Core Research and Innovation Areas in Cyber-Physical Systems of Systems (CPSoS)

Initial Findings of the Support Action CPSoS, November 26, 2014

Summary

The CPSoS project is developing a roadmap for future research activities in Cyber-Physical Systems of Systems. To support this process, the project has set up three Working Groups to capture the views of industry and academia:

- Systems of Systems in Transportation and Logistics,
- Physically Connected Systems of Systems, and,
- Tools for Systems of Systems Engineering and Management.

The working groups currently comprise of 35 members, leading specialists from industry and academia, and include delegates from ongoing EU-funded projects in the area of Systems of Systems to ensure that as many views as possible are represented. A list of the members of the Working Groups can be found in the appendix.

This document presents preliminary findings and proposals that are put forward as a result of internal discussions in the consortium, in the three Working Groups (WGs) and at public meetings of the Working Groups. A number of meetings have been held starting with a joint meeting in January 2014 where the scope of cyber-physical systems of systems research and innovation was discussed and first proposals for research and innovation topics were collected and prioritized. A much wider consultation was then held via performance of a large number of interviews with representatives of industry in the domains of transportation and logistics, electrical grid management, the process industries and smart buildings.

The domain of cyber-physical systems of systems and the key research and innovation challenges in CPSoS were presented by the Coordinator and discussed at the HYCON II Final Workshop at the European Control Conference in June 2014 and in a Panel Discussion at the IFAC World Congress in August 2014. Interestingly, the views of leading experts from industry, academia and funding institutions from Europe, Japan and the US largely coincided in stressing the need to address system-wide issues in present-day socio-technical systems.

A second round of Working Group meetings with wider external participation of key actors from their domains was organized in September/October 2014. Here the initial findings were presented and further additional input on research and innovation priorities was gathered.

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On the basis of the input obtained by the interviews, the discussions in the WGs, and further discussions in the consortium, this first draft of a roadmap document for CPSoS has been produced identifying three key challenges:

- **Distributed, reliable and efficient management of cyber-physical systems of systems**
- **Engineering support for the design-operation continuum of cyber-physical systems of systems**
- **Cognitive cyber-physical systems of systems.**

This report firstly gives a brief overview of cyber-physical systems of systems, their specific features and challenges in operation and design. Building upon this analysis, the three main areas that have been identified as key for future research and innovation are then outlined.

This initial document will be posted for public consultation in January 2015. After receiving feedback from the WG members and from the public, a matured roadmap document will be prepared and sent to the Commission by April 2015.

