factory. There is a need for appropriate plug-and-play control system architectures for dynamic reconfiguration, SOA and agent based control. For the manufacturing industry the complexity of IT systems should be made invisible to users.

Enablers from a socioeconomic perspective are new business models, but there is a need for integration and migration strategies. This requires knowledge transfer and education of stakeholders. Safety and security are also key concerns where systems security across company borders is required. There is also a need for clarification of IP issues. The creation of functional industrial demonstrators was advocated.

It was commented that most of the issues highlighted are already well known problems for the supply chain.

Energy Domain

The energy domain was not presented at the meeting as work on developing the roadmap will be completed by the end of the year.

Top Five ICT Needs in Each Domain

Multi-modal Traffic Control	1. Standards development 2. Reusability of systems /components /software 3. Efficient handling of big data 4. Suitable interaction interfaces 5. Safety of the system
Integrated Multi-site Production	1. Real time capability 2. Networking capabilities, data transfer, data rate, ... 3. Seamless integration of systems/components 4. Standards development 5. Expandability of systems/components
Distributed Energy Generation and Smart Grids	1. Real time capability 2. Data security (privacy) 3. Self-healing 4. Suitable protocols and interfaces 5. Self protection
Emergency and Crisis Management	1. Networking capabilities, data transfer, data rate, ... 2. Efficient handling of big data 3. Safety of the system 4. Efficient energy management 5. Real time capabilities

New Projects

DYMASOS Dynamic Management of Physically Coupled Systems of Systems (Prof Sebastian Engell, TU Dortmund)

DYMASOS is addressing the management of large physically coupled systems of systems.

Challenges

- The project will develop new methods for the distributed management of large physically connected systems with distributed autonomous management and global coordination.

Research

- Population-control techniques that are motivated by the behavior of biological systems
- Market-like mechanisms that try to achieve global optimality by the iterative setting of prices or resource utilization constraints
- Coalition games, where agents group dynamically to pursue common goals

Planned Outcomes

- Innovation in distributed management methods for SoS
- Methods for the rigorous analysis and validation of systems of systems
- Demonstration in realistic large-scale simulations of real use cases

Applications

- The research will be driven by case studies in electrical grid management and control, including the charging of electric vehicles, and industrial production management.

The aim of the project is to investigate market like situations. This will not be done with real industry experiments as this is not possible but will be performed using co-simulations in Modelica. This will involve information modelling and management. It is planned to exploit the SoS engineering tools developed for the applications via the SMEs working on the project. The aim will be to provide prototype solutions for industrial case studies. Feedback on these will come from the partners and industrial advisory board. The potential benefits of the work will be better efficiency leading to financial gains and also ecological benefits.

CPSoS Cyber-Physical Systems of Systems (Prof Sebastian Engell TU Dortmund)

CPSoS is a 30-month application driven Support Action that will provide a forum and an exchange platform for systems of systems related communities/projects.

Aims

- Bridge between the different approaches to the design, analysis and control of systems of systems that are pursued by different communities in theory and applications
- Relate the different methods and tools proposed for dealing with SoS to key application domains

Working Groups

- Systems of Systems in Transportation and Logistics (Chair: Professor Haydn Thompson)
- Systems of Systems in Electrical Power Grids, Industrial Systems, Distribution Networks, Smart Buildings (Chair: Professor Sebastian Engell)
- Tools for Systems of Systems Engineering and Management (Chair: Professor Wan Fokkink)

Outcomes

- Identification of industrial & societal needs and of the state-of-the-art of tools and theories
- Identification of synergies, open issues and promising trans-disciplinary research directions, which will go into work programs of the EU, national funding programs, etc.
- Build up a network of key researchers and application domain experts in the area
- Stimulate the take-up of research by industry (vendors and end-users)
- Raise public awareness of the impact of research on systems of systems engineering, analysis and control

It was highlighted that the goal of the project was to provide focused outputs for the working group topics. This will be supported by working papers from working group members. The project is also providing a bridge between running STREPS and people from ongoing projects will also be invited onto the working groups to contribute and provide feedback on reports. It is also planned to perform structured interviews with key actors in the area. The schedule for work has been brought forward to allow for a first draft of priority areas to be presented around June 2014.

