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Roadmaps and Recommendations for Strategic Action in the field of Systems of Systems in Europe

ROAD 2 SoS
Roadmaps for System-of-Systems Engineering

SEVENTH FRAMEWORK PROGRAMME

Steinbeis-Edition

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Executive Summary

This document summarizes the findings of the Road2SoS project, co-financed by the European Commission under the 7th Framework Programme to develop a roadmap and recommendations for strategic action required for future deployment of Systems of Systems.

The term *System of Systems* (SoS) describes the super-system resulting from the large-scale integration of many independent, self-contained systems in order to satisfy global goals. SoS may vary in the degree of temporal stability, they may just come into existence for an ad-hoc cooperation or show longer term stability. The resulting meta-system is assumed to offer more functionality and performance by synergy than the sum of the constituent systems.

Two trends make SoS both *possible* and *necessary*: Driven by technological maturity and thus cost reduction, the first trend is an increasing number of IT systems and sensors dispersed in the world, moving or at fixed locations, ranging in dimension from very large to very small. The second trend is an increasing interconnection among such systems. Most of these systems are equipped with communication capabilities, they can be networked either permanently or communicate wirelessly from time to time. The number of connected devices has already exceeded the number of people on the planet. According to a recent study by IDC, a technology consultancy, 30 billion connected devices will exist by 2020.[1] A similar report of Cisco's Internet Business Solutions Group predicts a number of 50 billion connected devices for 2020.[2]

The described two trends have an *enabling quality* and a *demanding quality* at the same time: On the enabling side, such a connected world offers an almost boundless innovation potential in diverse domains and helps tackle grand societal challenges. Never before in history has information been so available and never before have distributed actors been able to cooperate so easily. Coming historically from a world in which people lived under a lack of information, we are at the start of an era where information abounds, enabled by the described trends. With these trends, however, comes also an unprecedented and drastic increase in complexity. If society is to be increasingly based on such complex technological systems then effective ways of dealing with and reducing complexity are required. Traditional approaches of central control and superordinate management seem incapable of dealing with the vast ecosystem of networked systems that, today, is only in its infancy. In this regard, a paradigm shift and the need to enhance the classical view of System Engineering (SE) toward Systems-of-Systems Engineering (SoSE) is considered necessary.

In the Road2SoS project, a range of *priority themes* have been identified that require strategic action for Europe in order to benefit from the described trends (enabling quality) while effectively limiting the evoked complexity (demanding quality). To identify them, four application domains have been analyzed in parallel: Multi-modal traffic control, emergency and crisis management,

[1] MacGillivray, Turner, Lund, Kumar, Tiazkun (2013)

[2] Evans, Dave (2011)

distributed energy generation and smart grids, and multi-site industrial production. The simultaneous analysis of four application domains allowed screening for common themes which exist independently in two or more domains. Themes that have been found independently in several application domains, and are likely of some general importance, are hence referred to as *priority themes*. These themes comprise required *technological capabilities*, *engineering challenges* as well as *socio-economic and socio-technical drivers and barriers* for successful deployment of SoS. Each priority theme implies opportunities for strategic action for Europe in order to benefit from the described trends while effectively limiting the evoked complexity.

The priority themes are summarized in the following.

Themes of **necessary technological capabilities** which become necessary with the large scale integration of systems into SoS:

- **Sufficient Communication Channels Speed and Energy Efficient Connectivity:** To aggregate systems into an SoS, to have the SoS behave in a coordinated way to achieve its goals, and for correlation or cross-analysis of data from numerous constituent systems, connectivity and sufficient communication channel speeds are fundamental. Beside bandwidth, cost-efficient last-mile connectivity and for a very large number of (potentially low-powered) systems via a multitude of technologies, most of them wireless communication technologies. Since insufficient bandwidth and a lack of connectivity will put a hard limit to the extent to which systems can form an SoS and act as an SoS, novel ways of providing wireless, low-power connectivity to a very large number of endpoints at sufficient bandwidth will have to be investigated.

- **Real-Time, Low-Latency Communication:** With SoS, the possibility of more informed decisions arises, based on context provided by the large number of systems and sensors in the SoS. In this regard, real-time communication enables a shift from making decisions in reporting mode, based on old information of the past, to decisions based on the *now*. Real-time, low-latency communication becomes necessary when it comes to time-critical coordination and control tasks within the SoS. The challenge is thus to ensure low-latency, real-time communication among a potentially large number of systems. Reliable methods to achieve this are to be investigated, especially in safety-critical systems.

- **Interoperability among Heterogeneous Systems:** To aggregate systems into an SoS, and to achieve coordinated action, interoperability among constituent systems is a fundamental condition. Since SoS may be formed from systems which are heterogeneous in terms of technological generation, standards, etc. integration entails considerable effort and can certainly not take place in the ad-hoc fashion one might need to flexibly or at least cost-efficiently form an SoS. While standardization of interfaces and protocols is certainly necessary in many domains, it falls short of solving the problem. Approaches which would allow to embrace the heterogeneity of systems and to ensure they can form an SoS, despite their variety, would be required. Developments already exist in the direction of adapters which translate with regards to syntax (protocols and data structures) and semantics (e.g.

ontologies). Further research is required in this direction. Furthermore, approaches need to be developed to network legacy systems which have not been designed to be networked or to exchange information.

- **Smart Sensors and Sensor Data Fusion:** An important species in an SoS are sensors, either standalone sensors with connectivity to an SoS or sensors which are a built into systems which are in turn connected to the SoS. The continuous acquisition by a large number of sensors will give rise to very large quantities of data. In this context, smart sensors have an important role in performing data reduction. Beyond the need for these sensors to be low-powered, potentially energy-harvesting devices, with energy efficient-connectivity, efforts have to be made to realize advanced analytics capabilities at the sensor level, at very low power consumption. Upwards from the sensor level, important information can be derived by means of *sensor data fusion*, referring to methods of treating, correlating, or reducing data from sensors – again playing an important role in handling the amount of gathered data efficiently. Research is required to perform efficient pattern recognition and correlation across a very large number of data streams from distributed sensors, of heterogeneous type, with varying data quality.

- **Efficient Handling of Big Data and Big-Data-Based Decision-Making:** The integration of a large amount of systems and sensors into SoS lead to the availability of substantial amounts of data. The data arises from correlating information available at the system level, being generated by systems, and from continuous data acquisition by sensors. The potential of Big Data in SoS is in economically extracting value from these very large volumes and wide variety of data; be it by making better, more informed decisions at the level of the SoS and at the system level, by machines and by human beings, or by optimizing systems and processes. The extraction of information from high volume, high velocity, and/or high variety information new forms of data treatment: Adequate database technologies, ways of analyzing and correlating distributed large datasets, data reduction mechanisms, and visual representation of Big Data in order to enable big-data-based decisions by human beings. To the extent that Big Data cannot be analyzed completely, methods of uncertainty quantification need to be available in order to deliver reliability information with the findings extracted from Big Data. Hard limits to big-data based decisions are frequently seen in the fact that, in a given large data set, the quality of the data may vary. That is, not all data points are equally reliable. Approaches need to be available to deal with this varying data quality.

- **Improved Forecasting:** SoS enable a) decisions based on great amounts of decision-relevant data and on b) real-time information. Note that SoS enable also something else: The vast amount of information available from systems, devices and sensors enables also c) better forecasts. While a) and b) enable more informed and decisions, the latter enables *strategic decisions*. Open research challenges exist in deriving and presenting forecasts on very large volumes of data, gained from a wide variety of sources. While a lot of data may be available, it will often be as heterogeneous as its sources. Semantic ways of involving such data in forecasts are required. Furthermore, the data points in a large dataset composed from multiple sources may vary greatly in quality and reliability. Methods to take this into account required, including means of providing uncertainty quantification with the forecast.

- **Autonomous Decision-Making:** With the number of systems increasingly outnumbering the number of human beings on the planet, the involvement of humans in decision making must be limited to only the necessary cases. Achieving this capability is tied to a number of technological challenges: Firstly, there is a need for improved algorithms for automated reasoning and decision making, capable of taking into account data from distributed sources, data of varying temporal and spatial resolution and data of varying reliability. It needs to be ensured that decisions made on such basis are safe and maybe even ethical. This will have to involve research in the field of Artificial Intelligence and also in the field of Awareness. In order for systems or „agents“ to make decisions, self-awareness but also awareness for its surroundings and even for intentions of other systems and actors is necessary. A system would thus require a model of the environment it is embedded in. Since the model is created and updated from various sources of varying reliability, uncertainty quantification plays an important role. Furthermore, forecasting plays an important role since a system will need to know about likely trajectories of the current situation into the future, also to evaluate consequences of a system’s actions. Lastly, ways of knowing and understanding other systems’ actions and objectives need to be available.

- **Collaboration Platforms and Tools for Coordinated Planning and Decision Making:** SoS are expected to greatly support planning and decision making of many entities. The development of platforms is necessary which allow efficient real-time information sharing across organizational boundaries, mindful of intellectual property and roles. Such platforms need to support decision makers with the necessary information to decide when to optimize a constituent system at the system level and when to favour optimization at the SoS level, for a common goal.

Themes of **Engineering Challenges** which become necessary to design, operate, control, and maintain SoS:

- **Modeling and Simulation:** Since there is usually no option to build a prototype of an SoS in the design phase, modeling and simulation plays an especially important role in SoS Engineering. Modeling approaches need to be investigated which are suitable to represent an SoS, prototype it, perform hazard analysis, and also to provide certification of an SoS.

- **Understanding Emergence:** In SoS, as in any complex system, emergence can be expected to be observed due to numerous interactions among constituent systems. From a classical engineering point of view, emergent behaviour is undesirable in the sense that it is unexpected system behaviour. But it may still be desirable due to the fact that it brings added functionality to the SoS. Investigations for a better understanding of emergence, the extent of its predictability, and ways of achieving emergence of desirable properties while limiting undesirable ones are necessary.

- **Measurement and Metrics for SoS:** For the operation and optimization of any system, it is necessary to know how well it is performing. This information is the basis for identification of inefficiencies, detection of system failures and adjustments towards an optimal system performance. For SoS, it may not be possible to identify a global optimum or the global optimum may not be feasibly or practically achievable. Research is required into feasible ways of measuring SoS performance and into useful ways of metrics definition. Furthermore, in an SoS, stakeholders are constantly facing the trade-off decision whether to optimize the performance of constituent systems at the system level or the SoS level. Decision support is thus required for stakeholders to determine the solution optimal to them, and highlighting the benefits of optimizing at the SoS level.

- **Architectural Patterns:** In order to enable organisations or associations to leverage the potential of SoS, suitable architectures and design patterns need to be available to join SoS at low implementation costs. Architectures need to reduce complexity, support interoperability and cooperation, allow for integration to happen at low effort and provide transparency in the overall SoS, while being mindful of security and IP issues.

- **Engineering for Resilience, Adaptability, and Flexibility:** SoS are required to provide stable service with constituent systems changing over time and under conditions which are changing over time. To achieve this, engineering approaches are required which deliver the required amount of flexibility and adaptability at run-time, under conditions not necessarily foreseen at the design stage. Also, novel engineering approaches are required to deliver resilient SoS. In classical systems, failure of a component is handled as an exception from normal operation. With SoS, failure of a constituent system must be considered as normal ("failure as normal" principle) and engineering approaches must be developed to achieve resilient behaviour of the SoS nevertheless.

Themes of socio-economic and socio-technical nature, necessary for **successful SoS implementation**:

- **Alleviation of Concerns with Pervasive IT Systems by Means of Demonstration:** A number of concerns are frequently expressed in connection with SoS, regarding e.g. stability, safety, security, privacy, or the flow of intellectual property. While the successful alleviation of such concerns requires certain technologies, capabilities and engineering approaches, *demonstration* plays an important role to tackle the social side of the coin. Demonstrators can play a two-fold role: Firstly, they are a means of alleviating concerns. Secondly, they are the starting points for an incremental process towards a full-scale SoS implementation. For future SoS development, the strategic development of small-scale SoS demonstrators is thus strongly recommended. In many domains, the involvement of public authorities is required.

- **Investment Associated with SoS and Risk-Benefits Ratio:** The fact that SoS demonstrators are largely not existent in application domains brings with it an unclear risk-benefits-ratio for potential stakeholders. This poses a dangerous impediment for SoS to come into existence. The unclear risk-benefit ratio consists of at least two issues: a) SoS-appropriate business models have yet to emerge and b) the costs of establishing SoS are assessed extremely differently. A way of making benefits visible are working demonstrators, as previously described.

- **Multiple Ownership, Governance and SoS-appropriate Business Models:** As per definition, SoS consist of systems which show managerial and operational independence. This likely entails that there is not a single owner of the SoS entirely because the constituent systems are owned by several legal entities. This implies the need for appropriate means to manage a large number of stakeholders and deal with this situation of multiple ownership. Patterns of suitable governance mechanisms and business models are thus required for SoS. Also, frameworks are required for handling the flow of intellectual property in SoS. Guidelines need to be produced to help organisations understand the options available to them, with some standardised contract templates available to help organisations with little IP experience (such as SMEs and public entities) participate in SoS.

- **Education of SoS Stakeholders and Users** is important to overcome resistance to change among decision makers. While caution towards novel approaches is rational and to be respected, it can also be observed that resistance to change is frequently caused by a lack of knowledge about the technology. Furthermore, education is important to endow users with necessary knowledge to interact with SoS. Since SoS are complex IT systems, the employees etc. who will be operating them need to be aware of their basic principles in order to accept their new tasks, trust the overall system, etc. Target group specific education programs have to be developed and conducted in order to avoid unnecessary delays in SoS deployment caused be resistance to change.

- **Human Machine Interfaces for SoS Interaction:** In the context of SoS, HMI fulfil at least two important functions: They need to allow humans to interact simply and seamlessly with complex systems, and they need to present vast, complex data in a way so humans can make decisions based on them. HMI can be thought of resolving interoperability issues between humans and systems. But they are more than that; they have to fulfil an important complexity reduction role in their own right; they enable a human user to operate complex systems, while shielding its complexity. HMI to interact with SoS and its constituent systems could well be underestimated barriers. SoS must be usable for the common man in order to fulfil their potential. SoS can be complex, but interaction with them must not be complex. Usability of involved systems must not require an understanding of the SoS. In order to avoid an impending complexity trap – a situation where humans are overwhelmed by the complexity of systems they depend on – efforts are required to provide HMI which fulfil the roles described above.

Based on the challenges described above, and the specific situation in important application domains, the following items of action are recommended address the most pressing needs and challenges:

Recommendations to support SoS implementation

- **Establishment of an SoS Engineering discipline** which would offer the methods and tools to deal with SoS in each stage of their life-cycle.
- **Establishment of SoS demonstrators** in several application domains as an effective way of alleviating concerns and raising interest in SoS application.
- **Standardisation efforts** considering vertical and horizontal integration aspects, including the development of guidelines for fast adaption of the developed standards and their integration with business processes.
- **Development of SoS-enabled** business models, considering aspects like multiple ownership, ad-hoc collaboration and the required legal frameworks.

Technological Recommendations

- **Advancement of technologies for real-time, low-latency communictation** by targeted research activities to investigate low-latency, real-time communication among a very large number of systems.
- **Research on interoperability mechanisms** to allow flexible and cost-efficient aggregation of systems into an SoS.
- **Advancement of smart sensor technologies, sensor data fusion approaches, and efficient handling of big data** by targeted research in areas such as big data analytics/reduction, advanced analytics capabilities at very low power consumption, sensor data fusion, and efficient pattern recognition across a very large number of data streams from distributed sensors, of heterogeneous type, with varying data quality.
- **Advancement of autonomous decision-making capabilities** by research activites addressing the need for improved algorithms for automated reasoning and decision making, capable of taking into account data from distributed sources, data of varying temporal and spatial resolution and data of varying reliability.
- **Improved understanding of emergence** by investigating the extent of its predictability and ways of achieving emergence of desirable properties while limiting undesirable ones are necessary.

1 INTRODUCTION

The term System of Systems (SoS) describes the super-system resulting from the integration of a certain number of systems.

A number of characteristics are usually associated with an SoS, distinguishing it from a mere super-system (see section 2 for more detail):[3] With an SoS, one usually does not have in mind a super-system which is built from scratch. Rather, it comes into existence by integrating existing systems or at least systems that are not intended to be part of an SoS in the first instance. Each constituent system is run independently and fulfils a defined purpose as a standalone system ("operational independence"). Only in the second instance are constituent systems members of the super-system called SoS. This likely entails that there is not a single owner of the SoS entirely because the constituent systems are owned by several legal entities ("managerial independence").

SoS may vary in the degree of temporal stability, they may just come into existence for an ad-hoc cooperation or show longer term stability. To the extent that an SoS is dynamic, phenomena like evolution and emergent behaviour are expected. Evolution describes a development of the SoS over time which is not necessarily driven by any of the constituent systems, but occurs almost naturally as systems interact in the SoS. Similarly in a way, emergent behaviour describes properties of the SoS which arise from the interactions of the constituent systems, but may be unpredictable from the properties of the single systems. Emergent properties may be mere synergies but also entirely new capabilities which the SoS will be able to provide. If a certain degree of these characteristics can be observed then it may be useful to speak of an SoS.

One may understand the need for an SoS perspective from two technological trends: Driven by technological maturity and thus cost reduction, the first trend is an increasing number of IT systems and sensors dispersed in the world, moving or at fixed locations, ranging in dimension from very large to very small. The second trend is an increasing interconnection among such systems. Most of these systems are equipped with communication capabilities, they can be networked either permanently or communicate wirelessly from time to time.