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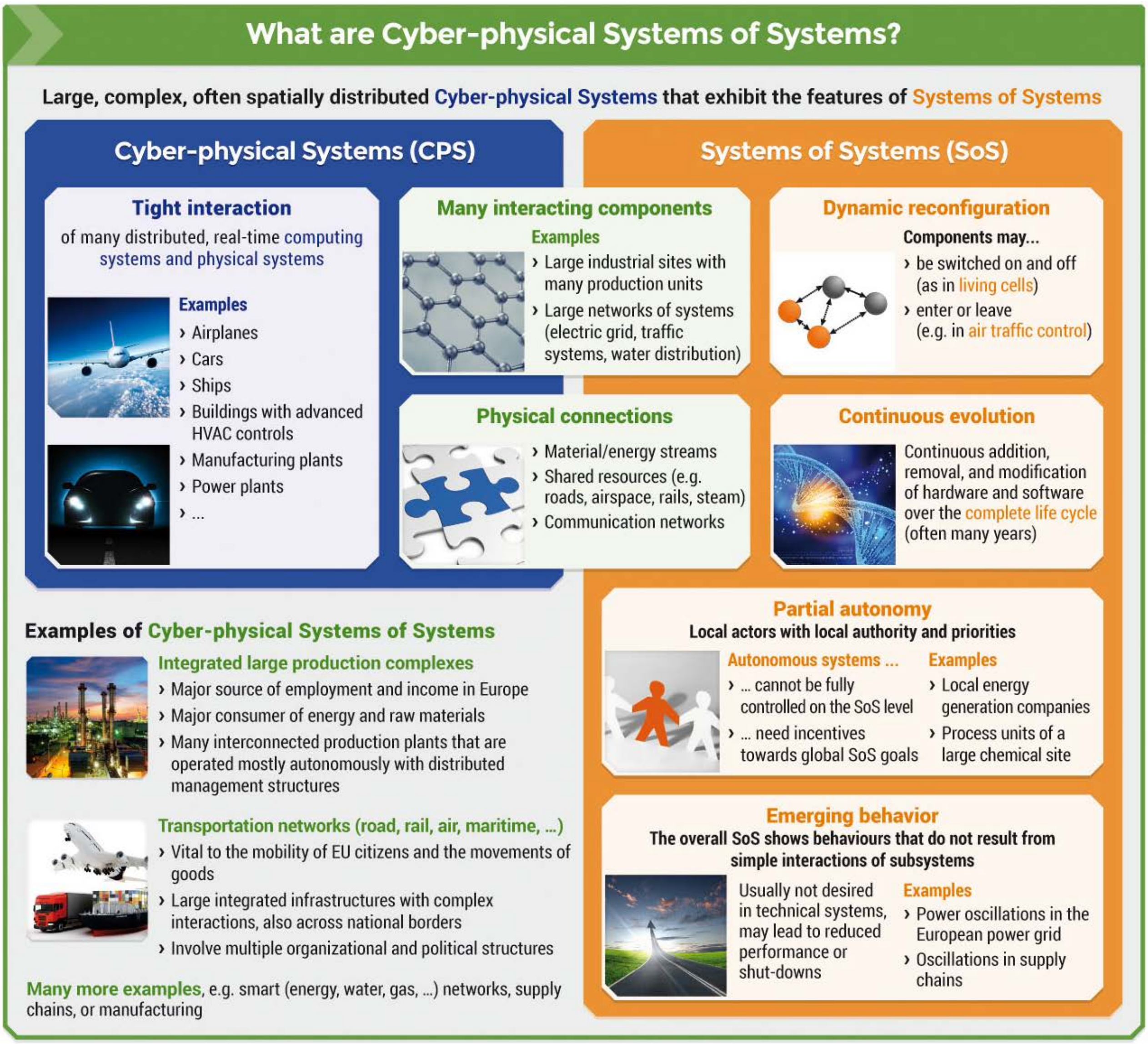
1. Cyber-Physical Systems of Systems and Their Role in Europe

The concept of Systems of Systems (SoS) has been developed to characterize large, distributed systems that consist of interacting and networked, but partially autonomous, elements and can show emergent behaviour. Generic approaches to the analysis, design, management and control of systems of systems has become an active domain of research in recent years at the interface of various disciplines, such as computer science, systems and control, and systems engineering. Cyber-physical systems are large complex physical systems that interact with a considerable number of distributed computing elements for monitoring, control and management. Additionally, they can exchange information between themselves and with human users. The elements of the physical system are connected by the exchange of material, energy, or momentum and/or the use of common resources (roads, rail-tracks, air space, waterways) while the elements of the control and management system are connected by communication networks which may impose restrictions on the frequency and speed of information exchange.



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Cyber-physical Systems of Systems (CPSoS) are cyber-physical systems which exhibit the features of Systems of Systems:

- Large, often spatially distributed physical systems with complex dynamics
- Distributed control, supervision and management
- Partial autonomy of the subsystems
- Dynamic reconfiguration of the overall system on different time-scales
- Continuous evolution of the overall system during its operation
- Possibility of emerging behaviours.

Examples of cyber-physical systems of systems are the electrical grid, a power plant, an airplane or a ship, a manufacturing process with many cooperating elements as e.g. robots, machines, warehouses, and conveyer belts, a large processing plant with many process units, a building with advanced distributed HVAC control, combined heat and power generation, etc.