CyPhERS Cyber-Physical European Roadmap and Strategy (Prof Martin Toerngren, KTH Stockholm)

The CyPhERS project is an 18 month Support Action aimed at combining and expanding Europe's competence in embedded and mobile computing, and in control of networked embedded systems. The main objective of the project is to develop a European strategic research and innovation agenda for Cyber-Physical Systems (CPS).

Aims

The project will systematically survey, analyse, and evaluate the economic, technical, scientific, and societal significance of Cyber-Physical Systems for Europe by:

- Providing a systematic classification of the CPS domain
- Modelling of the markets and their players relevant for CPS
- Developing a structured analysis and assessment of core technologies and the current state in science and technology related to CPS
- Analysing the future technological, economic and social implications of CPS, and
- Assessing challenges, bottlenecks and risks for research and development in CPS

Outcomes

Along with the integrated strategic CPS research agenda CyPhERS will derive comprehensive recommendations for action that will address:

- The identification and prioritization of research areas
- Support measures for both horizontal and vertical cooperation
- Research funding policies, and training and standardization
- Cyber-Physical European Roadmap and Strategy
- Importance of cyber-physical systems

Driven by the new size and scale of CPS applications coming up, the project will run a number of workshops to gather information on economic, technical, scientific and societal challenges. It will assess existing roadmaps and CPS agendas. Already one workshop has been held which was attended by 14 academic institutions, 8 industries and 1 policy making organisation.

AMADEOS Architecture for Multi-criticality Agile Dependable Evolutionary Open System-of-Systems (Prof Andrea Bondavalli, University of Florence)

AMADEOS is targeted at critical systems certification for SoS.

Challenges

- The goal of AMADEOS is to establish a sound conceptual basis and a generic architectural framework that address the challenges of guaranteed responsiveness, evolvability, dynamicity and emergence in Systems of Systems (SoS) supported by extended mainstream UML-based tools

Research

- Introducing explicit, global, synchronized time into SoS models & SoSE. To guarantee responsiveness, reduced cognitive complexity, higher dependability and a simplification of the certification of safety-critical services
- Capturing and formalising SoS evolvability and dynamicity. Evolution of a SoS is necessary for the adaptation to environmental changes such as new business cases, legal requirements, compliance, changing safety regulations, evolving environmental protection rules, etc.
- Managing emerging properties in SoS. Understanding the mechanisms of emergence will help in the composition of constituent systems, especially in predicting the effects of composition on dependability, safety, security, and availability

Applications

THALES are providing industrial input

The aim of the project is to provide a sound conceptual model of time and a generic architectural framework. It is hoped to also tackle emergence that occurs when pre-existing systems are connected. This is being achieved through extensions to UML tools. These approaches will be tested on a proof-of-concept prototype smart grid application. An intention will be to provide guaranteed best adaptation for evolution. The key outcome will be an engineering approach for SoS synchronized time, SoS evolution and dynamicity.

AGILE RApidly-deployable, self-tuninG, self-reconfIgurabLE, nearly-optimal control design for large-scale nonlinear systems (Elias Kosmatopoulos, Technical University of Crete)

Challenge

- Develop an automated tool that provides self-tunable, self-reconfigurable, modular, scalable and nearly-optimal control design for general nonlinear systems of arbitrary scale, heterogeneity and complexity

Research

- Develop a systematic and automated tool capable of designing efficient Large-Scale Control Systems (LSCS) for general nonlinear large-scale systems
- Develop a scalable/modular Linear Switching Controller design
- Develop self-tuning properties for rapid, robust and safe operation under uncertainties, modelling errors and variations and that can also cope with fault-recovery and self- reconfigurability
- Interface to open-architecture SCADA/DCSs

Applications

- Urban Traffic Control (UTC) for a road network of Chania, Greece, and control of an Office Building

The aim of the project is to provide plug-and-play control for SoS. The current approach to designing and tuning controllers is expensive and requires experts. Three approaches were investigated in the project: plug-and-play control with highly accurate models, plug-and-play for real life using a model free approach and plug-and-play control with no model or controller using fully adaptive control. This had been applied to an office building with 10 offices and to 20 junctions in a transport network in Chania with very good results.