The number of connected devices has already exceeded the number of people on the planet.[4] According to a recent study by IDC, a technology consultancy, 30 billion connected devices will exist by 2020.[5] A similar report of Cisco's Internet Business Solutions Group predicts a number of 50 billion connected devices for 2020.[6] Machine to machine (M2M) traffic via the internet protocol alone has projected growth rate of 82%.[7] In the near future, one may speak of *embedded humans* – human beings surrounded by IT systems, communicating with each other and human beings, making

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[3] Most of the described characteristics have been stated by Maier (1998)

[4] Evans, Dave (2011)

[5] MacGillivray, Turner, Lund, Kumar, Tiazkun (2013)

[6] Evans, Dave (2011)

[7] Cisco Systems (2013)

autonomous decisions or supporting humans in making decisions, being controlled by human beings, exercising control autonomously, or exercising shared control with human beings.

It is well to note that the described two trends have an "enabling quality" and a "demanding quality" at the same time: On the enabling side, such a connected world offers an almost boundless innovation potential in diverse domains and helps tackle grand societal challenges. Never before in history has information been so available and never before have distributed actors been able to cooperate so easily. Coming historically from a world in which people lived under limited information, we are at the start of an era where information abounds, enabled by the described trends. With these trends, however, comes also an unprecedented and drastic increase in complexity. If society is to be increasingly based on such complex technological systems then effective ways of dealing with and reducing complexity are required. Not least because increasing complexity was identified by Tainter (1988) as a recurring scheme for the demise of advanced societies in human history.

In view of the described trends, a paradigm shift to an SoS perspective is considered necessary. As has become evident, SoS are at the same time enabled and demanded by the described trends. Traditional approaches of central control and superordinate management seem incapable of dealing with the vast ecosystem of networked systems that, today, is only in its infancy. More flexible approaches are required to have the constituent systems of an SoS collaborate, negotiate, or organize themselves. Throughout the entire lifecycle of an SoS, novel approaches will be necessary which an evolution of the systems engineering discipline into SoS Engineering will have to offer.

In the Road2SoS project, a range of themes have been identified that require strategic action for Europe in order to benefit from the described trends while effectively limiting the evoked complexity.

2 THE SYSTEMS OF SYSTEMS CONCEPT

The System of Systems (SoS) concept describes the large scale integration of many independent self-contained systems in order to satisfy a global need or multiple requests e.g. for global traffic control or in distributed energy systems. The resulting meta-system is assumed to offer more functionality and performance by synergy than the sum of the constituent systems. The increasing number of interacting – mostly embedded – systems in our strongly connected society and industry as well as the growing overall complexity of systems have triggered a paradigm shift and the need to enhance the classical view of System Engineering (SE) toward System of System Engineering (SoS Engineering) by providing an interdisciplinary approach to leverage and optimize the independent development of multiple interoperable systems and to implement operationally flexible capability.

The SoS approach promotes a new way of thinking in order to address grand challenges, where the interaction of technology, policy and economics are the primary drivers. The concept has its roots in the US defence industry and SoS is already well-established in the military sector where interoperability and synergism of command, control, computers and communication as well as information and intelligence systems are linked together as a whole.

The most frequently cited characterization of System of Systems, is provided by Maier (1998) who identified five key characteristics:

- **Operational independence of component systems:** The individual constituent systems of a SoS can and may be required to exist and respond as coherent whole apart from the SoS.
- **Managerial independence of component systems:** The rights and ability to choose to belong to a particular SoS, and the role as well as responsibilities of all stakeholders and their interactions with one another can enable or impede SoS development, management and operation.
- **Geographical distribution of the constituent systems**
- **Emergent behaviour:** An SoS behaves as collective whole dynamically interacting with its environment and may become greater than and different from the sum of its parts.
- **Evolutionary development processes:** The conceptual, functional, physical, and temporal set up of the SoS is continually evolving and affected by both the internal collective behaviour, and by environmental interaction.

Although not every SoS will exhibit all these five characteristics, it should demonstrate the majority of them.

Other characteristics include the following:[8]

- **Adaptability**: The ability of a system to change internally and undergo self-modification.
- **Agility**: The ability of a system to be both flexible and undergo change rapidly.
- **Flexibility**: The property of a system that is capable of undergoing changes based on the external environment with relative ease.
- **Modularity**: The degree to which the components of a system can be designed, made, operated and changed independently of each other.
- **Resilience**: The attribute of a system, in this case a SoS that makes it less likely to experience failure and more likely to recover from a major disruption.
- **Scalability**: The ability of a system to maintain its performance and function, and retain all its desired properties when its scale is increased greatly without a corresponding increase in the system's complexity.
- **Sustainability**: Maintaining economic growth and viability while meeting concerns for environmental protection, quality of life and social equity.

SoS find their application in many highly relevant areas of our society. Currently emerging fields where SoS are investigated include among others: airport and air-traffic, urban transport, smart energy grid for electricity, enterprise and supply chain operations, health care.

Table 1 illustrates some differences between classical systems and SoS.[9]

	Classic Systems	**Systems of Systems**
Scope of system	Fixed, know	Not known
Specification	Fixed	Changing
Control	Central	Distributed
Evolution	Version controlled	Uncoordinated
Testing	Test phases	Continuous
Faults	Exceptional	Normal
Technology	Given and fixed	Normal
Emergence	Controlled	Accidental
System development	Process model	Undefined

Table 1: Comparison of classical systems and SoS

[8] Valerdi et al. (2008)

[9] Table by Kopetz, H. in Thompson (2012)

Table 2 highlights differences between classical Systems Engineering the emerging discipline of SoS Engineering.[10]

	Systems Engineering	**System-of-Systems Engineering**
Focus	Single complex system	Multiple integrated complex systems
Objective	Optimization	Satisfying, sustainment
Boundaries	Static	Dynamic
Problem	Defined	Emergent
Structure	Hierarchical	Network
Goals	Unitary	Pluralistic
Approach	Process	Methodology
Timeframe	System lifecycle	Continuous
Centricity	Platform	Network
Tools	Many	Few
Management framework	Established	Research in progress

Table 2: Comparison of Systems Engineering and SoS Engineering

[10] Gorod, Sauser, Boardman (2008)

3 OBJECTIVES AND APPROACH OF ROAD2SOS

Two technological trends have been mentioned in the introduction to this document which, at the same time, enable and require SoS: The first trend is an increasing number of IT systems and sensors dispersed in the world, moving or at fixed locations, from very large to very small. The second trend is an increasing *interconnection* among systems.

To leverage the benefits of SoS for the European economy and European society, strategic action is required to ensure undelayed development of SoS and to have engineering methods at hand to deal with the inherent complexity. To inform future EC-funded research and innovation, the *Road2SoS* project has developed roadmaps which identify necessary technologies and capabilities, as well as drivers and barriers to SoS developments.

In the *Road2SoS* project, roadmaps have been developed in four domains in which the *System of Systems* approach is thought to be of particularly high relevance and particularly beneficial to the competitiveness to European companies and the European society. The domains examined in Road2SoS are:

- The domain of **Integrated Multi-site Industrial Production**, where considerable potential exists by aggregating manufacturing facilities into a greater system of systems, to reach entirely new dimensions of scale and scope, and support a more sustainable manufacturing.

- The domain of **Distributed Energy Generation and Smart Grids:** Describing the energy system of the future, with numerous energy sources and decentralized production, where traditional consumer may turn into producers at times, and where the flow of energy needs to be accompanied by a flow of information as a basis for solving the a large scale control problem which this system poses.

- The domain of **Multi-modal Traffic Control**, which offers great potential for making transport not only more intelligent, and usable, but also more resource-efficient and safe.

- The domain of **Emergency and Crisis Management** where the challenge is to realize coordination of large amounts of people on short notice and an information lack has to be overcome.

Having, in the first instance, examined the four applications domains independently, subsequent analyses were conducted to identify common themes among these domains. These themes are referred to as *priority themes* because they have been found to emerge independently in several of the examined application domains.
The developed roadmaps and the identified priority themes provide the grounds for the development of recommendations.

The described approach has certain advantages: Firstly, by following such a bottom-up approach, it is assured that identified priority themes and derived recommendations are based on actual needs in real-world application domains. Secondly, be abstracting from domain-specificities in the analysis of cross-domain commonalities, the identified priority themes can be expected to be of relevance not only to the examined domains, but also for many more application domains that have not even been explicitly examined in the context of Road2SoS. In short, the followed approach ensures generalizable results, on a bottom-up foundation.

The described activities to build and validate the roadmaps, perform an analysis of commonalities and derive recommendations were conducted in the period October 2011 - December 2013. Overall, more than 250 experts from academia and industry contributed with their opinions and perspectives.

3.1 Roadmaps Development and Validation

The first steps in the roadmap development process comprised the simultaneous but independent establishment of two complementing perspectives:

- **A technology push perspective:** A technological perspective, analyzing technological and research challenges established through extensive analyses by domain experts, supported by perspectives from interviews with external experts.

- **A market pull perspective:** A market-oriented, socio-economic perspective established by identifying trends, needs, drivers, barriers regarding SoS in the application domains through extensive analyses by domain experts in the consortium, supported by an online survey.

Subsequently, both perspectives have been jointly reflected, validated, and prioritized in the core roadmapping process with participants from industry and academia.

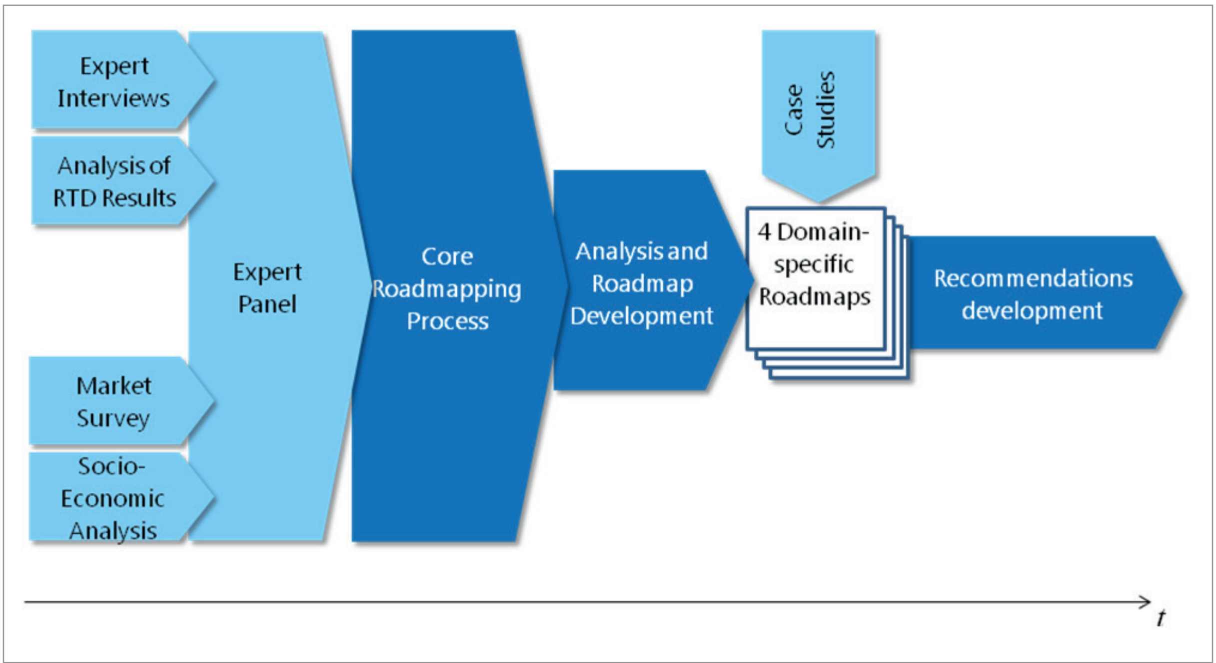

Figure 1: Road2SoS Approach for Recommendations Development

3.2 Cross-domain Analysis and Identification of Priority Themes

Various steps were implemented to identify the most important common themes across the four application domains:

- Identification of common themes during an **expert panel:** An expert panel (May 12th 2012, Karlsruhe, Germany) was designed to jointly reflect the independently established push and pull perspectives for each domain and to evaluate cross-domain commonalities. The workshop derived strong relevance of many priority technologies and innovation opportunities.

- Identification of common themes after the **roadmapping workshops**: The content of the domain roadmaps was validated, enhanced and prioritised during four different workshops where both academic and industrial participants contributed. After the completion of the workshops, the consortium partners analysed the content of the four domain specific roadmaps to identify common trends, drivers, needs, technologies and enablers. Themes relevant across all four domains were given the highest priority. The common priority technologies and innovation opportunities identified were compared to the ones identified through the expert panel meeting and the list was updated accordingly.

- Identification of common themes during **workshops with FP7 SoS partner projects**: A series of workshops took place between Road2SoS and other EU-funded SoS projects (T-Area-SoS: October 15th 2012, Loughborough, UK; July 1st 2013, Stuttgart, Germany; COMPASS: March 18th, Trieste, Italy) to compare approaches, findings and to identify the common themes of the Road2SoS domain driven bottom up-approach and the top-down approach of the other projects.

- Identification of common themes by **expert consultations** (academia, industry, platforms e.g. ARTEMIS): Throughout the Road2SoS project more than 250 experts have been involved. Studies like the Road2SoS market survey and expert interviews revealed common themes in the early phase of the project. At a leater stage of the project various case studies and dissemination workshops were held and besides the domain specific topics the common themes of the Road2SoS project evaluated. The common themes where compared with the priority topics of various communities, e.g. the Cyber Physical Systems community at the final event of the Road2SoS project held on October 30th 2013.

These common themes derived from the various activities built the basis for the recommendations for priority themes and future RTD strategic action.

3.3 Application Domains Examined in Road2SoS

In the following, the application domains selected for examination in Road2SoS shall be introduced shortly.

3.3.1 Domain of Multi-Site Industrial Production

Systems of Systems in multi-site industrial production are regarded as systems which consist of constituent systems such as singular production sites and which have a common goal, the production of (complex) products. Nowadays, SoS in this domain are mainly known as "Supply Chains", "Production Networks", "Virtual Organisations", etc. which represent various control and management concepts for distributed manufacturing. Multi-site industrial production is generally the manufacturing of products throughout two or more production sites belonging to one or more companies.

Future multi-site manufacturing System of Systems (SoS) are foreseen to be complex systems of geographically dispersed manufacturing organisations that self-organise in response to customers' needs, dissolving once these needs have been satisfied. The vision for multi-site manufacturing is for a global network of interoperable factories, allowing the dynamic allocation of manufacturing. In such a scenario, manufacturing enterprises will be able to assign production to available capability and capacity, wherever it may be. The ability to 'switch-on' production at such factories can enable companies to respond more rapidly to changes in customer demand as they do not have the sunk costs associated with capital equipment. Economies of scale will not be as significant as they are today; instead the ability to individualize products according to customer demands will be more important.

In order to be able to individualize products, such factories will need to be both reconfigurable and adaptable, with communication interfaces to the outside world that are globally accepted. The dynamic allocation of capacity also holds potential for the more dynamic formation of SoS. While the majority of multi-site manufacturing SoS take the form of supply chains and supply networks, the flexibility that will exist within and across these factories of the future will enable supply and distribution systems to be created more rapidly, and without companies using computer-based auctions to contract for work.

In summary, an SoS-enabled global manufacturing network would bring about increased transparency on available manufacturing capacity and capability, allowing greater participation from SMEs, and fostering a more efficient manufacturing system in which competition drives down costs.

3.3.2 Domain of Distributed Energy Generation and Smart Grids

The vision for the future energy system can be described as the shift to emission-free, decentralized generation of energy from a variety of renewable sources. This implies that energy generation will change from being limited to a few central sites (power plants) to mostly decentralized production from renewables by a large number of generators. Furthermore, the number of active stakeholders in the energy grid is expected to greatly increase, as many of today's consumers turn into so-called "prosumers" who act as producers in the energy grid at times.

The future energy system will exhibit a tremendous complexity manifested by its diversity, heterogeneity, dynamic behavior, and widely varying scales in time, space, and power output. The future energy system will have to ensure security of supply despite the volatility of the renewable sources wind, sun, water, etc. and while suitably controlling a large number of energy producers. To do this, energy flow in the future energy grid will have to be accompanied by a flow of information. Information and communication technologies will have to ensure the grid is "smart" to cope with the non-trivial control problem of guaranteeing security of power supply at all times. SoS approaches are considered a promising approach to deal with the future energy system and to handle in a promising way.

The smart grid is enabled by exchange of information about the current energy demand and offer between the consumers and producers. A system in this setup can be a power generator like a power plant or a private house with solar energy installation that acts as a consumer at the same time. An agglomeration like a village with a local power supply and a set of consumers can also be considered a system which again is a part of the overall Europe-wide or even global energy system. Therefore, the energy system can be considered as a typical SoS architecture, featuring all characteristic SoS features to the point that the energy system is not properly hierarchical and its components or subsystems are also used by other systems. These subsystems are of different technological generations; they come from diverse suppliers and include a variety of types of stakeholders. They will typically have been designed and constructed by independent and possibly competing stakeholders based on inconsistent requirements. Additionally, they are of various types, like electrical components with their inherent properties, systems that are driven by physical (e.g. wind turbines) or chemical (e.g. engines) factors, embedded systems in form of intelligent household devices etc. By linking all these systems the energy SoS also displays emergent behaviour—behaviour not able to be anticipated from the characteristics of the original component systems—that however may result in useful or harmful effects. Moreover, the development of the energy system will typically be extensions, integrations, updates and maintenance to existing systems; i.e. development and revision of energy systems that are in operation. Therefore, the concepts of SoS manifest themselves in the area of net-centric architectures (e.g. the power grid with energy sources and consumers), heterogeneous components (e.g. different kind of power plants with different properties), unpredictability (e.g. power generation from renewable energies, failures in power plants and grid problems), adaptability (e.g. reaction on high power demand) and decentralisation (e.g. decentralised generation, many interacting power supplier companies).