Cyber-physical systems of systems are of crucial importance for the well-being of the citizens of Europe as they represent some of the most important infrastructures, e.g. systems for the generation and distribution of electric energy, drinking water and gas, rail, road, air and marine transportation systems and their elements, and large industrial production processes.

The engineering and operation of SoS must build upon theories, tools and knowledge from a large number of domains, from population dynamics and nonlinear systems theory over advanced modelling, simulation, optimisation and signal processing to software engineering, computer networks, validation and verification and user interaction. The need for an interdisciplinary approach is even more pronounced for cyber-physical SoS where the knowledge about the physical side of the systems is indispensable to arrive at solutions that are taken up in the real world. To integrate these diverse research and development communities to realise the opportunities and to respond to the challenges of large-scale, interconnected, distributed synergistic systems and to mitigate the associated risks and challenges is the most crucial aspect for a successful future development of the domain of CPSoS. Relevant theory and tools for CPSoS can only be developed with awareness and in-depth knowledge of application needs and industry trends.

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2. Features of Cyber-Physical Systems of Systems and Industrial Challenges in their Development and Operation

In this section the key features that characterise Cyber-Physical Systems of Systems are highlighted. This is put into context of real applications to explain the key challenges faced by industrial developers of such systems. Major challenges are in dealing with constantly evolving, highly complex systems with distributed management, a mixture of autonomous and human control interactions, and dynamic reconfiguration to deal with local failure management.

Size and distribution

The Cyber-physical systems of systems comprise a *significant* number of *interacting* components that are (partially) physically coupled and together fulfil a certain function, provide a service, or generate products. The components can provide services independently, but the performance of the overall system depends on the "orchestration" of the components. The physical size or geographic distribution of the system are not essential factors to make it a system of systems, but rather is its complexity. A factory with many "stations" and materials handling and transportation systems is structurally not much different from a large rail transportation network that extends over several countries and may have a similar number of nodes.

Examples of CPSoS are rail and road transport systems, power plants, large production facilities, gas pipeline networks, container terminals, water systems, supply chains and many more.

A distinguishing feature for a system of systems is that at least some of the components can provide useful services also independently. So a car engine with several controllers that are connected by a communication system is a cyber-physical system, but the components only provide a useful function together with the engine, and there is no local autonomy of the subsystems but only a distributed deployment of control functions on pieces of hardware.

Control and management

Due to the scope and the complexity of the overall system or due to the ownership or management structures, the control and management of CPSoS cannot be performed in a completely centralized or hierarchical top-down manner with one authority tightly controlling and managing all the subsystems. Instead, there is a significant distribution of authority with partial local autonomy, i.e. partially independent decision making.

The distribution of the management and control structure usually follows the physical distribution of the system elements. Large systems are always controlled in a hierarchical and distributed fashion where local "uncertainties", e.g. the effects of non-ideal behaviours of components or of disturbances, are reduced by local control. In conventional automated systems, however, usually there is no local decision making; the subsystems provide a defined service to the overall system and fulfil no local management tasks, perform optimization etc. In cyber-physical systems of systems, there are partly autonomous human or automatic decision makers that steer the subsystems according to local priorities. The "managerial element" of the components of the management and control systems in cyber-physical systems of systems goes beyond

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classical decentralized control where decentralized controllers control certain variables to externally set reference values.

Communication between the physical sub-systems and the control and management of sub-systems takes place via sensors and actuators and various types of communication channels, from wires to connections over the internet that may be unreliable or have limited bandwidth. The elements of the management and control systems similarly communicate via suitable channels. Internet communication mechanisms and wireless channels have provided a much greater connectivity of distributed system elements and this trend will continue ("Internet of Things"). CPSoS research and innovation is about how to *use* this connectivity for better management and control of the overall systems of systems. The increased connectivity is an enabler for better monitoring, management and control. Internet connectivity adds a significant element of flexibility but also of vulnerability to technical systems that can have consequences that go far beyond issues of privacy, as potentially large damages (accidents, power outages, standstills) can be caused. Therefore, security against unauthorized access is a major system issue, and detection of manipulated signals or commands are important aspects of CPSoS design.