LOCAL4GLOBAL System-of-Systems that act LOCALly For optimizing GLOBALly (Elias Kosmatopoulos, Technical University of Crete)

The LOCAL4GLOBAL methodology will provide a scalable and computationally efficient "plug-and-play control mechanism" for the constituent systems of a SoS with the ability to fully exploit each constituent system's abilities.

Challenge

- To develop and extensively test and evaluate in real-life Traffic Systems of Systems (TSoS), a generic, integrated and fully-functional methodology/system for TSoS comprised of fully autonomous units that react and interact depending only on their local environment in order to optimise the TSoS emerging performance at the global level

Research

- Control for Learning and Learning to Control (C4L/L2C) mechanism
- Embed a self-learning mechanism which provides a "just enough" estimate of the TSoS dynamics
- Create a situation awareness mechanism that extracts from local measurements global TSoS information
- Use a distributed optimiser that calculates the constituent system optimal actions

Applications

- Traffic TSoS Use Case and an Efficient Building TSoS Use Case

The approaches to be adopted in Local4Global are a follow-on to those developed in AGILE. The key goal is to use "control for learning and learning for control" and provide a plug-and-play approach to implemented controllers within SoS. For this to work the system needs to be observable so perturbations are required to stimulate the system. A distributed optimiser will optimise the overall system.

Underpinning Research Projects

WIBRATE Wireless, Self-Powered Vibration Monitoring and Control for Complex Industrial Systems (Prof Paul Havinga, University of Twente)

The WiBRATE project is exploring new paradigms and strategies for wirelessly monitoring and controlling vibration using a network of intelligent embedded devices that power themselves using harvested vibration energy.

Aim
Provide a self-powered, wireless platform for vibration monitoring and control supported by collaborative and distributed techniques for robust control and actuation.

Research
WiBRATE addresses the following areas:

- Systems of systems engineering (SoSE)
- Real-time vibration analysis and control
- Distributed and cooperative networked control strategies
- Intelligent actuators
- Robust, real-time wireless communication in harsh industrial environments
- Vibration-based energy harvesting for sensing, control, actuation and communication

Applications

- Automotive manufacturing, aerospace (helicopter and gas turbine) and the railway industry

Industry Partners

- Fiat Research, Honeywell Research and LMS International, Inertia Technology and Perpetuum

The project is addressing a number of applications in automotive manufacturing, helicopter and gas turbine monitoring. A key success has been in the railway industry where a demonstrator system implemented on 10 trains had led to a commercial order to equip 150 trains. The aim is to provide fully automated condition based maintenance and control.

PROXIMA Probabilistic Real-Time Control of Mixed-criticality Multi-core and Many-core Systems (Tullio Vardanega, University of Padoa)

PROXIMA is an IP project investigating temporal analysis of multicore and many core processors.

Challenge

- To provide probabilistic real-time control of mixed criticality multicore and many core processors
- PROXIMA will define new hardware and software architectural paradigms based on the concept of randomisation

Research

- Analyse temporal behaviour in complex single core and simple multicore processors using probabilistic timing analysis
- Demonstrate time composability if behaviour follows a random pattern
- Determine worst case timing for system
- Probabilistic analysis methods will be integrated into commercial design, development, and verification tools, complemented by appropriate arguments for certification

Applications

Avionics, space, automotive

The approach of using probabilistic timing analysis is a new and exciting approach that is demonstrating its effectiveness for worst case execution time analysis. The ability to have time composability is particularly interesting which is evidenced by the large number of industries involved, e.g. Rapita Systems, INRIA, Airbus, Sysgo, Infineon, IKERLAN, Aeroflex Gaisler and Astrium Satellites.