3.3.3 Domain of Multi-Modal Traffic Control

In multi-modal traffic control, a vast potential impact of the SoS approach can be seen in enabling the integration of existing systems into more global ones, in increasing the collaboration among operators and in providing extra services to operators and users.
Today, transportation systems such as road networks, public transportation, trains or airplanes, are not sufficiently interconnected to ensure an optimal usage of the infrastructures and natural resources. Transportation networks are run by a patchwork of operators, even in limited geographical areas as around large cities, freeways, urban roads, arterial roads, subway, bus, tramway, trains, taxis, or airports. Theses operators have different levels of technical and financial means and a panel of legacy systems that were not necessarily designed to be operated together.

Transportation systems are naturally evolutionary in the sense that sensors, communication networks and operation rules are constantly evolving. The rapid evolution of enabling technologies in the transportation industry, e.g. sensor networks and vehicle-to-infrastructure communication, has led to more and more complex systems that are difficult to maintain using traditional techniques.

A vision for multi-modal traffic control is a global transportation infrastructure, operated as a whole without administrative and technological boundaries. On top of this physical layer would be a service layer, providing transportation services to end-users, making the transportation system much more flexible than it is today. This requires the integration of state of the art and emerging technologies like sensors, telecommunication networks and embedded systems. It also requires the integration of new systems and legacy systems that cannot be renewed on a short notice because of complexity or cost. The field of multimodal traffic control will also have to integrate innovative means of transportation such as on-demand car rental – electric or conventional –, dynamic car pooling and communicating vehicles: Car2Car, Car2Infrastructure, Car2X.

The emergence of collaborative road operations is a necessary step towards a better operation of the existing transportation networks and the integration of new means of transportation in a seamless global transportation infrastructure. This step, that can greatly benefit from an SoS approach, will allow transportation to become an integral part of the smart city revolution that is currently taking place.

3.3.4 Domain of Emergency and Crisis Management

The management of emergency situations requires oversight and control of a vast amount of parameters and effective collaboration of several types of emergency responders. To deal with the complexity of this scenario, a system of systems approach is considered promising.

The interconnection of a large amount of systems and sensors into SoS can significantly improve the forecast and response to emergency and crisis situations. SoS allow sharing data and information among all constituent systems and involved emergency responders; SoS allow the correlation of images and video streams from multiple locations, captured by fixed cameras or gained from social networks, to construct a real-time representation of the emergency or crisis situation. To emergency responders, it is vital to have information about the current status of the situation in order to respond effectively and to not learn only on site that the real situation is different to the situation the response action has been planned for. SoS can support decision-making and greatly help to reduce the response time in a critical situation. SoS can also ensure that collaborative action of different emergency responders is based on the same, shared information and thus happens in a coordinated most effective way.

4 MARKET SURVEY

To establish a departure point for the roadmap development, national and European RTD projects, publications and studies were analysed in the four domains, accompanied by an extensive internet research on SoS relevant emerging ICT concepts (like cloud computing, big data processing) and their exemplary application in the sectors. Additionally, expert interviews were conducted; an expert panel held to validate the data and the information was compiled into 4 domain specific reports. Besides obtaining an overview of the state-of-the-art in each domain, new concepts, methods, architectures and tools relevant for the implementation of SoSE were identified. Moreover the most pressing barriers and technological and research challenges across all 4 domains were identified. Within the market pull approach 'Analysis and definition of socio-economical needs', the socio-economical aspects and industrial needs in the field of SoSE were elaborated. Apart from the analysis of existing studies and the participation at various conferences and strategy meetings a market driven online survey was conducted. The data was compiled in 4 domain specific reports. The market survey is available via the project website and was performed to identify domain specific needs, barriers and trends as well as domain spanning research challenges. The following graphs show the results of the most pressing research challenges for each application domain in comparison to the common challenges to all 4 application domains:

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

Table 3: Top five IT and technological challenges in the four domains

Question posed: In the following list of IT and technological challenges, please tick those you consider to be of greatest importance for a *System of Systems* approach to be sucessfully implemented in your domain. Please tick five boxes.

Table 4: IT and technological challenges of greatest importance for the implementation of SoS approaches

5 Domain specific Roadmaps

Within the central 'Development of research and Engineering Roadmaps' a roadmapping methodology was elaborated and adapted to the SoSE field. This process fused the results gathered in the technology-driven analysis in and in the market-driven analysis. Furthermore, specific information was added and the results were prioritised by internal and external experts. For each of the 4 domains roadmapping workshops with invited experts were conducted. The results were analysed and integrated to form the 4 roadmaps. In the following the main results from the 4 domain specific simplified summary roadmaps are presented shortly.

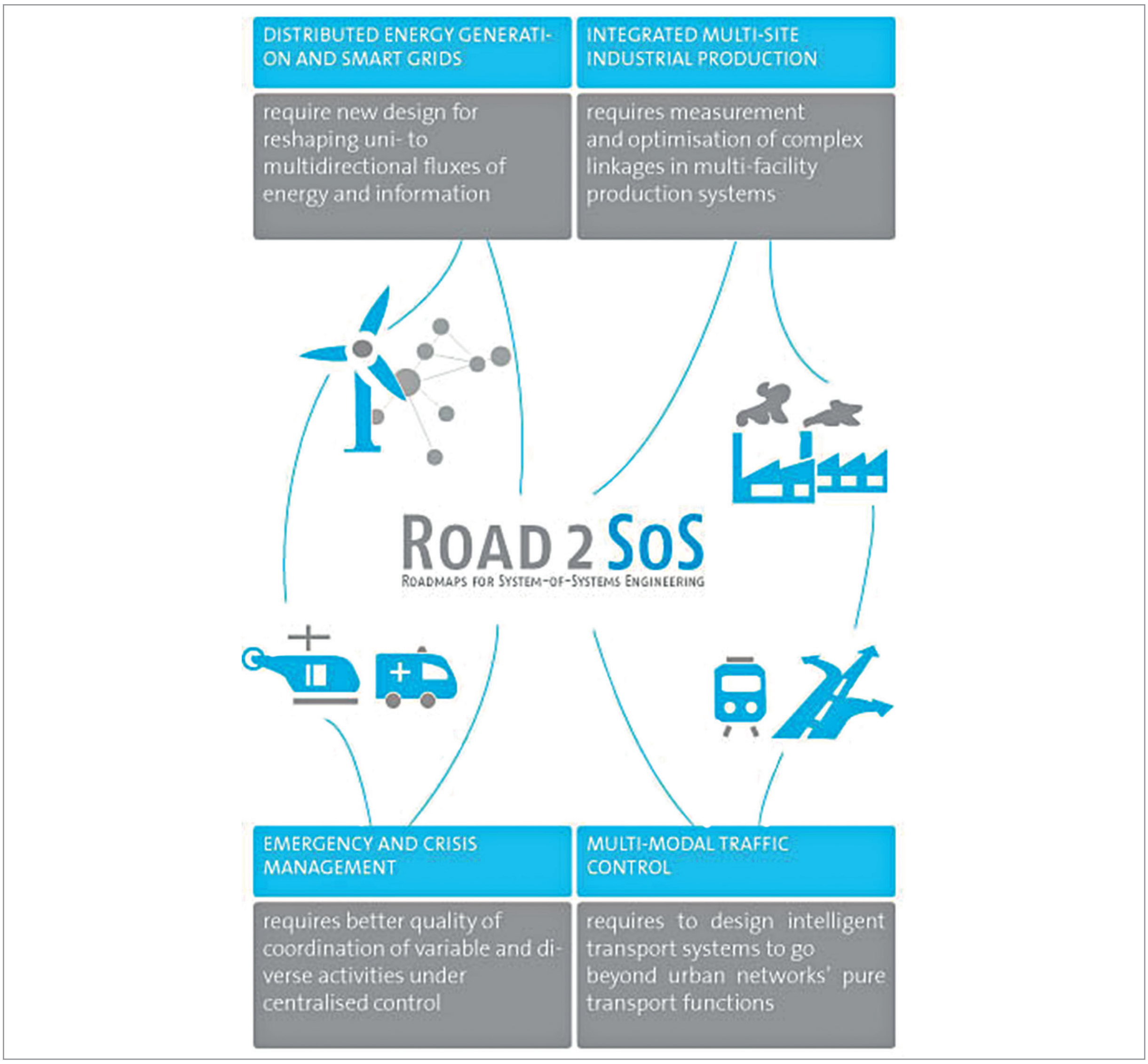

Figure 2: Road2SoS Application Domains

5.1 Roadmap for integrated multi-site manufacturing

Multi-site manufacturing system of systems (SoS) are complex systems of geographically dispersed manufacturing organisations that self-organise in response to customers' needs, dissolving once these needs have been satisfied. The simplified summary roadmap (Figure below) depicts the five most significant technological advances that have been identified as necessary for the realisation of the future manufacturing vision, along with detailing the current needs, the industry drivers and enablers that will support the development of these technologies.

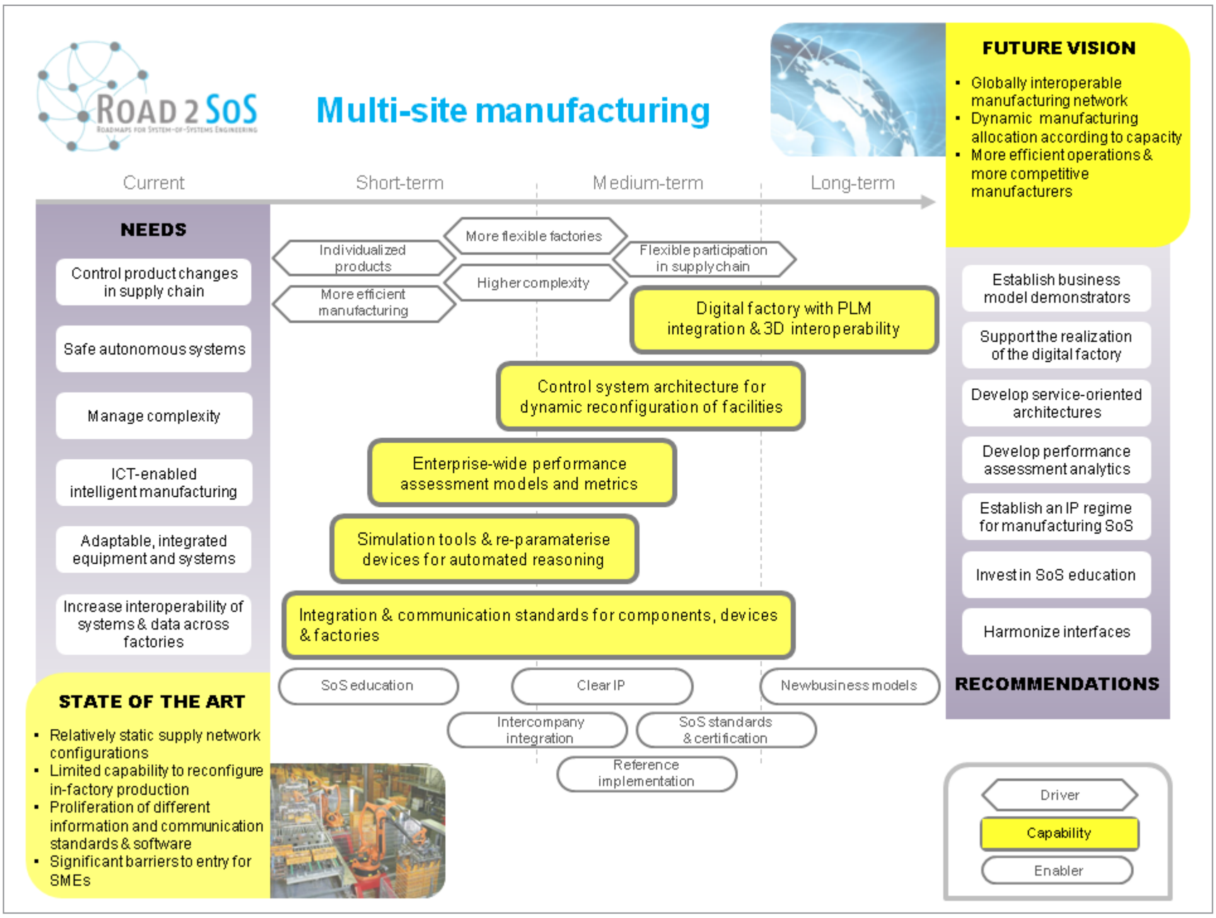

Figure 3: Simplified SoS roadmap for the domain of Multi-site manufacturing

The vision for multi-site manufacturing is for a global network of interoperable factories, allowing the dynamic allocation of manufacturing. In such a scenario, manufacturing enterprises will be able to assign production to available capability and capacity, wherever it may be.

Investing in production capabilities can also be very costly and in some sectors the ability to outsource production to the manufacturing SoS may reduce the barriers to market entry. The ability to 'switch-on' production at such factories can enable companies to respond more rapidly to changes in customer demand as they do not have the sunk costs associated with capital equipment. Economies of scale will not be as significant as they are today; instead the ability to individualize products according to customer demands will be more important.

In order to be able to individualize products, such factories will need to be both reconfigurable and adaptable, with communication interfaces to the outside world that are globally accepted. The dynamic allocation of capacity also holds potential for the more dynamic formation of SoS. While the majority of multi-site manufacturing SoS take the form of supply chains and supply networks, the flexibility that will exist within and across these factories of the future will enable supply and distribution systems to be created more rapidly, and without companies using computer-based auctions to contract for work.

In summary, in this vision, the global manufacturing network will bring about increased transparency on available manufacturing capacity and capability, allowing greater participation from SMEs, and fostering a more efficient manufacturing system in which competition drives down costs.

Summary of domain specific outcomes:

Trends and drivers

- Reduction of costs and lead times / more efficient manufacturing
- Handling higher complexity and customer requirements
- Faster, more flexible factories and supply chain participation
- Local adaptation/manufacturing close to markets

Domain needs

- Increase interoperability of systems and data across factories
- Adaptable, integrated equipment and systems that can be readily configured
- Complexity management
- Increased control of product changes across supply chain

Key innovation opportunities identified in the domain

- Integration and communication standards
- Enterprise-wide performance assessment analytics & models
- Service-Oriented Control System architecture for dynamic reconfiguration
- Digital Factory & 3D interoperability between design and manufacturing (3DMBE)
- Control system architecture to enable dynamic reconfiguration of assembly, production and transportation
- Digital Factory with PLM integration & 3D interoperability between design and manufacturing (3DMBE)

Enablers

- Education – customer and engineers
- Global expertise
- Intercompany integration of processes/systems
- Clear IP

Summary of Domain specific recommendations derived from the roadmap are:

Interface harmonization

- Due to the proliferation of existing standards, the emphasis should be on the harmonization of these existing information and communication standards rather than the creation of new standards.

- The harmonization process should be achieved through a public-private process or a joint venture to overcome industry self-interest.

Support the development of performance assessment analytics and models

- Fund pre-competitive consortia to ensure that performance analytics and models are developed for multi-site manufacturing SoS

Support the development of service-oriented control system architectures (SoA)

- Provide funding for SoA demonstrator projects at technology readiness levels 4-6
- Fund SoA demonstrator projects at TRLs 7-9 through industry-matched funding

Support the realization of the digital factory

- Fund the development of an integrated set of tools and processes for the simulation of manufacturing operations
- Provide seed funding to define interfaces and standards in order to overcome local optimization

Establish business model demonstrators

- Create business model demonstrators for technology readiness levels 7-9 and beyond

Invest in SoS education

- Communicate the benefits of SoS to stakeholders through case studies
- Initiate training programmes to improve SoS skills

Establish an IP regime for manufacturing SoS

- Provide guidelines for the SoS IP framework
- Create and make available standardized contract templates

5.2 Roadmap for multi-modal traffic control

Transportation is an interesting example of a System-of-Systems (SoS). Indeed, the administrative organisation in this domain has led transportation networks to be operated by a patchwork of operators, even in limited geographical areas as around large cities, freeways, urban roads, arterial roads, subway, bus, tramway, trains, taxis, or airports. Theses operators have different levels of technical and financial means and a panel of legacy systems that were not necessarily designed to be operated together (different communication protocols, different standards, different maintenance procedures). Systems are often rather closed with little information shared between operators, both for technical reasons and due to a lack of motivation to share strategic information. New SoS architectures and software are needed to increase collaboration among operators in order to manage the transportation resource as a whole in a safe and secure way.

Coordination among road operators is very likely to lead to interesting synergies (load balancing, energy efficiency, continuity of service across different operators, mobility optimization) that are not possible in the current systems. Furthermore, some favourable emergent behaviour is expected which could yield unplanned, yet desirable, features.

Transportation systems are naturally evolutionary in the sense that sensors, communication networks and operation rules are constantly evolving, sometimes even without notice. The rapid evolution of enabling technologies in the transportation industry, e.g. sensor networks and vehicle-to-infrastructure communication, has led to more and more complex systems that are difficult to maintain using traditional techniques. Modelling and adaptability should be developed further to be able to help automate certain routine maintenance tasks.

Data sharing through standardised models is at the core of the development of multimodal transportation systems. Transportation network operation requires real-time data that goes beyond what is available today in traditional open data spaces such as low frequency traffic information or public transportation timetables, and maps. The dynamics involved in such data requires robust protocols and software implementations to make data sources reliable. Developing this reliability is necessary for operators to be confident in the data they broadcast and receive from other operators. Moreover, extensive data sharing architectures should preserve privacy through secured information exchange systems.