For cyber-physical systems of systems, the management of the overall system as well as of its sub-systems will usually not only be driven by technical criteria but rather by economic, social, and ecologic performance indicators, e.g. profitability, acceptance and satisfaction of users, and environmental impact. Technical performance criteria usually either constrain the operating range or are intermediates to achieve the real performance goals. CPSoS are managed by humans, and many performance criteria concern providing services to human users. Thus, cyber-physical systems of systems have to be addressed as socio-technical systems with the specific feature of a large technical/physical structure that determines and constrains the behaviour of the system to a large extent.

Partial autonomy

Partial autonomy of the subsystems both in terms of their independent ability to provide certain services and of partial autonomy of their control and management systems is essential in the definition of CPSoS. Often, the sub-systems can exhibit "selfish" behaviour with local management, goals, and preferences. The autonomy can in particular result from human users or supervisors taking or influencing the local decisions. The decision structures of the overall system can vary largely, from a (possibly multi-layered) hierarchy, where goals for the sub-systems are set but the sub-systems have degrees of freedom how to reach their goals, to a fully decentralized structure where only technical constraints and economic incentives provide the "glue" between the sub-systems.

Autonomy is understood in this context as the presence of local goals that cannot be fully controlled on the system of systems level. Rather, incentives or constraints are given to the subsystem control in order to make it contribute to the global system targets. An example is the operation of units of a chemical plant that consume and produce steam as a necessary resource or by-product of their main task. Their operators or managers run their processes autonomously to achieve local goals and meet local targets. The site owner/operator sets mechanisms to negotiate about the steam generation/consumption in order to balance the steam network and in addition should provide suitable incentives so that the global profit of the site is maximized.

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If a subsystem is controlled by humans, there always is a certain degree of autonomy. As humans act following reasons, preferences, and emotions which are external to the technical system and are not controllable, their actions are not fully predictable.

Besides the possible selfishness of autonomous sub-systems, autonomy also describes the ability of a sub-system to cope with certain tasks, disturbances, faults, on its own, without intervention from the system of systems level. The autonomous sub-systems can absorb variability and to the outside show a more predictable behaviour than what would result without their ability to regulate, react, and compensate disturbances. Ideally, a subsystem is given a task and fulfils the task (or "contract") under any circumstance, and the higher level can ignore the details of the behaviour of the autonomously controlled subsystem.

Autonomy can lead to self-organizing systems: Consider the flow of cars in a city when there is a new construction site. Due to their autonomous intelligence, the drivers seek new paths, quite predictably, and after a few days each one re-optimizes her or his route to minimize travel time, and a new flow pattern establishes itself. This may not be provably optimal, but the autonomous actions of the "agents" lead to resilience of the overall system.

Dynamic reconfiguration

Dynamic reconfiguration, i.e. the frequent addition, modification or removal of components is a widespread phenomenon in CPSoS. This includes systems where components come and go (like in air traffic control) as well as the handling of faults and the change of system structures and management strategies following changes of demands, supplies or regulations.

Fault detection and handling of errors or abnormal behaviours is a key issue in cyber-physical systems of systems design and operation. Due to the large scale and the complexity of CPSoS, failures occur all the time in a CPSoS. The average system performance, as well as the degree of satisfaction of the users, is strongly affected by the impact of unforeseen events and outer influences that require non-continuous actions and cannot be compensated on the lower system levels. There is a massive need for detecting such situations quickly and, if possible, preventing them, and for fail-soft mechanisms and resiliency and fault tolerance at the systems level. The handling of faults and abnormal behaviour is challenging from a systems design point of view as in many cases it cannot be done optimally by a design based on separation of concerns but requires a trans-layer design of the reaction to such events.