Panel Discussion – The Innovation Potential of SoS Technologies

The panellists each made a statement on their views of innovation potential for SoS technologies.

Guido Sand, ABB

A driver in the industry is the closing of loops for asset performance management. This will lead to development of industrial services to improve productivity and reliability. The impact of this will be to improve the level of up time for plant. There is a feeling that everyone is working in the solution space and more time needs to be spent in the problem space to understand the needs and problems. Overall there is a need for new business models.

Dee Denteneer, Philips

The drivers inside Philips from their lighting business is for adding smartness through software and increased connectivity between systems. Different types of lighting are required for studying, giving presentations and relaxing. The company is looking beyond its own lighting systems and at linkages with other systems such as HVAC. There are a number of challenges. Currently, there is no interoperability and there is a need to rearrange the value chain. Another key thing that needs understanding is what customers want.

Sebastian Engell, TU Dortmund

It was highlighted that the real benefit comes at the higher level from orchestration of systems. In the process industry there is a strong interaction between technical decisions and economic impact. A driver is CO_2 footprint per ton of chemical product. Control of the overall system is required but there is over-regulation in some areas.

John Fitzgerald, Newcastle University

A key area that is required is management of SoS considering the dynamic problems. It must be remembered that the underlying systems may never have been designed for the purpose of the SoS. The SoS is not designed from a blank sheet of paper and in order to understand them there is a need to combine radically different cost, discrete event and continuous models.

Michael Henshaw, University of Loughborough

A driver is agility and there is a need to focus on technologies that enable agile behaviour. Dependability, affordability, interoperability and availability are key factors.

Fast decision making is required and there is a need to grow a systems of systems process. It will be necessary to live with partial and heterogeneous models and the effects of complexity need to be considered. For industry de-risking is crucial, and the longer term view also needs to be considered, e.g. drivers such as climate change.

Key points made by speakers are summarised in Table 1.

Speaker	Key Points
G Sand, ABB	Developers need to spend more time in the problem space
D Denteneer, Philips	Interoperability is a key enabler
S Engell, TU Dortmund	There is a need to orchestrate systems at high level
J Fitzgerald, Newcastle University	A method for combining radically different models is needed
M Henshaw, University of Loughborough	Agile behaviour is a key requirement

Table 1 Key Points Highlighted in Meeting

Summary and Key Messages

The workshop brought together a number of established and new projects working on aspects of Systems of Systems. The presentations from these projects and also from invited industrial speakers identified a number of scientific, technical, organisational and sociological challenges.

Key socio-economic issues highlighted were:

- There is an organisational revolution currently underway which is being enabled by ICT. To understand the needs of SoS it is necessary to spend more time in the problem space.
- Sociotechnical issues need to be considered as humans are intimately involved at many levels within a SoS. How humans interact and influence the SoS in terms of decision making, authority and degree of autonomy needs to be addressed.
- Enablers for development of SoS are interoperability, affordability, incentives and standardisation
- Organisational challenges need to be considered including development of new business models while also addressing concerns such as the need for privacy and confidentiality.

Key technical isssues were:

- The benefits of creating a SoS come from orchestration of the overall system but the problem is that we are not working from a blank sheet of paper – engineers thus need to build on what is available already
- There are many trade-offs and constituent systems needed to commit to additional obligations, constraints and complexity to be part of an SoS
- There is a need for modelling, simulation and optimisation tools that can deal with different model abstractions (there may be little or no information available about a constituent system). Other needs are for predicting dynamic interactions, economic modelling, market driven optimisation and approaches to handling of big data.
- Safety-critical applications require an approach for validation and verification of SoS, dealing with emergence and providing security

In summary, the cluster of Systems of Systems projects funded by the European Union is already addressing many of these issues but more work is needed at the National and European levels engaging with actors along the value chain from component suppliers to system integrators and end users. The European Commission has put into place new funding approaches in Horizon 2020 designed to bootstrap this process such as the concept of European Networks of Embedded Systems Design Centres. Here the intention is to bring together, researchers, SMEs and mid-cap companies to exploit new emerging markets in CPS and SoS. This combination of instruments will help address the technical, organisational, political and sociotechnical challenges highlighted and support the future development of Systems of Systems by industry.