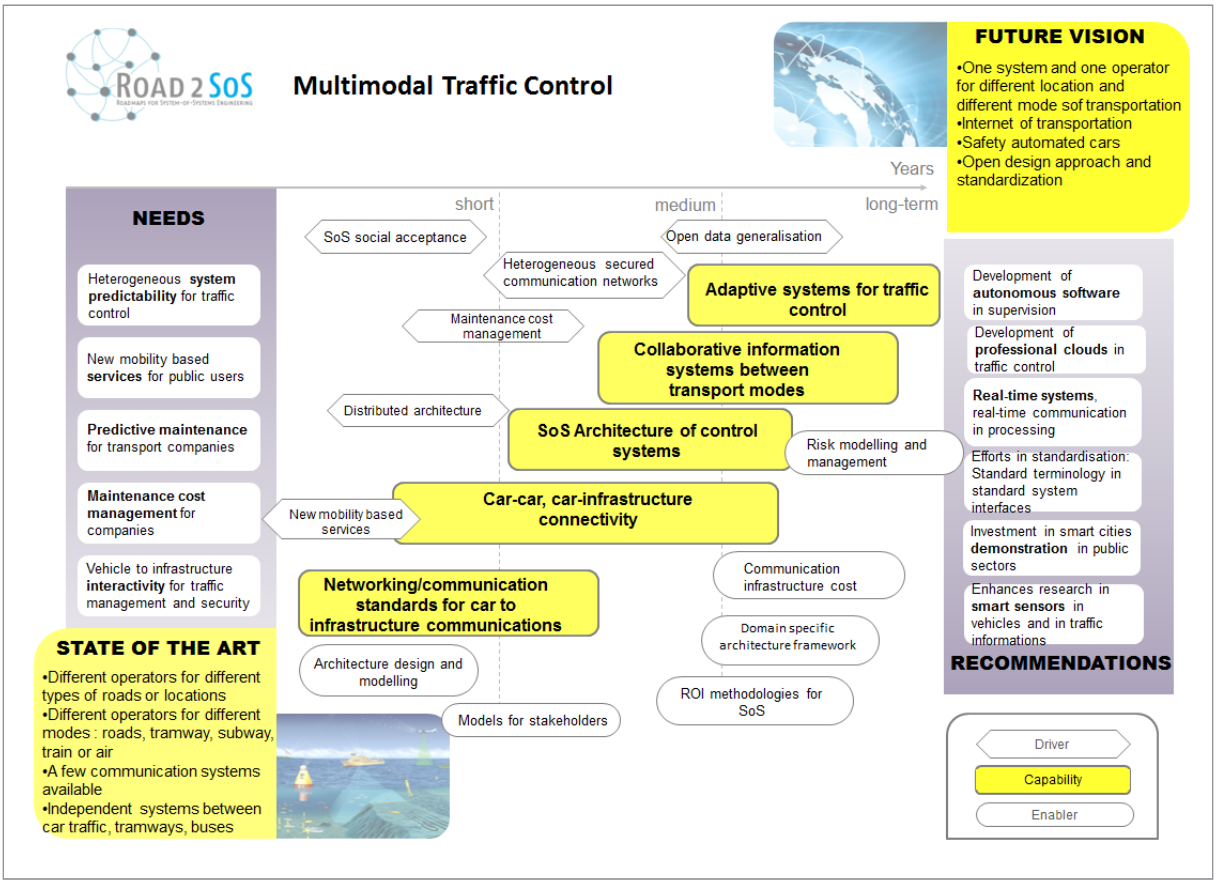

Figure 4: Simplified SoS roadmap for the domain of Multi-modal traffic control

Today, transportation systems such as road networks, public transportation, trains or airplanes, are not sufficiently interconnected to ensure an optimal usage of the infrastructures and natural resources. A closer interconnection can now be envisioned thanks to the advance of networking and information technologies. This interconnection of systems gives rise to what can be treated as Systems-of-Systems (SoS).

The vision for multimodal traffic control is a global transportation infrastructure, operated as a whole without administrative and technological boundaries. On top of this physical layer would be a service layer, providing transportation services to end-users, making the transportation system much more easily and flexibly usable than it is today. This requires the integration of state of the art and emerging technologies like sensors, telecommunication networks and embedded systems. It also requires the integration of new systems and legacy systems that cannot be renewed on a short notice because of complexity or cost. The field of multi-modal traffic control will also have to integrate innovative means of transportation such as on-demand car rental – electric or conventional –, dynamic car pooling and communicating vehicles: Car2Car, Car2Infrastructure, Car2X.

Communication is a crucial for future multi-modal traffic control. On the one hand, transportation network are critical infrastructures that should be operated in a secure and safe way. On the other hand, collaboration between operators that manage different means of transportation or different regions requires the opening of their information systems, at least partially. The development of frameworks that allow this feature, such as secured clouds, is critical to the development of SoS in multimodal traffic control.

The emergence of collaborative road operations is a necessary step towards a better operation of existing transportation networks and integration of new means of transportation in a seamless global transportation infrastructure. This step, that can greatly benefit from SoS approaches, will allow transportation to become an integral part of the smart city revolution that is currently taking place.

From our analysis, the challenges are multi-dimensional:

Technology: Even if networking and information technologies are globally available today, many technologies have to become more mature to enable a full implementation of the SoS concept, such as complex real-time control systems, distributed architectures, secured clouds, self-configurable systems or complex event processing amongst others. Moreover, standardisation of protocols and system interfaces will be a fundamental step for companies to be able to implement SoS in transportation networks. Public authorities have a key role in this standardisation process. The definition of quality norms specific to SoS in transportation is also necessary.

Socio-economic: Today, transportation systems are operated by multiple independent institutions. An SoS scenario would require these institutions to work together, share information and decision processes. From our analysis, this is among the most important challenge for SoS to become reality. At a transnational level, as countries still have a lot of authority in the transportation domain, policies will have to be implemented to promote the emergence of SoS in this domain. The promotion of SoS practices from public authorities could be initiated by the European Commission through supporting use cases.

Summary of Domain specific outcomes:

- Heterogeneous secured communication networks
- Distributed architectures
- New mobility based services
- Maintenance cost management
- Real-time control systems

Domain needs

- Predictive maintenance
- Vehicle-to-infrastructure interactivity
- Heterogeneous system predictability
- Standard system interfaces
- Auto-maintenance

Key innovation opportunities identified in the domain

- Adaptive systems
- Standardised models
- Collaborative information systems
- Technologies and capabilities
- Networking and communication standards

- Collaborative information systems
- Self-configuration
- Car-car, car-infrastructure connectivity
- Decision making in cloud services

Enablers

- Knowledge management tools
- ROI methodologies for SoS
- Architecture design and modelling
- Standardisation
- Models for stakeholders

Summary of domain specific recommendations:

Identify sectors where SoS can bring value and focus on them. The risk with emerging technologies and engineering practices such as SoSE is to develop them in too many sectors. Though the four Road2SoS domains are good candidates, there should be a deeper analysis to establish the priorities between subtopics for each sector.

Involve public authorities. As new business models are emerging, public authorities should be involved for creating value in this activity. Smart city demonstrators will provide a possibility for public authorities to assess, the economic benefit of SoS on real implementations.

Reference documentation with clear terminology and concrete examples. With SoS being an emerging an increasingly relevant topic, terminologies are sometimes misused. Moreover, reference textbooks are lacking to spread SoSE as an engineering practice. The description of concrete examples may serve more general purposes and help newcomers to get more insight about how to deal with SoS along their life-cycles.

R&D in sensor technologies:

- **Continue to support research and development activities in sensors, embedded systems and telecommunications.** Technologies like sensor networks and autonomous system are enabling technologies for SoS.
- **Smart sensors.** Sensing plays a role for many SoS. Substantial innovation occurred in this field in the last decade and the amount of sensors is growing vigorously. Smart sensors are extensively using wireless technologies, so power management is needed to fuel the development of large SoS such as smart cities. These sensors should provide enough features and be robust enough to avoid heavy maintenance costs.

R&D in software technologies:

- **Stimulate the emergence of professional clouds.** It seems difficult to deploy large scale SoS that concern strategic assets by using the current offer of cloud services on the market. Each organisation may implement its own cloud but it would require technical and financial efforts and lead to antiquated architecture not necessary related to cloud computing. Large integrators should lead the development and spreading of professional clouds tailored to their industry.

- **New research and development activities should be launched in the field of autonomous software.** The management of changes, device or telecommunication failures and legal changes is not sufficiently taken into account to develop SoS in strategic sectors. Still in the software industry, distributed architectures should be proposed for SoS.
- **Real-time systems, real-time communication.** One of the potential benefits of SoS is the possibility to monitor and control in real-time large complex systems. Real-time operation is present in most industrial domains, including transportation networks. Nonetheless, real-time implementations like control loops, most of the time are specifically developed for each subsystem. There is a need to have standardised interfaces to be able to interconnect real-time control and communication systems in order to manage the SoS as a whole at the upper level. This would be a tedious task given the strategic operation of real-time systems in each sub-system.

Standardisation. Standardisation is one of the most important aspects to be developed. The development of standard terminology and standard system interfaces are necessary steps to further develop SoS in the industry. This standardisation process can be done partially in the industry and partially by authorities such as the European Union. Standardisation is a long and tedious process but it is necessary to make big industrial companies commit to SoS technologies. The development of standards will naturally lead to multiple implementations that will stimulate the community in systems engineering and specific sectors where SoS is naturally arising.

Demonstration. In public applications like smart cities and smart transportations, there is a need to build realistic demonstrators. This task should be led by public authorities, as they manage these assets, with or without the help of the European Union. Smart Santander and the city of Nice are good examples of such demonstrators. Contrary to other industrial domains, only public authorities can initiate such demonstrators. These demonstrators will provide a way for public authorities to assess the economic benefit of SoS on real implementations and analyse the risk-benefit ratio in terms specific to public authorities such as level of services provided to users, security or monetised benefits for transportations.

5.3 Roadmap for emergency and crisis management

The efficient management of emergency situations requires fast detection and control of a vast amount of parameters. To deal with the complexity of this scenario, a Systems-of-Systems approach is considered promising. It is expected to support the response to critical situations by providing the possibility of sharing data and information among all constituent systems and with emergency responders. Emergency situations are hardly predictable and the different types and categories imply the need for different emergency responders. There are three stages in emergency situations: the pre-event stage, the emergency stage and the restoration stage. In the pre-event stage, an SoS would control different types of device networks (sensors, cameras, etc.) that monitor the status of several critical parameters. In the emergency situation, the goal is to resolve the danger as fast as possible avoiding damage. The restoration stage focuses on re-establishing the original state in the crisis area. One of the main tasks for an efficient emergency management through an SoS is to develop a method to determine an optimal chain of command. In emergency bodies such as police or the army, there are strong hierarchies to be respected. Moreover, a better organisational management between agencies has to be achieved. Software and hardware tools significantly facilitate the work of emergency responders and greatly contribute to improve the efficiency managing the situation. Simulation and modeling tools which allow reliable forecasts and decision support tools are crucial to identify optimal solutions to each specific emergency situation.

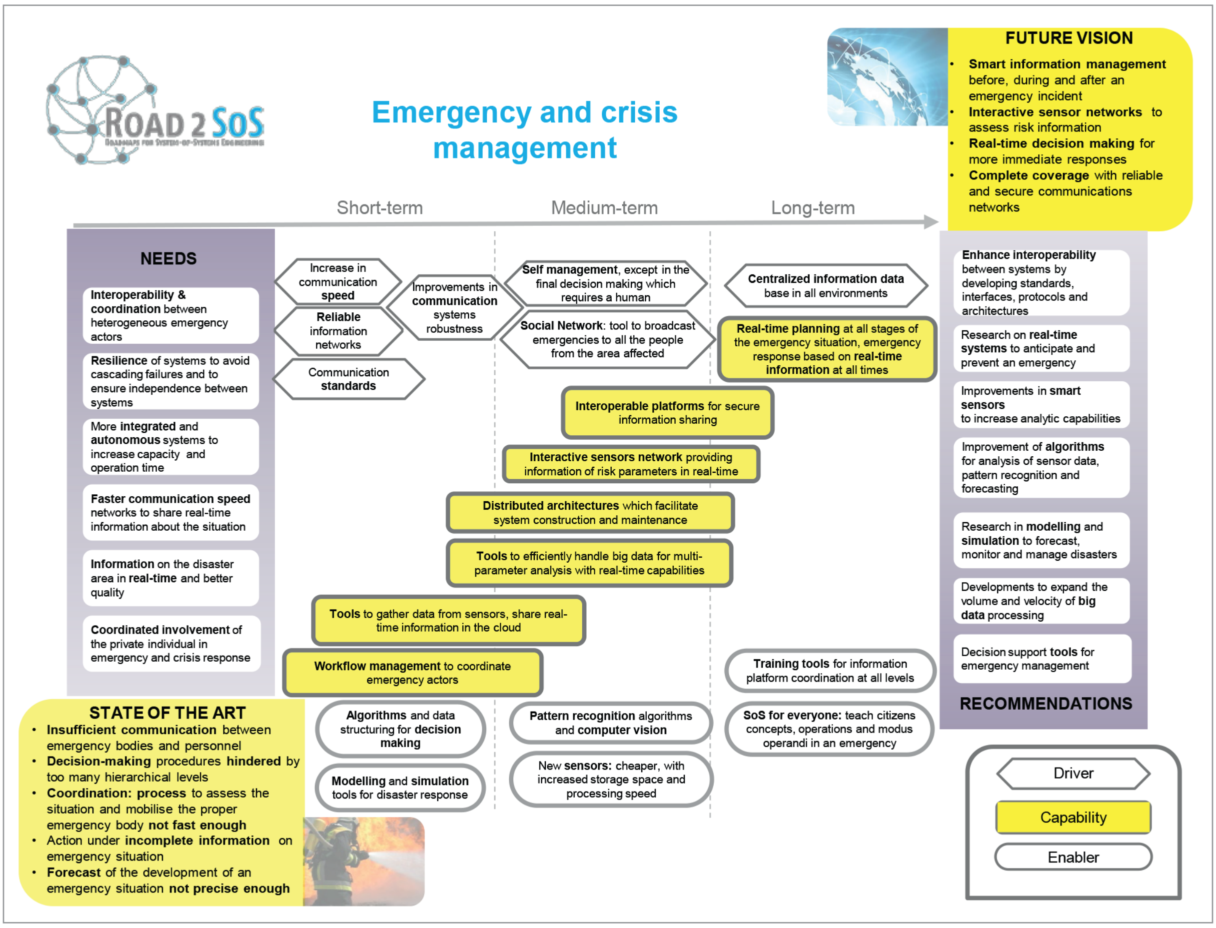

Figure 5: Simplified SoS roadmap for the domain of Emergency and Crisis Management

The role of emergency and security responders is of vital importance in system of systems. In an emergency management SoS, a specific level of autonomous behaviour could be implemented, but decision-making remains the responsibility of humans. However, SoS can support decision-making and greatly help to reduce the response time in a critical situation. Real-time information, pre-alert systems, visual surveillance and specific protocols will contribute to increase the speed of reaction.

A key part of SoS focused on emergency management is the pre-alert and monitoring of critical parameters that may indicate a dangerous situation. Sensors and sensor networks are important technologies for this task. For example, a network of sensors installed in a building with smoke detectors, humidity, visibility, motion, etc. can detect fire or intrusion in forbidden areas and can also control actuators such as power-lights, emergency ventilation, irrigation fire systems, etc. A sensor network that is able to interact and feedback information is the best tool to monitor specific situations and control them under certain threshold of security. Additionally, as this technology continuously improves, many more tools will be available in order to implement an emergency management-oriented system. Information obtained through sensor networks has to be treated and analysed through intelligent information management.

In SoS' dedicated to emergencies and crisis management, prevention technologies (such as sensor networks), communication technologies (for fluid and efficient communication during an emergency) and intelligent management of information shall be fully taken into account.

Summary of domain specific outcomes:

Trends and Drivers

- Standardisation and legislation procedures in emergencies
- Increasing communication speed
- Increased transfer of military technology
- Overall control of environmental parameters

Domain Needs

- Robust emergency systems able to adapt to any circumstance
- Adaptive performance depending on events
- Shorter decision making in emergency systems, automated and less error rate
- Faster speed communication networks

Key Innovation opportunities identified in the Domain

- Real time simulation and enactment and predictive modeling
- Interactive sensor networks
- Autonomous technology

Technologies and Capabilities

- Interoperable platforms and simulations
- Real time planning
- Modeling applications
- Workflow management

Enablers

- Standardization and legislation procedures.
- Development of business models
- Multi-party / organizations
- SoS applications in all fields

Summary of Domain specific Recommendations
Technological recommendations: R&D should focus on improvements / new solutions in

- **Interoperability of heterogeneous systems: Standards, interfaces, protocols**
  Communication and information exchange standards, interfaces and protocols to be developed facilitating different systems or networks to communicate and exchange information in real time to enable a timely resolution or prevention of a dangerous situation.
- **Real-time systems, real-time communication, data acquisition**
  To be able to effectively solve a hazardous situation is of vital importance to have all the information necessary and to handle all parameters that enable us to find a solution. Acquired information must be available in real time for all the parties involved in resolving the crisis: fire-fighters, police, health, military, etc.
- **Smart sensors**
  The development and implementation of interconnected smart sensor networks that can carry and make available important information to a system itself as well as other systems is important for a timely resolution of a crisis or an emergency.
- **Networking capabilities, sufficient data rate, communication channel speeds**
  There are many capabilities able to be achieved by a network system. It is very important to integrate the appropriate number of devices to have proper control of all parameters that can cause a catastrophe. With the constant improvements in device technology improved data rates and raised communication speed could be achieved.
- **Big Data including increased complexity**
  The three main characteristics of big data are: volume, speed and variety. Big data provides knowledge to institutions, improving as such the service offered to citizens and contributing to solve problems. Systems that allow the management and real time access to big data can provide a real benefit in a crisis and emergency situation.
- **Improved algorithms (automated reasoning, autonomous decision making, etc.)**
  An improved system for pattern recognition and identification of objects will allow the use of automated systems in direct intervention and crisis resolution catastrophes with a lower rate of errors in decision-making. Developing data processing software and more powerful processors, able to handle more data per minute will increase the speed of data processing and therefore pattern recognition, simulation of emergency situations in the data analysis of artificial precision devices, etc.
- **Modeling and simulation tools for SoS**
  Modeling and simulation tools for forecast and prevention and to develope warning and monitoring systems to avoid hazards and predict disasters. They greatly contribute to identify the best solutions available for each situation. Implement new and complex algorithms to manage the simulations, extend the capacity of the computers and processors used to simulate real situations. Will be very useful generate a large list with all the possible catastrophes that have already been simulated and modeled.
- **Architectures**
  The combined and coordinated actions of the different parts of a system can achieve more results than all the parts acting independently. This concept known as “synergy” is critical in the field of emergency management. These systems have three main tasks to address: (i)

communication between actors involved; (ii) data processing; and (iii) decision making unit. Designing and developing suitable architectures and / or frameworks for different emergency situations can result to better, faster and more efficient use of available resources and prevention of loss of human lives. All system components and inter-communications should be based on mobile web services using Simple Object Access Protocol (SOAP) and the emerging technology of Service Oriented Architecture (SOA). The technologies that this system needs are a web service, a mobile web service, SOA, GPS and HL7 and alternative communications (cable, satellite, radio frequency, etc.) in case any of the forms of communication fail.