Living cells with their multiple metabolic pathways are an example of a system that has optimized its ability to reconfigure itself to cope with changing conditions (availability of nutrients and other external factors) by keeping many options (metabolic pathways) intact and being able to switch between them. They may be used as a paradigm for the design of resilient CPSoS that do not operate in a strictly controlled environment.

Continuous evolution

Cyber-physical systems of systems are large systems that operate and are continuously improved over long periods of time. In many systems, from railways to chemical plants, the hardware (real physical hardware) infrastructure "lives" for 30 or more years, and new functionalities or improved performance have to be realized with only limited changes of many parts of the overall system. Management and control software as well usually has long periods of service, while the computing hardware base and the communication

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infrastructure change much more rapidly. Components are modified, added, the scope of the system may be extended or its specifications changed. So engineering to a large extent has to be performed at runtime.

The waterfall paradigm "Requirements – modelling – model-based design – verification – commissioning – operation - dismantling" is not applicable in its pure form to systems of systems where the requirements change during operation.

It was reported from the aerospace industry that systems engineers are often stuck in a "requirements first" clean sheet design paradigm and are used to having a level of control over all system elements that is not available to them in systems of systems engineering. Hence there is a need for a scientific foundation to handle multi-layer operations and multiple life cycle management.

Specification needs to be particularly thorough in the context of systems of systems, and should be as simply and clearly articulated as possible. Testing also needs to be thorough in the context of real systems of systems and must include also "mis-use cases". Once rolled out, operating and maintaining a system of systems requires a good knowledge of the "as-deployed-and-configured" system's physical, functional and behavioural configuration. Here the aviation industry has great experience.

When a new system is developed and deployed, the two activities of design and operational management usually can clearly be distinguished and often different groups of people are responsible for them. But later, the distinction is blurred, the experience gained in (day-to-day) management must be taken into account in revisions, extensions etc., and the operational management must also take care of the implementation of engineered changes in a running system. Validation and verification has to be done "on the fly". This integration strengthens the role of models in both engineering processes. Up-to-date (because continuously updated) models of the running operation can be used for both purposes. If they are adapted to the real operational practice, they reflect reality better than the original engineering models and can be used to investigate options for modifications as well as improved operational policies without modifications. The engineering of system of systems requires methods and tools that can be used seamlessly during design as well as operation (design-operations continuum).

Possibility of emerging behaviours

Emerging behaviours are an issue that is highly disputed. It is a simple and often stated fact that the system as a whole is more than its parts and can provide services that the components cannot provide autonomously. Sometimes the term emerging behaviour is used for the consequences of simple dynamic interactions, e.g. that a feedback loop that consists of stable subsystems may become unstable (and vice versa), or of design flaws due to an insufficient consideration of side-effects. The term emerging behaviour however seems more appropriate for the occurrence of patterns, oscillations or instabilities on a system-wide level, as it may occur in large power systems or in transportation systems, and to self-organization and the formation of structures in large systems.

Emerging behaviour should be distinguished from cascades of failures, like if a traffic jam on one motorway leads to one on the alternative route. However, if faults lead to instabilities and possible breakdowns of a large system due to "long-range interactions" in the system, like in power blackouts, then this can be called emerging behaviour. In technical systems, emerging behaviours usually are seen as problematic as a predictable behaviour of the system is preferred. On the other hand, in large systems with subsystems that show significant diversity in their behaviours, the formation of stable structures on a higher level due to the

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interactions between the subsystems despite their local diversity is very important and enables the design and management of the overall system without precise knowledge of all its elements. Emerging behaviour should be addressed both from the side of system analysis – under which conditions does emerging behaviour occur – and from the side of systems design – how can sufficient resiliency be built into the system such that local variations, faults, and problems can be absorbed by the system or be confined to the subsystem affected and its neighbours and do not trigger cascades or waves of problems in the overall system. Formal verification (e.g. assume/guarantee reasoning) as well as dynamic stability analysis for large-scale systems are possible approaches to prove the non-existence of unwanted emerging behaviours.