Participants and Input

(Editor) Thompson Haydn	Haydn Consulting/THHINK	CPSoS
Albrecht Christian	Steinbeis-Europa-Zentrum	Road2SoS, Road4FAME
Ascheid Gerd	RWTH Aachen University	TETRACOM
Athanassopoulou Nicky	IfM ECS	Road2SOS
Badii Atta	University of Reading	MOSAIC
Beferull-Lozano Baltasar	Universidad de Valencia	HYDROBIONETS
Bernabeu Eusebio	Universidad Complutense de Madrid	Road2SoS
Bondavalli Andrea	DIMAI - University of Florence	AMADEOS
Broenink Jan	University of Twente	DESTECS
Calsolaro Giancarlo	Selex ES	
Casimiro António	University of Lisbon	KARYON
Delsing Jerker	Lulea University of Technology	Arrowhead
Denteneer Dee	Philips	Scuba
Doran Chris	Geomerics	LPGPU
Einwich Karsten	Fraunhofer IIS/EAS	Verdi
Engell Sebastian	TU Dortmund	DYMASOS, CPSoS
Fitzgerald John	Newcastle University	COMPASS
Främling Kary	Aalto University / ControlThings Inc.	LinkedDesign
Havinga Paul	University of Twente	WIBRATE, CLAM
Henshaw Michael	Loughborough University	T-AREA-SoS
Isaksson	Alf ABB	
Josko Bernhard	OFFIS	DANSE
Kamgarpour Maryam	ETH Zurich, ACL	MoVeS
Keis Andreas	EADS	SPRINT, ARTEMIS, CRYSTAL, ARTEMIS MBAT, ARTEMIS HoliDes
Klessova Svetlana	inno TSD	CPSoS
Koljonen Tatu	VTT	
Kosmatopoulos Elias	CERTH	AGILE, Local4Global
Larsen Peter Gorm	Aarhus University	COMPASS
Leeuw Matt	TNO	DEMANS, ACCUS
Liatard Philippe	CEA LETI	Road2SoS
Lorincz Andras Eotvos	Lorand University	EuRoSurge

Marron Pedro Jose	University of Duisburg-Essen	PLANET, BESOS, SMARTKYE, SMART-ACTION, GAMBAS
Neuy Christine	MicroTEC Südwest c/o MST BW e.V.	
Nijs Daan	Codeplay	LPGPU, CARP
Ollero Anibal	Universidad Sevilla, FADA-CATEC	EC-SAFEMOBIL, ARCAS, MUAC- IREN
Ordóñez Mª Dolores	Prodigy Consultores	Road2SoS
Ozkan Leyla	Eindhoven University of Technology	AUTOPROFIT
Paulen Radoslav	Technische Universität Dortmund	DYMASOS
Pell Oliver	Maxeler Technologies	FASTER, HARNESS, POLCA, SAVE
Petrioli Chiara	University of Rome La Sapienza	GENESI
Phillips Ian	ARM Ltd	EUROSERVER
Prem Erich	eutema Technology Management	FLEET, COFET
Rea Susan	Nimbus Centre for Embedded System Research	SCUBA
Reimann Meike	Steinbeis-Europa-Zentrum	Road2SoS
Reniers Michel	Eindhoven University of Technology	CPSoS
Sand Guido	ABB AG	PAPYRUS
Siemieniuch Carys	Loughborough University	T-AREA-Sos
Silvano Cristina	Politecnico di Milano	2PARMA
Steffes Julian	EADS Astrium	EC SAFEMOBIL
Toerngren Martin	KTH Stockholm	CyPhERS
Tokuda Akio	EHESS	
Tsigas Philippas	Chalmers University of Technology	EXCESS
Vardanega Tullio	University of Padova	PROARTIS/PROXIMA
Verhoef Marcel	Chess Embedded Technology International B.V.	DESTECS