Socio-economic recommendations

- **Enhance demonstration**
  In the emergency domain, the risk-benefit is normally unclear, since the major goal of any operation is to secure human lives. Demonstrators will play a major role to define situations and analyze better ways to act.
- **Improve education among decision-makers**
  In the emergency field, final decision should be taken by the person in charge of each emergency. In many cases, different persons are involved to support the decision maker.
  Defining easy procedures addressed to decision makers are needed. To ensure the success of acceptance and use of SoS, very intuitive systems should be defined in order they can be used by any person involved in the emergency.
- **Optimise human machine interface (HMI)**
  Emergency human–machine interfaces (HMIs) could be used to avoid or minimize losses. These interfaces should be designed to accommodate the human capabilities that have been altered by danger-induced emotional responses. In a modern socio-technical or human–machine system, when an emergency arises, it invariably involves interaction with technology and appropriate HMIs need to be developed to communicate, neutralize or eliminate the imminent dangers posed by such an emergency.
- **Focus on security and privacy, IP-issues**
  In managing a hazard, emergency bodies are responsible for analyzing all the information available and controlling a situation to best resolve or prevent an emergency. Advanced access to information can be critical. Clear protocols and procedures need to be established and follow on check up mechanisms to ensure that any information is not misused or accidentally released into the public domain. Moreover, improving public trust in the internet privacy, the internet right away as a user, a need for our time, the cloud computing, the risks of geo-location, advances in facial recognition, international flows data: flexibility and globalization, focusing research in these areas and implementing necessary improvements will increase both security and privacy of citizens.

5.4 Roadmap for distributed energy generation and smart grids

The vision for the future energy system can be described as the shift to emission-free, decentralized generation of energy from a variety of renewable sources. According to the renewable energy goals set by the EU, an 80% cutting of emissions has been envisioned by 2050 and Europe's energy production will have to be almost carbon-free.

This implies that energy generation will change from being limited to a few central sites (power plants) to decentralized production from renewables by a large number of generators. Furthermore, the number of active stakeholders in the energy grid is expected to greatly increase, as many of today's consumers may turn into so-called "prosumers" who act as producers in the energy grid at times. The future energy system will have to ensure security of supply despite the volatility of the renewable sources wind, sun, water, etc. and while suitably controlling a large number of energy producers. To do this, energy flow in the future energy grid will have to be accompanied by a flow of information. Information and communication technologies will have to ensure the grid is "smart" to cope with the non-trivial control problem of guaranteeing security of power supply at all times. SoS approaches are considered a promising approach to deal with the future energy system.

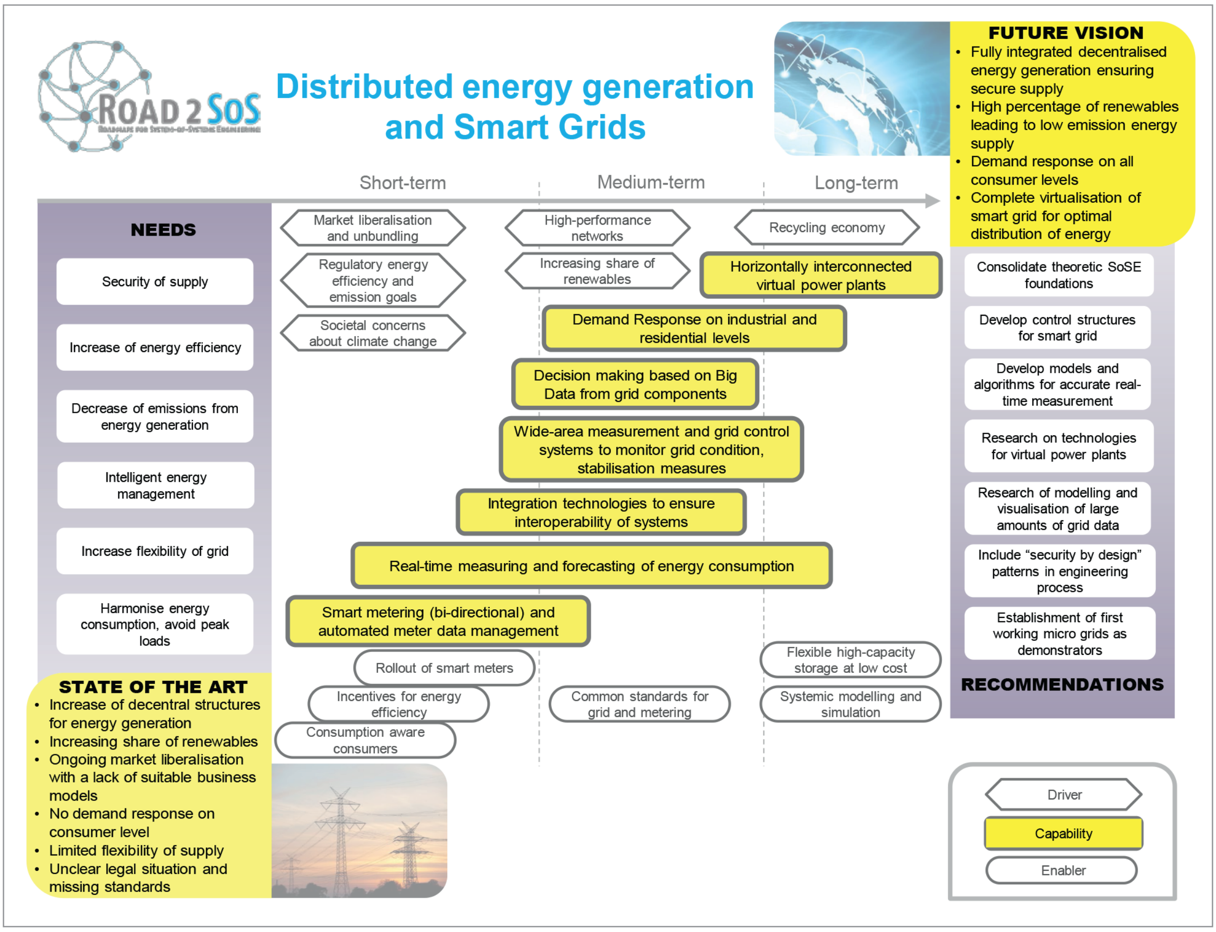

Figure 6: Simplified SoS roadmap for the domain of Distributed Energy Generation and Smart Grids

It is generally expected that the future energy system will exhibit a tremendous complexity manifested by its diversity, heterogeneity, dynamic behaviour, and widely varying scales in time, space, and power output. It will consist of a vast diversity of components and subsystems, including large power plants and renewable energy technologies. It will also feature different-sized decentralised generation units. The system will involve a large number of customers acting not only as energy consumers, but also as independent small energy providers. Intelligent energy management and smart grids are considered the keys for the energy system of tomorrow. This includes the paradigm shift of reshaping our energy system from unidirectional to multidirectional fluxes of information and energy. The goal of intelligent energy management is to integrate heterogeneously behaving, highly distributed, small-scale energy providers and users, along with central power plants. The desired outcome is a reliable, efficient, and sustainable energy supply combining fluctuating renewable energies, and a large number of stakeholders acting as energy consumers and providers at the same time (prosumers).

The predominant properties of the future energy system are:

- Integration of decentralised energy generation, especially wind turbines and solar collectors;
- Integration of other energy forms and carriers (for heat, cold, and mobility);
- Flexibilisation on the demand and generation side by a bi-directional energy flow;
- Interaction of energy consumers and producers by sharing information about their current status; and
- System regulation and control by an intelligent energy management

It is agreed, that the smart grid concept not merely represents the future vision for the energy system but the necessary enhancement of the energy system with information and communication technologies to make the transition to emission-free, decentralized generation of energy from a variety of renewable sources possible, while guaranteeing security of supply

Summary of domain specific outcomes:

Trends and Drivers
- Increasing share of renewables, decentralized energy generation
- Increased participation of prosumers, large number of stakeholders, market liberalisation and the unbundling of before central structures; smart markets
- High fluctuations in and restricted predictability of power production

Domain Needs
- Flexibility on demand (flexible electricity consumption technology) and generation side
- Real-time pricing and control
- Intelligent energy management

Technologies and Capabilities
- Demand response
- Real-time measuring
- Distributed coordination and optimisation
- Systemic modelling and simulation / Complex system modelling tools

Enablers
- Grid capacities / grid infrastructure
- Flexible high-capacity and cheap storage
- Educated consumers/prosumers

Summary of Domain specific Recommendations

SoS research priorities for energy should focus on improvements / new solutions in

- Demand response, encompassing research to technically and socially integrate different flexible users and different parallel control systems into an energy SoS, taking into account standardisation, market liberalisation, interoperability, resilience and robustness
- The development of technical solutions to integrate flexible electrical and thermal storage capacities as well as for load management of electric vehicles and other storages should also be of high priority
- The development of a suitable design, infrastructure, models and algorithms for an accurate real-time measurement and observability on low and medium voltage levels to allow state estimation, control and forecasting in the distribution grid and on lower levels
- New tools for the understanding of behaviour, interoperability, cross-layer communication and adaptability of the overall SoS
- Distributed co-ordination, optimisation, control to allow grid control and system optimisation under unpredictable and unreliable energy generation from RES. Necessary technical innovations comprise optimization techniques, architectures, algorithms and interfaces
- New comprehensive SoS models for optimization, collective adaptive systems, prediction, virtual deployment, simulation and planning have to be developed, together with advancements in computing power and parallelization techniques. Standardisation of interfaces and protocols should be an integral part of this topic
- Enhance work on missing standards
- Continue to support research and development activities in sensor networks, embedded systems, wireless systems, energy reduction and harvesting.

Recommendations socio-economic

- The information and education of consumers/prosumers should be addressed
- The contradiction of local actors serving global needs has to be considered
- Aspects like the comprehension of stakeholders and their roles and the support of cross-discipline knowledge and expertise should also be considered
- Identification of key application areas and a deeper commitment of "big players" (industry)
- Lack of awareness, potential from rapid advances in industrial ICT should be exploited
- Cybersecurity, privacy and legal problems should be addressed (by security by design)
- New business models: support new actors, stakeholders and business models to emerge

6 RECOMMENDATIONS FOR RESEARCH PRIORITIES

In the following, themes of required technological capabilities and engineering challenges will be described. These themes can be referred to as *priority themes* because they have been found to emerge independently in several of the application domains examined in the Road2SoS project. They can therefore be expected to be of relevance not only to the examined domains, but likely for many more application domains. The presented priority themes therefore represent areas where strategic research activities are recommended.

All priority themes presented in the following can be understood as serving at least one of two overarching goals:

1. To enable **better, faster decisions**, based on a greater variety of sources and a greater amount of underlying data.

2. To **handle the complexity** of SoS and to enable humans to interact with such SoS.

These two goals shall provide us with a useful narrative, tying the several themes together. The themes require strategic action for Europe in order to benefit from the described trends of an increasing number of systems and sensors, and their ever stronger interconnection, while effectively limiting the evoked complexity.

We shall begin by exploring a first set of themes from the point of view of the first goal: enabling better, faster decisions, based on a greater variety of sources and a greater amount of underlying data (section 6.1). Speaking of "better decisions" more precisely means "more informed decisions". Consider the many decisions a person makes in a day. Now reflect that practically each of these decisions is based on incomplete information and on assumptions about the current state of the real world and on assumptions about its dynamic and further development. This holds even more so for IT systems. Rarely is a system supplied with all the input data that would be necessary to make a holistic decision. The control system of a car engine, for instance, will effect an acceleration of the car, based on input data being a signal from the gas pedal. Consider, however, that the real world is full of information which – if provided as input data to the engine control system could lead to a much better, that is, a more informed decision. Knowing, for instance, that the car will experience strong side wind 100 meters ahead (data coming from a sensor grid), or that the stability system of a previous car has just detected an icy patch on the road ahead could lead the engine control system to make a more informed decision. In short, the drastically increasing number of systems and sensors, and their ever stronger interconnection enables both humans and technological systems to make use of copious amounts of "context" for decisions.

We have grown quite accustomed to the fact that our decisions as humans and the decisions of systems are based on incomplete information. Just the more exciting it is, and innumerable opportunities exist, to exploit the context from surrounding (in a geographical and a semantic sense) sensors and systems.

A second set of priority themes will be presented from the point of view of the need to reduce complexity (section 6.2). While the interconnection of systems into systems-of-systems brings enormous potential for a smarter world, it also ramps up complexity by orders of magnitude. The themes presented under section 6.2 then, comprise approaches and engineering methods which become necessary with such systems.

As has been described by way of introduction, SoS are at the same time *enabled* and *required*. They are enabled by the technological trends of an increasing number of systems in the world and an increasing interconnection between them. And they are required as way of handling the complexity of the large scale super-systems that come into existence through such integration. The first set of themes (section 6.1), then, corresponds to the enabling side: What are important themes that will enable SoS? The second set of themes (section 6.2) corresponds to the demanding side: What are necessary capabilities to deal with the complexity of SoS?

6.1 Themes of required technologies and capabilities

Let us start with the set of themes describing the technologies/capabilities which become necessary with the large scale integration of systems into SoS. All of them can be understood as enabling better, faster decisions based on a greater variety of sources. Figure 1 ties them together.

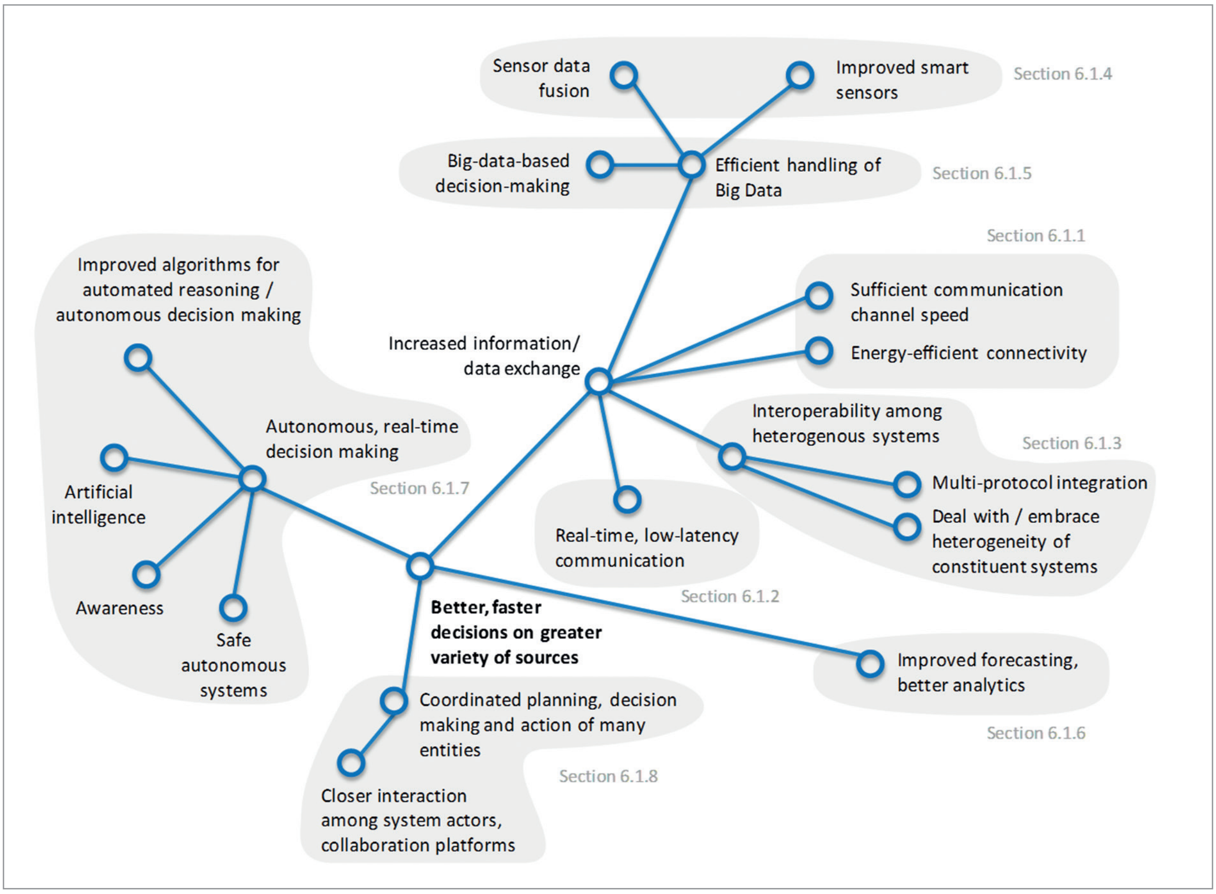

Figure 7: Overview of technological Priority Themes identified in Road2SoS

6.1.1 Sufficient Communication Channel Speed and Energy-efficient Connectivity

To aggregate systems into an SoS, and to have the SoS behave in a coordinated way to achieve its goals, connectivity and sufficient communication channel speeds are fundamental. In an SoS, the amount of data exchanged among constituent systems can be considerable. Already, the Cisco Visual Networking Index reports growth rates of M2M traffic of beyond 80% and projects this rate to be steady in the future.[11] Insufficient bandwidth and a lack of connectivity will put a hard limit to the extent to which systems can form an SoS and act as an SoS.