Cyber-physical systems of systems cannot be designed and managed using theories and tools from only one single domain. The behaviour of the large coupled physical part of the system must be modelled, simulated and analysed using methods from continuous systems theory, e.g. large-scale simulation, stability analysis, and design of stabilizing control laws. Also methods and tools from computer science for the modelling of distributed discrete systems, for verification and testing, assume-guarantee methods, contract-based assertions etc. are indispensable to capture both the behaviour on the low level (discrete control logic, communication, effects of distributed computing) and global effects, in the latter case based on abstract models of complete subsystems. Logistic models as well as models and tools for performance analysis of discrete systems will be useful for system-wide performance analysis. Finally, theories from physics, e.g. structure formation in large systems, and from economics and social science (market mechanisms, evolution of beliefs and activity in large groups) may also prove to be useful.

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3. Enabling CPSoS Technologies and Methodologies

In order to build and to operate cyber-physical systems of systems, knowledge and technologies from many domains are needed. We distinguish between enabling technologies that are required to realize cyber-physical systems of systems but are developed independently and for a broad range of purposes, and core technologies that are specific and have to be specifically developed for cyber-physical systems of systems.

Examples of enabling technologies and methodologies:

- Communication technologies and communication engineering. Standardized protocols, exploiting the Internet of Things, e.g. interactions between phone and car, to provide new functionality/services, LiFi – light communications.
- Computing technologies, high-performance and distributed computing. Multicore computing and new computer architectures to deal with more data and provide localised processing, low power processing for ubiquitous installation (with energy harvesting supplies), ability to implement mixed criticality on multicores.
- Sensors, e.g. energy harvesting, Nano NEMs sensors - the next generation beyond MEMs.
- Management and analysis of huge amounts of data ("big data").
- Human-machine interfaces, e.g. head up displays, display glasses, polymer electronics and organic LEDs to display information.
- Dependable computing and communications.
- Security of distributed/cloud computing and of communication systems.

Research and innovation in these areas contributes strongly to the ability to build more efficient and more reliable cyber-physical systems of systems , but have broader applications. CPSoS research and innovation includes investigating how to best make use of these technologies and to trigger and jointly perform specific CPSoS-related developments.

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4. Key Research and Innovation Challenges in Cyber-Physical Systems of Systems

Challenge 1: Distributed, reliable and efficient management of cyber-physical systems of systems

Due to the scope and the complexity of Cyber-Physical Systems of Systems as well as due to ownership or management structures, the control and management tasks in such systems cannot be performed in a centralized or hierarchical top-down manner with one authority tightly controlling all subsystems. In cyber-physical systems of systems, there is a significant distribution of authority with partial local autonomy. The design of such management systems for reliable and efficient management of the overall systems poses a key challenge in the design and operation of cyber-physical systems of systems.

The following sub-topics should be addressed:

- Decision structures and system architectures
- Self-organization, structure formation, and emergent behaviour in technical systems of systems
- Real-time monitoring, exception handling, fault detection and mitigation of faults and degradation
- Adaptation and integration of new components
- Humans in the loop and collaborative decision making
- Trust in large distributed systems.

Decision structures and system architectures

The interaction and coordination of dynamic systems with partial autonomy in systems of systems, possibly with dynamic membership, must be studied broadly. Examples of applicable methods are population dynamics and control and market-based mechanisms for the distribution of constraining resources. The partial autonomy of the components from the overall system of systems perspective leads to uncertainty about the behaviour of the subsystems. Therefore the system-wide coordination must take into account uncertain behaviour and must nonetheless guarantee an acceptable performance of the overall system. Stochastic optimization and risk management must be developed for CPSoS. It must be understood better how the management structure (centralized, hierarchical, distributed, clustered) influences system performance and robustness.

Self-organization, structure formation, and emergent behaviour in technical systems of systems

Due to local autonomy and dynamic interactions, cyber-physical systems of systems can realize self-organization and exhibit structure formation and system-wide instability, in short, emergent behaviour. The prediction of such system-wide phenomena is an open challenge at the moment. Distributed management and control methods must be designed such that CPSoS do not show undesired emerging behaviour. Inputs from the field of dynamic structure or pattern formation in large systems with uncertain elements must be combined with classical stability analysis and assume-guarantee reasoning. Methods must be developed such that sufficient resiliency is built into the system so that local variations, faults, and problems can be absorbed by the system or be confined to the subsystem affected and its neighbours and no cascades or waves of disturbances are triggered in the overall system.

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Real-time monitoring, exception handling, fault detection, and mitigation of faults and degradation

Due to the large scale and the complexity of systems of systems, the occurrence of failures is the norm in CPSoS. Hence there is a strong need for mechanisms for the detection of abnormal states and for fail-soft mechanisms and fault tolerance by suitable mechanisms at the systems level. Advanced monitoring of the state of the system and triggering of preventive maintenance based on its results can make a major contribution to the reduction of the number of unexpected faults and to the reduction of maintenance costs and downtimes. Faults may propagate over the different layers of the management and automation hierarchy. Many real-world SoS experience cascading effects of failures of components. These abnormal events must therefore be handled across the layers.

Adaptation and integration of new or modified components

Cyber-physical systems of systems are operated and continuously improved over long periods of time. New functionalities or improved performance have to be realized with only limited changes of many parts of the overall system. Components are modified and added, the scope of the system may be extended or its specifications may be changed. So engineering to a large extent has to be performed at runtime. Additions and modifications of system components are much facilitated by plug-and-play capabilities of components that are equipped with their own management and control systems ("decentralized intelligence").

Humans in the loop and collaborative decision making

HMI concepts, i.e. filtering and appropriate presentation of information to human users and operators are crucial for the acceptance of advanced computer-based solutions. Human interventions introduce an additional nonlinearity and uncertainty in the system. Important research issues are the human capacity of attention and how to provide motivation for sufficient attention and consistent decision making. It must be investigated how the capabilities of humans and machines in real-time monitoring and decision making can be combined optimally. Future research on the monitoring of the actions of the users and anticipating their behaviours and modelling their situation awareness is needed. Social phenomena (e.g. the dynamics of user groups) must also be taken into account.

Trust in large distributed systems

Cyber-security is a very important element in cyber-physical systems of systems. A specific CPSoS challenge is the recognition of obstructive injections of signals or takeovers of components in order to cause malfunctions, suboptimal performance, shutdowns or accidents, e.g. power outages. The detection of such attacks requires taking into account both the behaviour of the physical elements and the computerized monitoring, control and management systems. In the case of the detection of unsecure states, suitable isolation procedures and soft (partial) shut-down strategies must be designed.

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Challenge 2: Engineering support for the design-operation continuum of cyber-physical systems of systems

While model-based design methods and tools have been established in recent years in industrial practice for traditional embedded systems, the engineering of cyber-physical systems of systems (CPSoS) poses key challenges that go beyond the capabilities of existing methodologies and tools for design, engineering, and validation. These challenges result directly from the constitutive properties of CPSoS:

- CPSoS are continuously evolving which softens, or even completely removes, the traditional separation between the engineering/design phases and the operational stages,
- The high degree of heterogeneity and partial autonomy of CPSoS requires new, fully integrated approaches for their design, validation, and operation,
- CPSoS are highly flexible and thus subject to frequent, dynamic reconfiguration, which must be supported by design support tools to enable efficient engineering,
- Failures, abnormal states, and unexpected/emerging behaviours are the norm in CPSoS, and
- CPSoS are socio-technical systems in which machines and humans interact closely.