By way of introduction, the capability of SoS for more holistic decision making was described. This will be possible by means of correlation or cross-analysis of data from numerous constituent systems but it implies extensive data exchange among systems. Consider the scenario of emergency and crisis management, where correlation of images and video streams from multiple locations, captured by

[11] Cisco Systems (2013)

fixed cameras or gained from social networks, could be used to construct a real-time representation of the emergency or crisis situation. It is evident, that the described SoS provide such capabilities, if sufficient data rate is available.

Note that the challenge is not primarily about fiber-optic high speed communication infrastructure, although strong backbones are undoubtedly necessary. The challenge is about providing cost-efficient last-mile connectivity and sufficient bandwidth to a very large number of systems via a multitude of technologies, most of them wireless communication technologies. Cisco VNI predicts traffic from wireless and mobile devices to exceed traffic from wired devices by 2017.[12] Providing wireless connectivity at sufficient bandwidth to a large number of devices will be a challenge, since bandwidth via the spectrum of electromagnetic waves is limited.

Note furthermore that constituent systems of an SoS will not only be physical servers or embedded systems with stable power supply, but may also comprise remotely located, miniaturized systems such as smart sensors. Since sufficient energy supply to these systems is a challenge of itself, connectivity will need to be provided mindful of energy consumption. A challenge will be to provide energy-efficient connectivity to these devices, so they can become part of an SoS despite their constrained energy supply. The wide and strongly increasing use of the RFID technology well demonstrates the potential of such low-power solutions in wireless communication. With projections of sensors in the world going to trillions of sensors, efficient connectivity is of paramount importance if these are to be integrated into SoS. To sum up, novel ways of providing wireless, low-power connectivity to a very large number of endpoints will have to be investigated.

6.1.2 Real-Time, Low-Latency Communication

With SoS, the benefit will not only be in making decisions based on information from a large number of systems. Also, the possibility arises to make decisions based on real-time information. Nowadays, the majority of decisions are made in reporting mode (report-based decisions), based on stored, past-oriented, “old” data. Having real-time information at hand, gathered from the constituent systems of an SoS, a system or a human decision maker is put in the position to make decisions based on current information. Consider the example of the manufacturing domain, where adjustments to a production line can then be made without delay, avoiding the weeks of suboptimal operation and poor efficiency that formerly lay between the occurrence of suboptimal operation and the necessary adjustment. In the scenario of emergency and crisis management, real-time systems are of course not just a cost-saver but can be a life-saver: To emergency responders, it is vital to have information about the current status of the situation in order to respond effectively and to not learn only on site that the real situation is different to the situation the response action was planned for. To sum up, real-time communication enables a shift from making decisions in reporting mode, based on old information of the past, to decisions based on the *now*.
Note that *real-time* is not necessarily synonymous with speed, rather, the real-time capability of a system usually expresses that it produces a response to a request within a guaranteed time interval. With respect to communication, additional requirements may exist for certain applications, namely the necessity for low-latency communication.

[12] Cisco Systems (2013)

Real-time, low-latency communication is necessary when it comes to time-critical coordination tasks within the SoS. Consider the example of an SoS consisting of autonomous or shared control cars: The braking systems and stability systems of the individual cars need guaranteed reaction times in the order of few milliseconds. If collision with other vehicles are to be avoided, coordinated action of multiple vehicles becomes necessary at times. Consider a sequence of cars, following one another. If the first car brakes then all following cars need to brake as well, within a defined maximum time. To achieve this, communication among the cars' braking systems needs to be real-time and low-latency in order to achieve timely coordinated behaviour of the SoS adequate to the situation. A multitude of similar safety-critical scenarios exist which offer enormous potential for adding safety.

In order for control to work on an SoS level, the challenge is thus to ensure low-latency, real-time communication among a potentially large number of systems. Reliable methods to achieve this are to be investigated, especially in safety-critical systems.

6.1.3 Interoperability among Heterogeneous Systems

Having outlined certain connectivity-related challenges in the two previous sections, this section describes a third, very fundamental one: To aggregate systems into an SoS, and to achieve coordinated action, interoperability among constituent systems is a fundamental condition.

Interoperability refers to the ability of systems to interact with each other directly. For systems which are based on the same architectures, technologies, logic elements, use the same interfaces, etc. interoperability is fairly easy to implement. Note, however, that this is not necessarily the case in an SoS. SoS may be formed from systems which are heterogeneous in many ways. Consider an SoS of longer-term stability: While the constituent systems in the initial setup may have been very similar, new systems may join the system over time, integrating with the legacy systems. After years of operation then, the SoS will comprise constituent systems of a multitude of different ages and technological generations. Beside the age and generation of systems, the type of systems can also vary. Consider the scenario of emergency response to a forest fire: A set of employed drones to extinguish the fire will need to coordinate their action among themselves (similar systems), plan and continuously re-plan their response based on weather data (e.g. wind direction and speed), based on information contained in image streams from fixed cameras, cameras attached to other emergency responders or from social networks. In short, they will interact with a great variety of systems.

Consider as another example the scenario of multi-modal traffic control, where, in many countries, administrative organisation of transportation has led to a situation where modes of transportation are operated by a patchwork of operators: Different operators for different types of roads or locations, different operators for different modes of transportations such as roads, tramway, subway, train or air. The operators each have certain legacy systems and standards which are hardly compatible today. Today, transportation modes are insufficiently interconnected to ensure an optimal utilization of the available assets and infrastructure. Interconnecting the information systems of different operators would enable the possibility to manage mobility as a whole.

Even if the systems that could form an SoS are endowed with networking capabilities today, true interoperability is challenging because the systems will differ in architectures, technologies, data structures, ontologies (i.e. the meaning of data structure elements), interfaces and related protocols. Integration will thus entail considerable effort, and can certainly not take place in the ad-hoc fashion one might need to flexibly or at least cost-efficiently form an SoS. Standardisation is important but it falls short of solving the problem. While standardization of interfaces and protocols is certain necessary in many domains, approaches which would allow to embrace the heterogeneity of systems and to ensure they can form an SoS, despite their variety, would be required.

Developments already exist in the direction of adapters which translate with regards to syntax (protocols and data structures) and semantics (e.g. ontologies). Research needs to continue in this direction. Furthermore, approaches need to be developed to network legacy systems which have not been designed to be networked or to exchange information.

6.1.4 Smart Sensors and Sensor Data Fusion

An important species in an SoS are sensors, either standalone sensors with connectivity to an SoS or sensors which are a built into systems which are in turn connected to the SoS. An example of the former are sensor grids spanning large areas, an example for the latter are sensors which are part of embedded systems in cars or machines or in devices such as smartphones.

The number of sensors in the world is projected to increase drastically. The market for sensors integrated with processors (so-called smart sensors) will reach 2.8 trillion devices in 2019, up from 65 million in 2013, as WinterGreen, a market research and forecast institution projects. A skin of sensors will cover the earth's surface; sensors will be in any object, in our clothes, in our bodies, continuously creating and updating a digital representation of the physical world, giving rise to the Internet of Things.[13] To illustrate the extent of sensor coverage, The Economist humorously, but factually correct, points out that even cows will be connected and digitally represented by means of sensors implanted in their ears, monitoring health and movement of the cows.[14]

The continuous acquisition through a large number of sensors will give rise to a substantial amount of data. The cow from the previous example is expected to produce 200 MB per year of data, surely a rather low amount in comparison with other types sensors which are greater in number and more intense in data rate. The substantial amount of data is usually referred to as *Big Data*, denoting that the volume of data, its variety, and the velocity of acquisition and necessary treatment are challenging using conventional methods (see also section 4.1.5).

In this context, smart sensors have an important role in performing data reduction. The smartness of these sensors lies in their capability of monitoring the data quality and perform advanced analysis. This data treatment close to the location where it arises ensures that not copious amounts of data are gathered which would then have to be analyzed centrally. Instead, not raw data is passed on by the smart sensor but actual information gained from the analysis of the raw acquired data, e.g. only

[13] Vermesan, O., et al. (2011)
[14] The Economist (2010)

events outside the ordinary would be reported by the smart sensor. Not only does this drastically reduce the data which has to be transferred via networks, it also effectively reduces the extent to which Big Data arises. The need for these sensors to be low-powered, potentially energy-harvesting devices, with energy efficient-connectivity has been mentioned in section 4.1.1. Beyond this, efforts have to be made to realize advanced analytics capabilities at the sensor level, at very low power consumption.

Upwards from the sensor level, important information can be derived by means of *sensor data fusion*, referring to methods of treating, correlating, or reducing data from sensors. Not only is sensor data fusion a second instance of limiting Big Data. By correlating information obtained from numerous sensors, additional information can be gained which are not available at the level of the single sensor:

- Patterns across numerous sensors can be detected in the acquired data
- Reliability of individual sensors can be assessed, data from faulty sensors can be dropped and instead interpolated using data from closely located sensors.

Methods of sensor data fusion are important enabling capabilities in an SoS context. Research is required to perform efficient pattern recognition and correlation across a very large number of data streams from distributed sensors, of heterogeneous type, with varying data quality.

6.1.5 Efficient Handling of Big Data and Big-Data-Based Decision-Making

The integration of a large amount of systems and sensors into SoS lead to the availability of substantial amounts of data. The data arises from correlating information available at the system level and being generated by systems, and from continuous data acquisition by sensors. IDC estimates that between 2013 and 2020, the data digitally available in the world will double every two years. Machine-generated data is a key driver in the growth of the world’s data – which is projected to increase 15-fold by 2020.[15] The substantial amount of data is usually referred to as *Big Data*, denoting that the volume of data, its variety (range of data types and sources), or the velocity of acquisition and necessary treatment are challenging using conventional methods.[16] Gartner, and now much of the industry, use these 3-V characteristics of Big Data.[17]

The potential of Big Data in SoS is in economically extracting value from these very large volumes and wide variety of data. Be it by making better, more informed decisions at the level of the SoS and at the system level, by machines and by human beings, or by optimizing systems and processes. Benefits can be expected in any domain – from manufacturing to medicine, transport, energy supply, or emergency forecast and response. In human history, the rise of science, at its core, was about discerning regularities in what seemed a chaotic cosmos of disconnected, arbitrary events. Such regularities – from Kepler’s laws, Newton’s laws, laws of thermodynamics, electrodynamics to quantum mechanics – more and more disenchanted the world and made it possible to make tools

[15] Gantz, J., Reinsel, D. (2011)
[16] White (2012)
[17] Laney (2001)

and systems, harnessing the natural phenomena the dynamics of which had been uncovered. Today, in SoS, innumerable correlations and dynamics may be found and exploited. A copious amount of context can be provided for any single decision. The challenge is making use of Big Data for decisions and optimizations; to turn Big Data into *information*, and even more importantly: to turn Big Data into information adequate for humans to act upon.

IDC estimates that by 2020, as much as 33% of the digitally available data will contain information that might be valuable if analyzed. Today, less than 1% of world's data is analyzed, a recent study estimates.[18] The benefits are numerous, but the extraction of information from high volume, high velocity, and/or high variety information requires research into new forms of data treatment: Adequate database technologies, ways of analyzing and correlating distributed large datasets, data reduction mechanisms, and visual representation of Big Data in order to enable big-data-based decisions by human beings. To the extent that Big Data cannot be analyzed completely, methods of uncertainty quantification need to be available in order to deliver reliability information with the findings extracted from Big Data. Hard limits to big-data based decisions are frequently seen in the fact that, in a given large data set, the quality of the data may vary. That is, not all data points are equally reliable. Approaches need to be available to deal with this varying data quality.

6.1.6 Improved Forecasting

By way of introduction, the perspective has been presented that SoS enable more informed decisions at the system level and the SoS level. As has been argued, one reason for this is that a) decisions can be based on greater amounts of decision-relevant data; another reason being that b) real-time information offer the possibility to not only make decisions based on information of the past, but based on the *now*. Note that SoS enable also something else: The vast amount of information available from systems, devices and sensors enables also c) better forecasts. While a) and b) enable more informed decisions, the latter enables *strategic* decisions.

The possibility to make better forecasts based on big data is considered even more valuable than the ability to make decisions based on past information. This has similarly been found in a recent study by The Economist Intelligence Unit: Among the surveyed managers and high-level executives, by far the most valuable insights expected from big data analytics are not insights about, for instance, past or current business processes but predictions of future developments.[19]

Open research challenges exist in deriving and presenting the forecasts on such a large volume of data, gained from a wide variety of sources. Among them the fact that, while lot of data may be available, its data structure will often be just as heterogeneous as its sources. Semantic ways of involving such data in forecasts are required. Furthermore, the data points in a large dataset composed from multiple sources may vary greatly in quality and reliability. Methods to take this into account required, including means of providing uncertainty quantification with the presented forecast.

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[18] Gantz, Reinsel (2011)

[19] The Economist Intelligence Unit (2013a)

6.1.7 Autonomous Decision-Making

Many of the themes presented so far play an important role in enabling better, faster decisions based on a greater variety of sources. But not all these decisions will be made by human beings. With the number of systems increasingly outnumbering the number of human beings on the planet, the involvement of humans in decision making must be limited to only the necessary cases. In such cases then, decision support will be provided by appropriately presented information (see also section 4.1.5 on big-data based decision making and section 5.5 on human machine interfaces).

In the many cases, however, systems need to make decisions autonomously, without necessary human involvement. Achieving this capability is tied to a number of technological challenges. Firstly, there is a need for improved algorithms for automated reasoning and decision making. Algorithms need to be capable of taking into account data from distributed sources, data of varying temporal and spatial resolution and data of varying reliability. It needs to be ensured that decisions made on such basis are safe and – considering that human decisions are to be taken over where possible, and considering that SoS are usually socio-technical systems – autonomous decisions will also have to be ethical. This will have to involve research in the field of Artificial Intelligence and also in the field of Awareness. In order for systems or „agents“ to make decisions, self-awareness but also awareness for its surroundings and even for intentions of other systems and actors is necessary. A system would thus require a model of the environment it is embedded in. This model arises from status information of other systems and also from a digital representation of the physical world acquired from distributed sensors. Since the model is created and updated from various sources of varying reliability, uncertainty quantification plays an important role.

Beyond building and continuously updating a model reflecting the current situation, forecasting plays an important role (see also section 4.1.6). In decision-making, a system cannot merely take into account the current situation; it needs to know about likely trajectories of the current situation into the future. Furthermore, in order for decisions to be safe (or even ethical), also consequences of a system's action have to be evaluated. Lastly, ways of knowing and understanding other systems actions and objectives need to be available.

6.1.8 Collaboration platforms and tools for coordinated planning and decision making

SoS are expected to greatly support planning and decision making of many entities. To do this, platforms are required for presenting all involved parties with available information of shared relevance, facilitating coordinated action and collaboration.

Consider the scenario of emergency and crisis management where diverse actors such as fire-fighters, police, health care providers, the military, etc. require very similar information in real-time to act most effectively. Today, while relevant information may be available in real-time, it is often only available to one of the parties and either not shared, insufficiently shared, or shared with delay.

The development of platforms is necessary which allow efficient real-time information sharing across organizational boundaries, mindful of intellectual property and roles. Such platforms need to support decision makers with the necessary information to decide when to optimize a constituent system at the system level and when to favour optimization at the SoS level, for a common goal.

6.2 SoS Engineering Challenges

As has been described by way of introduction, SoS are at the same time *enabled* and *required*. They are *enabled* by the technological trends of an increasing number of systems in the world and an increasing interconnection among them. And they are *required* as way of handling the complexity of the large scale super-systems that come into existence through such integration. A first set of themes, corresponding to the enabling side, has been explored in the previous section. In this section, a second set of theme shall be presented, corresponding more to the demanding side of SoS: Many of these themes can be understood as serving the goal of complexity management and complexity reduction; they can also be described SoS Engineering challenges. Figure 3 ties these themes together.

With SoS, one may be speaking of very large scale systems, not necessarily with static borders, which can be quite dynamic. This has important implications for methods for design, operation, control, and maintenance. By 2020, the number of servers is projected to multiply tenfold, whereas the number of IT experts will only have increased 1.5-fold.[20] Traditional approaches of central control and superordinate management seem incapable of dealing with the vast ecosystem of networked systems that, today, is only in its infancy. More flexible approaches are required to have the constituent systems of an SoS collaborate, negotiate, organize, and maintain themselves. Throughout the entire lifecycle of an SoS, novel approaches will be necessary which an evolution of the systems engineering discipline into *SoS Engineering* will have to offer.

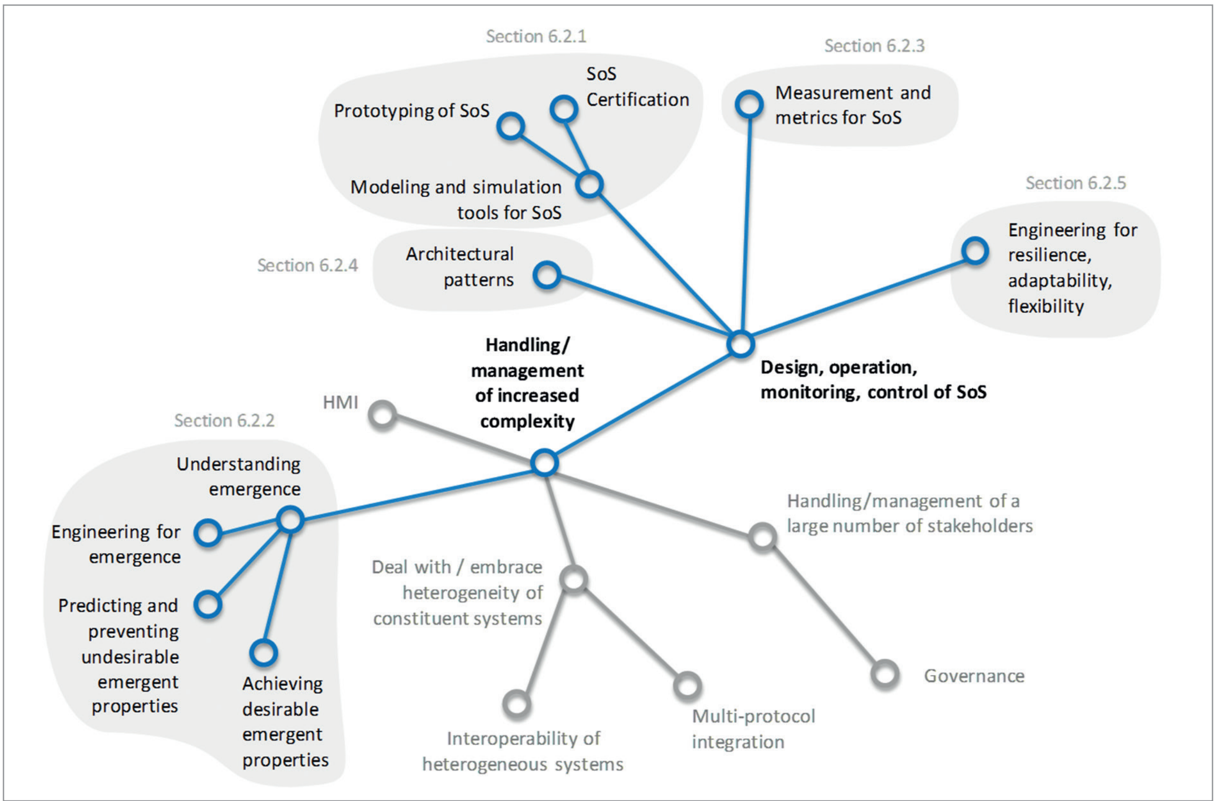

Figure 8: Overview of engineering Priority Themes identified in Road2SoS

[20] Gantz, J., Reinsel, D. (2011)

6.2.1 Modeling and Simulation

Since there is usually no option to build a prototype of an SoS in the design phase, modeling and simulation plays an especially important role in SoS Engineering. When engineers create a safety-critical system, they need to perform an adequate hazard analysis. Modeling provides a conceptual framework for analysis and simulation of systems that otherwise could not be known until the modelled situation occurs. For SoS, however, hazard analysis is difficult because of the complexity of SoS and the environments they inhabit. Traditional hazard analysis techniques often rely upon static models of component interaction and have difficulties exploring the effects of multiple coincident failures.

Hazard analysis techniques using multi-agent modeling and simulation to explore the effects of deviant node behaviour within an SoS can be promising. This comes from the fact that agent-related concepts allow the representation of organisational and behavioural aspects of individuals in a society and their interactions. With SoS being socio-technical systems, these or similar modeling and simulation capabilities are required to suitably represent an SoS, prototype it, perform hazard analysis, and also to provide certification of an SoS.

6.2.2 Understanding Emergence

The concept of emergence firstly occurs in ancient Greek philosophy. With regards to SoS, emergence describes properties which can be observed at the SoS level, as a result of the interactions among the constituent systems. Emergent properties may be mere synergies but also entirely new capabilities which the SoS will be able to provide.

Despite the fact that emerging properties are caused by the sum of constituent systems they may be unpredictable from the characteristics the single constituent systems. The question whether emergent behaviour can be predicted is of an almost philosophical sort, but also a question of definition: Certain definitions preclude the argument by taking unpredictability as the defining characteristic of the term. With regards to predictability, there is also the notion that varying predictability of emergence exists, namely, that predictability depends on certain parameters.

Since with SoS, as in any complex system, emergence can be expected to be observed due to numerous interactions among constituent systems, there is a need to better understand emergence, predict it when possible, and also understand the possibilities and limits of emergent behaviour prediction. From a classical engineering point of view, emergent behaviour is undesirable in the sense that it is unexpected system behaviour. But it may still be desirable due to the fact that it brings unexpected functionality to the SoS.

The role of understanding emergent behaviour for SoS Engineering is thus: To make emergent behaviour less unexpected, to avoid undesirable emergent behaviour in the design phase, and to allow for desirable emergent behaviour. Modeling and simulation (see previous section) plays an important role in achieving these capabilities.

6.2.3 Measurement and Metrics for SoS

For the operation and optimization of any system, it is necessary to know how well it is performing. This information is the basis for identification of inefficiencies, detection of system failures and adjustments towards an optimal system performance.

For SoS, it may not be possible to identify a global optimum or the global optimum may not be feasibly or practically achievable. Despite this, suitable metrics and approaches for measuring overall performance of an SoS are required. Furthermore, since stakeholders in an SoS are constantly facing the trade-off decision whether to optimize the performance of constituent systems at the system level or the SoS level decision support is required for stakeholders to determine the solution optimal to them, and highlighting the benefits of optimizing at the SoS level. In order to do so, metrics and measurement approaches are a precondition. Research is required into feasible ways of measuring SoS performance and into useful ways of metrics definition.

6.2.4 Architectural Patterns

Architectures are basic structures for building systems. Usually they consist of several components (e.g. functional services) which interact with each other via interfaces. Within an SoS, each system can be regarded as such a component.

In order to enable organisations or associations to leverage the potential of SoS, suitable architectures and design patterns need to be available to join SoS at low implementation costs. Architectures need to reduce complexity, support interoperability and cooperation, allow for integration to happen at low effort and provide transparency in the overall SoS, while being mindful of security and IP issues.

In addition to those architectures, integration and migration strategies have to be defined in order to enable existing infrastructures to adapt SoS concepts or to enable pre-existing components / sub-systems being used within the SoS. Those integration and migration strategies may also consider intelligent services, reasonably integrated to the architectures which will enable us to use legacy systems, local information, etc. in any other relevant context of the SoS.

6.2.5 Engineering for Resilience, Adaptability, and Flexibility

SoS are required to provide stable service with constituent systems changing over time and under conditions which are changing over time. To achieve this, engineering approaches are required which deliver the required amount of flexibility and adaptability at run-time, under conditions not necessarily foreseen at the design stage.

Also, novel engineering approaches are required to deliver resilient SoS. The resilience of a system describes its ability to recover from disturbances and disruptions. Systems which are able to recover rapidly from major disturbances or disruptions can be described as highly resilient. At the example of a supply network in the manufacturing domain, an SoS can be described as resilient if it is able to recover itself from a disruption and still satisfy a customer’s demand. This may be realised in a number of ways. These include having redundancy within the SoS in the form of multiple suppliers providing the same components or having the ability to replace one supplier with another with little delay.

In classical systems, failure of a component is handled as an exception from normal operation. With SoS, failure of a constituent system must be considered as normal (“failure as normal” principle) and engineering approaches must be developed to achieve resilient behaviour of the SoS nevertheless.

7 SUCCESSFUL IMPLEMENTATION OF SOS

In order for SoS to be successfully deployed, the availability of certain technologies, capabilities and engineering approaches is a necessary condition. The priority themes which were identified in this regard have been presented and explored in section 4. While the themes presented in section 4 affect the *technological possibility* of building SoS, the themes presented in this section affect the *socio-technical and socio-economical possibility* of building SoS.

Figure 4 shows the most important aspects in this regard and how they are tied together:

- Many aspects in the connected set at the bottom are related to the fact that there is an absence of demonstration of SoS. As is usually the case with novel technologies, acceptance can be achieved by a convincing alleviation of concerns – and maybe even more effectively by demonstrating the utility and convenience which the novel technology entails (see section 5.1). Furthermore, the risk-benefit ratio has to become clearer (see section 5.2) and SoS-appropriate business models have to emerge, circumventing also issues that would arise with the multiple ownership situation in SoS (see section 5.3).

- As with many novel technologies, education and training is of importance – to make humans comfortable with novel technology but also as a means to overcome resistance to change (see section 5.4).

- Probably the most technological aspect in figure 4 is the need for adequate Human Machine Interfaces (HMI) allowing humans to interact simply and seamlessly with complex systems, and to present to them vast, complex data in a way so humans can make decisions based on them (see section 5.5).

Despite the fact that the sort of socio-economic and socio-technical aspects presented in figure 4 are sometimes referred to as "soft factors", they may well put a hard stop to SoS adoption and must therefore not be overlooked. Recommendations for strategic action would thus be incomplete without elaborating on such aspects on the following sections.

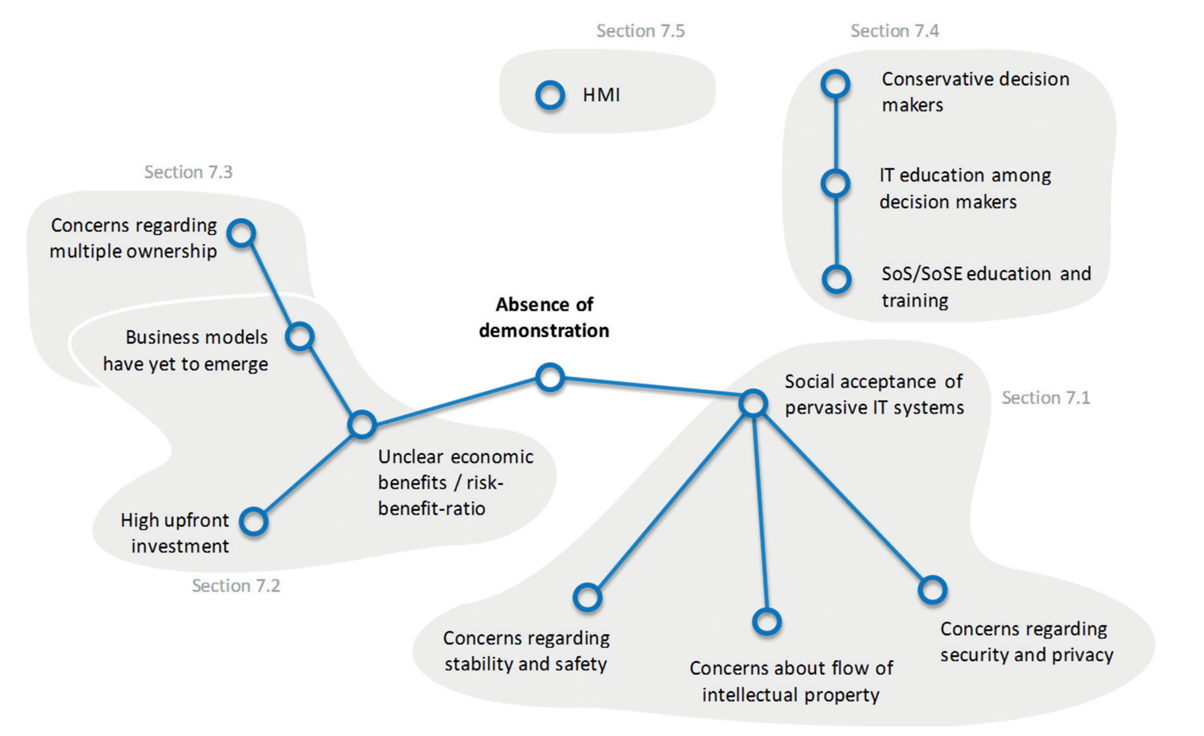

Figure 9: Overview of potential implementation barriers to identified in Road2SoS

7.1 Alleviation of Concerns with Pervasive IT Systems by Means of Demonstration

A number of concerns are frequently expressed in connection with SoS. Some of them are similar to concerns usually expressed about any sort of large-scale, pervasive technological system.

Among these are concerns about **SoS stability**. If humans and society are to increasingly rely on SoS then stable service has to be ensured. The dependence of modern society on e.g. secure power supply is immense and studies have shown dramatic economic and societal vulnerability in the case of longer-term power outages.[21] The extent to which SoS will be deployed strongly depends on the extent to which stable operation can be ensured.

Other concerns have to do with **SoS safety**. As with any tool, device, or system, the reasonable requirement is that it does not cause damage or harm. Consider the example of cardiac pace makers where it has to be ensured that malfunction of the device does not add further harm to the patient. Note, that the device may fail and not provide its function, but when it does so it must not add further harm to the patient. This may be the level of safety that one will also require from an SoS.

Further concerns are about security, privacy and to the **flow of intellectual property** (IP) within the SoS, when the SoS involves multiple IP owners and spans organizational boundaries (see also section 5.3).

[21] Petermann (2000), German publication

While the successful alleviation of such concerns requires certain technologies, capabilities and engineering approaches, *demonstration* plays an important role to tackle the social side of the coin. Demonstrators can play a two-fold role: Firstly, they are a means of alleviating concerns. Secondly, they are the starting points for an incremental process towards a full-scale SoS implementation. This principle of incremental development from demonstrators as starting points could lend itself well for the implementation of SoS in many application domains.

Consider the example of an almost ideal large-scale SoS: the future smart energy grid. A smart grid is not expected to arise by transforming or renovating an entire trans-national energy grid on the spot. Rather, it is expected to evolve from local „seeds“: Smart grids of a very limited, local scale; so-called micro-grids. Work successfully at their limited local scale, they are expected to grow larger over time, at certain points merging with other micro-grids forming ever greater systems.

Small-scale SoS demonstrators are likely to alleviate the abovementioned concerns by the following means:

- Demonstrators constitute working examples, which allow studying an SoS approach with limited risk and costs (the issue with unclear risk-benefits ratio and high upfront investment will be discussed in section 5.2).

- Working demonstrators create the (justified) feeling that SoS are controllable and that their complexity is well mastered.

- Demonstrators can achieve acceptance by showing the utility and convenience SoS can bring.

Starting from small-scale demonstrators then, a comfortable evolution towards larger SoS can take place in parallel with growing social acceptance. For future SoS development, the strategic development of small-scale SoS demonstrators is thus recommended. In many domains, the involvement of public authorities is required to do this effectively.

7.2 Investment Associated with SoS and Risk-Benefit Ratio

The fact that SoS demonstrators are largely not existent in application domains brings with it an unclear risk-benefits-ratio for potential stakeholders. This poses a dangerous impediment for SoS to come into existence. The unclear risk-benefit ratio consists of at least two issues: a) SoS-appropriate business models have yet to emerge and b) the costs of establishing SoS are assessed extremely differently.

Two perspectives exist which lead to these opposing assessments of investment costs:

Perspective A: Large scale integration of heterogeneous systems makes substantial upfront investments in infrastructure, hardware, and software necessary. The ROI is unclear and the break-even point may be far in the future. Alongside the costs of new technologies, significant costs are associated with learning how to use these new systems. These switching costs involve overcoming the inertia of individuals who have experience and expertise in the use of incumbent systems, selling them the benefits of using the new systems and training them in the use of these systems to ensure that the new systems are adopted.

While transitioning to any new system that features such costs, the particular challenge within an SoS is that it involves multiple stakeholders making these investments concurrently when the SoS is first created. At this stage there is considerable uncertainty regarding the success of the SoS, and the costs of new systems is prohibitive. Overcoming these inhibitions can require SoS participants to leverage their social capital in order to convince, while funding from national and international institutions can also help reduce the barrier to adoption.

Many aspects of this perspective A hold for instance for the scenario of the future energy grid, where existing systems of depreciation times of many decades have to be equipped with networking capabilities and be made interoperable. Systems, which have never been designed to interoperate or be controlled with external signals.

Perspective B: The elegance of SoS lies in the fact that all necessary assets already exist. Therefore, no major investment is necessary to build the SoS, it comes into existence by joining already existing systems together. Each of these systems (according to SoS definition) shows operational and managerial independence and thus likely covers the cost of its operation already by fulfilling its purposes as a standalone system. The costs with establishing SoS is thus limited to ensuring interoperability. Consider the scenario of multi-site manufacturing, where the financial costs of establishing a new supply network are less concerned with the purchase and installation of new hardware and software but rather that there are a plethora of different ERP and MRS software available and that efforts must be made to integrate these.

As opposed to perspective A, which stresses the requirement of mobilizing a large number of actors simultaneously to build an SoS, perspective B sees the SoS as evolving from an initially moderate dimension, as further systems join to benefit from the synergies and added value the SoS can offer. Ideally, negligible costs and no particular risks are tied to joining an SoS.

Likely, it will be much dependent upon the scenario if perspective A or B best describes reality. In both cases however, a smooth way of integrating constituent systems will limit costs drastically; and clear benefits will need to be visible to entice actors to engage in the SoS.

A way of making benefits visible are working demonstrators, as described in section 5.1. The topic of interoperability has been explored in section 4.1.3.

7.3 Multiple Ownership, Governance and SoS-appropriate Business Models

As per definition, SoS consist of systems which show managerial and operational independence. Each constituent system is run independently and fulfils a defined purpose as a standalone system ("operational independence"). Only in the second instance are constituent systems members of the super-system called SoS. This likely entails that there is not a single owner of the SoS entirely because the constituent systems are owned by several legal entities ("managerial independence"). This implies the need for appropriate means to manage a large number of stakeholders and deal suitably with this situation of multiple ownership. This raises questions of governance and appropriate business models.

The term governance refers to the system for controlling a socio-political entity. SoS can be categorised according to their governance mode. Dahmann's categorisation distinguishes between four modes: (1) directed, (2) acknowledged, (3) collaborative, and (4) virtual. The modes are distinguished by the control mechanisms that exist for the SoS to operate.[22] At one end of the spectrum, the directed SoS control is exerted through hierarchical power, while at the other end, the virtual SoS control is achieved through influencing relationships. Consider the example of multi-site manufacturing, where supply networks are acknowledged SoS; the 'customer' in the supply network acts as the designated manager of the SoS, with the suppliers being able to retain their operational independence and financial autonomy. Meanwhile, other forms of multi-site manufacturing such as virtual enterprises, distributed manufacturing, dispersed network manufacturing, cloud manufacturing and manufacturing-as-a-service can be classified as being either acknowledged or collaborative SoS modes. Historically, multi-site manufacturing SoS involving multiple organisations have taken the form of the acknowledged SoS. While there are instances of virtual enterprises and organisations, these are far from common and the industry is gradually becoming aware of their appropriate adoption. Supporting the growth of collaborative SoS is the trend towards cloud manufacturing and manufacturing-as-a-service whereby customers have greater manufacturing choices and suppliers need to be more responsive to changes in customer requirements.

Note that SoS-level goals can rarely be optimised but instead be 'satisfied', and its goals are both numerous and dynamic. Each organisation or system within the SoS possesses its own goals and will seek to optimise its own operations. However, this local optimisation may be to the detriment of the effective operation of the SoS. In some SoS, there may be organisations that possess greater influence or control over the governance and operation of the SoS, which may enable local optimisation to be overcome. Considering again the example of the multi-site manufacturing domain, where an SoS most frequently takes the form of a supply chain or supply network. Such an SoS is commonly described as comprising a number of different 'tiers' of suppliers which describe their distance in the network from the organisation coordinating the SoS. Within these supply networks, individual suppliers have their own goals, which are not necessarily in alignment with the goals of the whole supply network. Thus, as the complexity of the SoS increases with the number of tiers and participants, so does the potential for divergent behaviours from within the SoS

[22] Dahmann (2008)

participants, with these behaviours amplified across the supply network. It is therefore proposed that investigations be conducted into how such local optimisation can be overcome, involving the creation of case studies focusing on the governance of SoS. Also, business models appropriate for SoS need to be studied in this context.
Beside questions of governance and business models, SoS bring with them also questions about how to manage the flow of intellectual property. While the operation of SoS may require that information and knowledge be shared across the members of the SoS, individual organizations may be reluctant to share IP in the manner necessary for the SoS to operate effectively. Clear frameworks are required for handling this IP. Guidelines need to be produced to help organisations understand the options available to them, with some standardised contract templates available to help organisations with little IP experience (such as SMEs and public entities) participate in SoS.

7.4 Education of SoS Stakeholders and Users

Education of SoS stakeholders is important with regard to two main challenges: a) To overcome resistance to change and b) to endow users with necessary knowledge to interact with SoS.

The resistance to change preventing SoS implementations is based on concerns related to stability, safety, security, privacy, risk-benefits-ratio, investment, which have been described in previous sections. While caution towards novel approaches is rational and to be respected, it can also be observed that resistance to change is frequently caused by a lack of knowledge about the technology. Due to this observation, it is essential for the wide-spread establishment of SoS to first spread the knowledge about SoS concepts and opportunities among stakeholders, i.e. decision makers and employees in order to create a foundation for acceptance of SoS.

Since SoS are complex IT systems, the employees etc. who will be operating them need to be aware of their basic principles in order to accept their new tasks, trust the overall systems, etc. However, humans interacting with – or: acting within – SoS cannot usually be expected to be endowed with a deeper technological understanding or education. For this reason, it is necessary to keep user interfaces as intuitive as possible (see also section 5.5) and to transfer some basic knowledge about SoS to them.

Both of these challenges can be addressed by appropriate education programs which have to be developed specifically for each target group. E.g. decision-makers have to be taught about the concepts and advantages of SoS, applicants have to be told about concepts, specific sub-systems and their usage.

7.5 Human Machine Interfaces for SoS Interaction

A human machine interface (HMI) is the device or system that realizes the interface between man and machine. Traditionally, these systems consist of panels composed of indicators and controls, such as pilot lights, digital and analog indicators, switches, selectors and others that were interconnected with the machine or process. For a long time, HMI design was about ergonomics. But already, much greater importance is rightfully attributed to HMI. In the context of SoS, HMI fulfil at least two important functions: They need to allow humans to interact simply and seamlessly with complex systems, and they need to present vast, complex data in a way so humans can make decisions based on them.

Regarding the first function: With complex systems, HMI determine how a system feels to a user and if the user is able to use the system to its full potential. The topic of interoperability among systems has already been discussed in section 4.1.3. HMI can be thought of resolving interoperability issues between humans and systems. But they are more than that; they have to fulfil an important complexity reduction role in their own right. Humans are linearly thinking animals and, as a famous quote goes, while humans will almost always be able to find an easy solution to a complex problem, it will also almost always be wrong.[23] Thus, HMI have to enable a human user to operate complex systems, while shielding its complexity. In a modern car, the driver is supported by numerous embedded systems but is able to interact with them at ease. A modern smartphone is a complex hardware-software system, yet this complexity is shielded from the user: The user is able to maximize the potential of the hardware in his hand, because the HMI enables him to do so, while effectively shielding its complexity. By way of introduction, the idea of the embedded human has been mentioned – the notion that humans will be increasingly outnumbered by the IT systems they are surrounded and supported by. In this dense mesh of IT systems HMI become highly relevant for they make humans and machines interoperable and make seamless interaction possible, employing multiple modalities (touch, voice, gestures etc.).

The complexity reduction role does also comprise the way information is presented to the human user, enabling him to make sound decisions based on large amounts of data, visually well presented to discern the information in this data (see also section on big-data-based decisions).

HMI to interact with SoS and its constituent systems could well be underestimated barriers. SoS must be usable for the common man in order to fulfil their potential: SoS can be complex, but interaction with them must not be complex. Usability of involved systems must not require an understanding of the SoS. Instead, interaction with complex SoS must be just as simply as the interaction with ones car of smartphone. Regarding the second function of HMI, namely to present vast, complex information adequate for human cognitive skills, so decision can be made based on them.
In order to avoid an impending complexity trap – a situation where humans are overwhelmed by the complexity of systems they depend on – efforts are required to provide HMI which fulfil the roles described above.

[23] As remarked by H.L. Mencken (1880 - 1956), American Journalist, Essayist, and Editor

8 Road2SoS Recommendation for Actions to be taken

The following table translates the overall Road2SoS findings into 'actionable Recommendations' for the European Commission.

Road2SoS Actionable Recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
Recommendations for SoS/CPS Implementation				
1. **Establishment of an SoS Engineering discipline**, offering generic methods and tools (i.e. domain-unspecific but generally applicable) along the entire life-cycle of an SoS	The SoSE discipline must not be established from scratch: Instead, it must inherit core concepts from the existing Systems Engineering (SE) discipline. Involvement and commitment of existing SE communities (such as INCOSE) must be ensured to achieve a sustainable SoSE discipline. A sound understanding of the needs in multiple SoS application domains based on a comprehensive collection of use cases from multiple application domains needs to be established to ensure that devised SoSE methods and tools will be applicable and useful to each application domain, despite their generic nature.	An SoSE discipline would offer powerful, generic, i.e. widely applicable approaches and tools to deal with SoS along the entire life-cycle. Due to the general applicability of these SoSE tools and approaches, SoS could be successfully designed, tested, built, operated, maintained, and phased-out in any application domain. Based on the same, proven engineering principles, economically beneficial, sustainable, resilient, safe, secure and thus societally accepted SoS can come into existence.	A serious barrier could be a lack of endorsement by the existing SE community resulting in a lack of trust for the enhancement of SE to SoSE. A crucial factor for success is the bottom-up foundation, i.e. the SoSE discipline must offer precisely the answers to SoS-related engineering problems experienced in application domains, otherwise the developed methods and tools will remain theoretical constructs without any practical use and benefit to the application domains. Domain-specific terminology must not be underestimated when trying to impose generic SoS concepts. While concepts may be generic, domain-specific terminology may still be useful to encourage their application.	We recommend that the EC funds RIAs and CSAs concerned with the following: ▪ Establishment of engineering methods and tools to deal with SoS in each stage of their life-cycle. Research is required in particular in the directions of modeling and simulation of SoS (early in life-cycle), emergent behavior (early to mid-life-cycle), graceful degradation of SoS (end of life cycle). ▪ Establishment of an SoSE task force embedded in, or tighly linked to, existing SE communities. ▪ Coordination among all projects the output of which can be considered contributions to an SoSE discipline; consolidating the existing body of knowledge and competencies in SoSE.

Road2SoS Actionable Recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
2. **Establishment of SoS demonstrators** in application domains	Successful establishment and operation of demonstrators would require an at least partially established SoSE discipline (see #1). At the same time, the establishment of demonstrators can be expected to be the cradle of new engineering approaches and best-practices which would further add to the body of the SoSE discipline.	With any novel technology, working demonstrators are the single most effective way of alleviating concerns and raising interest in its application, to benefit from its advantages. It is reasonable to expect this for SoS as well. The impact in SoS application domains will thus be: reduced concerns and increased eagerness to implement an SoS concept. As a consequence, SoS adoption will increase, constituting ever more demonstrators, and thus self-reinforce SoS adoption.	It is in the nature of SoS that they are rather large in scale. Thus, a useful demonstrator will require the involvement of a large number of systems which may require the involvement of a large number of owners of existing systems and/or substantial capital investment to build the SoS from scratch. These aspects may impede the development of convincing SoS demonstrators.	We recommend that the EC funds IAs or RIAs concerned with SoS demonstration activities, overcoming the described barriers. In such projects, special attention should be on the following aspects: ▪ Coverage of the whole SoS integration (vertical and horizontal) and usage of appropriate intelligent IT-tools. In the manufacturing domain, for instance, participants from sensor / CPS / equipment level up to SCM level should be involved. For horizontal integration, several manufacturing sites or companies should be involved. Integration of additional sites could e.g. also take place via open calls intending to establish virtual production networks managed by the SoS technologies to be demonstrated. It would also be imaginable to demonstrate results from different projects jointly (in order to cover the whole horizontal and vertical value chain). Such consortia could be established by clustering / networking of projects associated to certain calls / topics. ▪ Showing clear economic benefit (by means of exemplary ROI calculations, lead time analysis before and after applying SoS technologies, etc.) of the respective SoS implementation. ▪ Applicability not only for the demonstrating parties, but also for further potential applicants (e.g. consortium-externals which evaluate the related application cases and SoS implementation by means of validation workshops etc.)

Road2SoS Actionable Recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
3. **Support standardisation** / harmonisation of existing standards	Commitment by leading industry players in multiple domains to engage in the definition of a novel standard. Identification of relevant standards (e.g. SEMI, SiLA, Odette, RosettaNet, etc. in the case of the manufacturing domain), their focus, potential gaps in standardization and current disadvantages (e.g. enormous complexity / implementation effort).	Fast and faultless integration of SoS (horizontal, e.g. various partners in a production network, and vertical, e.g. from the sensor / equipment to the supply chain management system) enables fast reaction to changing demands / conditions.	Key industry players may want to keep their competitive position by maintaining certain standards without considering the overall benefit for the domain of more general standards and harmonization. A lack of endorsement of the standardization effort could impede the take-up of the standard, strongly limiting the effect of the standardization effort.	We recommend that the EC funds CSAs concerned with: ▪ Supporting the definition / harmonization of SoS integration standards (e.g. for the manufacturing domain), considering vertical and horizontal integration aspects. ▪ Supporting the creation of guidelines for fast adaption of the developed standards and their integration with business processes. ▪ Supporting the set-up of consistent evaluation environments showing the benefits of the newly defined / harmonized standards. ▪ Supporting and monitoring the implementation of strategies for standard-roll-out and development, which make sure that standards are accepted by industry / applicants (e.g. due to reduced complexity, coverage of domain-specific requirements, acceptance / implementation by key players, etc.)

Road2SoS Actionable Recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
4. Development of SoS-enabled business models	No pre-conditions. However, in order for novel business models to be successfully applied, convincing demonstration of SoS benefits, and alleviation of concerns will be necessary (achievable via recommendations #1, #2, and #3).	While SoS will support traditional ways of doing business in multiple application domains, they will likely enable entirely new ways of value creation. Thus, the economic benefits of SoS will only be fully appreciated if novel business models are investigated.	No barriers are expected regarding the investigation of novel business models.	We recommend that the EC funds CSAs concerned with the development of novel SoS-based business models. Aspects to be considered: ▪ Multiple ownership in SoS: Efficient and ad-hoc collaboration of multiple legal entities and sharing economic benefits and losses ▪ Platforms to standardize procedures/ contracts ▪ Frameworks for handling intellectual property in SoS ▪ Collaboration platforms and tools for coordinated planning and decision making which allow efficient real-time information sharing across organizational boundaries, mindful of intellectual property and roles. (Such platforms need to support decision makers with the necessary information to decide when to optimize a constituent system at the system level and when to favour optimization at the SoS level, for a common goal.)

Technological Recommendations

Road2SoS Actionable Recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
5. Advancement of technologies for real-time, low-latency communictation	No pre-conditions.	With SoS, the possibility of more informed decisions arises, based on context provided by the large number of systems and sensors in the SoS. In this regard, real-time communication enables a shift from making decisions in reporting mode, based on old information of the past, to decisions based on the *now*. Real-time, low-latency communication becomes necessary when it comes to time-critical coordination and control tasks within the SoS.	No particular barriers.	We recommend that the EC funds research to investigate low-latency, real-time communication among a very large number of systems. Reliable methods to achieve this are to be investigated, especially in safety-critical systems.
6. Research on interoperability mechanisms	No pre-conditions.	To aggregate systems into an SoS, and to achieve coordina-ted action of these systems, interoperability is a funda-mental condition. Since SoS may be formed from systems which are heterogeneous in terms of technological gene-ration, standards, etc. inte-gration entails considerable effort and can certainly not take place in the ad-hoc fashion one might need to flexibly or at least cost-efficiently form an SoS.	No particular barriers.	While standardization of interfaces and protocols is certainly necessary in many domains, it falls short of solving the problem. Approaches which would allow to embrace the heterogeneity of systems and to ensure they can form an SoS, despite their variety, would be required. We recommend that the EC funds further research in this direction. Furthermore, approaches need to be developed to network legacy systems which have not been designed to be networked or to exchange information.

Road2SoS actionable recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
7. Advancement of smart sensor technologies, sensor data fusion approaches, and efficient handling of big data	No pre-conditions.	An important species in SoS are sensors, either stand-alone sensors with connec-tivity to an SoS or sensors which are a built into systems which are in turn connected to the SoS. The continuous acquisition by a large number of sensors will give rise to very large quan-tities of data. In this context smart sensors have an important role in perform-ing data reduction. Beyond the need for these sensors to be low-powered, potentially energy-harvesting devices, with energy efficient-connectivity, efforts have to be made to realize advanced analytics capabilities at the sensor level, at very low power consumption. Upwards from the sensor level, important information can be derived by means of *sensor data fusion*, referring to methods of treating, correlating, or reducing data from sensors – again playing an important role in handling the amount of gathered data efficiently.	No particular barriers.	We recommend that the EC funds research to enhance the capabilities of smart sensors: ▪ Leveraging their potential in big data handling/reduction ▪ Providing advanced analytics capabilities at very low power consumption. Furthermore, research in the field of sensor data fusion is required to perform efficient pattern recognition and correlation across a very large number of data streams from distributed sensors, of heterogeneous type, with varying data quality.

Road2SoS actionable recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
8. Advancement of autonomous decision-making capabilities	No pre-conditions.	With the number of systems increasingly outnumbering the number of human beings on the planet, the involvement of humans in decision making must be limited to only the necessary cases. Achieving this capability is tied to a number of technological challenges.	Ethical concerns regarding the take-over of decisions by systems. An interim step towards fully autonomous decisions will likely be decision-support systems. Today, legislation defines the limits for the degree of autonomy in decision making. As concerns are being alleviated, legislative limits can be expected to be extended.	We recommend that the EC funds research to advance autonomous decision making capabilities: ▪ Firstly, there is a need for improved algorithms for automated reasoning and decision making, capable of taking into account data from distributed sources, data of varying temporal and spatial resolution and data of varying reliability. ▪ It needs to be ensured that decisions made on such basis are safe and maybe even ethical. This will have to involve research in the field of Artificial Intelligence and also in the field of Awareness. ▪ In order for systems or „agents“ to make decisions, self-awareness but also awareness for its surroundings and even for intentions of other systems and actors is necessary. A system would thus require a model of the environment it is embedded in. Since the model is created and updated from various sources of varying reliability, uncertainty quantification plays an important role. ▪ Furthermore, forecasting plays an important role since a system will need to know about likely trajectories of the current situation into the future, also to evaluate consequences of a system’s actions. ▪ Lastly, ways of knowing and understanding other systems’ actions and objectives need to be available.

Road2SoS actionable recommendation	Preconditions for the implementation of the recommendation	Impact (Benefit) of the recommendation	Expected resistance (barriers) to the implementation of the recommendation	Proposed EC-activity
9. Understanding of emergence	No pre-conditions.	In SoS, as in any complex system, emergence can be expected to be observed due to numerous interactions among constituent systems. From a classical engineering point of view, emergent behaviour is undesirable in the sense that it is unexpected system behaviour. But it may still be desirable due to the fact that it brings added functionality to the SoS.	No particular barriers.	We recommend that the EC funds research for a better understanding of emergence, the extent of its predictability, and ways of achieving emergence of desirable properties while limiting undesirable ones are necessary.

Table 4: List of actionable recommendations

9 CONTACT DETAILS

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Information and Communication Technologies (ICT) get increasingly integrated and embedded into our everyday environment. Becoming connected and intelligent, today's embedded systems evolve to Cyber-Physical Systems (CPS) and Systems of Systems (SoS). They represent a great opportunity for innovators and industry in Europe. In future, embedded ICT will become mainstream making smarter our homes, offices, factories, cars, trains, public spaces and cities.

This handbook was developed within the framework of the European project Road2SoS, coordinated by the Steinbeis-Europa-Zentrum, Germany. It presents strategic research and innovation roadmaps, comprising the latest high-level scientific results, developments, trends and innovation drivers relevant to CPS/SoS engineering and gives recommendations for future actions. It outlines which solutions are technically, socially and economically most promising and presents concepts to address existing societal needs. The Road2SoS roadmaps will help research institutions as well as companies to adapt their development of novel methodologies and engineering approaches for designing, developing and running these systems. Among the innumerable examples, systems for traffic control, energy distribution, emergency and crisis management and for controlling multi-site industrial production are elaborated in more detail within this handbook.

The Road2SoS booklet serves a strategic guide for further investment into CPS/SoS technologies and aligns future ICT research with needs, trends and demands of European businesses.

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