The efficient design and operation of such systems requires new design support methodologies and software tools in the following areas:

- Integrated engineering of CPSoS over their full life-cycle,
- Modelling, simulation, and optimization of CPSoS,
- Establishing system-wide and key properties of CPSoS,

Integrated engineering of CPSoS over their full life-cycle

The disappearance of the separation between the design and engineering phases and the operational stage necessitates new engineering frameworks that support the specification, adaptation, evolution, and maintenance of requirements, structural and behavioural models, and realizations not only during design, but over their complete life cycle. The challenges in rolling out systems of systems are the asynchronous lifecycles of the constituent parts and also the fact that many components are developed independently and that legacy systems may only be described insufficiently.

New engineering frameworks must enable the engineers to design fault-resilient management and control architectures by an integrated cross-layer design that spans all levels of the design and of the automation hierarchies, and by providing model-based analysis facilities to detect design errors early and to perform risk management. Such engineering frameworks must be integrated closely with industrial infrastructure (e.g. databases, modelling and simulation tools, execution and runtime systems, …).

CPSoS usually are not designed and maintained by a single company, but instead many providers of tools and hardware may be involved. Thus, collaborative engineering and runtime environments are essential that enable providers to jointly work on aspects of the CPSoS while competing on others. Integration must be based on open, easy-to-test interfaces and platforms that can be accessed by all component providers. Methods and software tools must provide semantic integration to simplify the interactions of existing systems as well as the deployment of new systems.

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The advantages of these new CPSoS technologies may not be immediately apparent to industrial users, in particular in smaller companies. Thus, the demonstration of industrial business cases and application results that clearly illustrate the benefits of these technologies is an important goal.

Modelling, simulation, and optimization of CPSoS

Challenges in modelling and simulation are the high cost for building and maintaining models, modelling of human users and operators, simulation and analysis of stochastic behaviour, and setting up models that include failure states and the reaction to abnormal situations for validation and verification purposes. Key for the adaptation of models during the life-cycle of a system and for reduced modelling cost are methodologies and software tools for model management and for the integration of models from different domains. Such model management requires meta-models.

Efficient simulation algorithms are needed to enable the system-wide simulation of large heterogeneous models of cyber-physical systems of systems, including dynamic on-the-fly reconfiguration of the simulation models that represent the reconfiguration of the underlying CPSoS. For performance and risk analysis, global high-level modelling and simulation of CPSoS is necessary including stochastic phenomena and the occurrence of abnormal states.

The model-based development of systems of systems necessitates collaborative environments for competing companies and the integration of legacy systems simulation as well as open approaches for tight and efficient integration and consolidation of data, models, engineering tools, and other information across different platforms. New business models may lead to a situation where for potential system components simulation models are delivered such that the overall system can be designed based on these models.

The real potential of model-based design is only realized if the models can be coupled to optimization algorithms. Single-criterion optimization of complex systems, including dynamic systems that are described by equation-based models has progressed tremendously in the recent decade. The next steps will be to develop efficient optimization tools for heterogeneous models, to progress towards global optimization and to use multi-criterial optimization in order to explore the design space.

Establishing system-wide and key properties of CPSoS

Establishment, validation, and verification of key properties of CPSoS is an important challenge. New approaches are needed for dynamic requirements management during the continuous evolution of a cyber-physical system of systems, ensuring correctness by design during its evolution, and for verification especially on the system of systems level. New algorithms and tools should enable the automatic analysis of complete, large-scale, dynamically varying and evolving CPSoS. This includes formal languages and verification techniques for heterogeneous distributed hybrid systems including communication systems, theory for successive refinements and abstractions of continuous and discrete systems so that validation and verification at different levels of abstraction are correlated, and the joint use of assume-guarantee reasoning and simulation-based (Monte Carlo) and exhaustive (model checking) verification techniques.

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Challenge 3: Cognitive cyber-physical systems of systems

Systems of Systems (SoS) by their very nature are large, distributed and extremely complex presenting a myriad of operational challenges. To cope with these challenges there is a need for improved *situational awareness.* Gaining an overview of the entire SoS is inherently complicated by the presence of decentralized management and control. The introduction of cognitive features to aid both operators and users of complex cyber-physical systems of systems is seen as a key requirement for the future to reduce the complexity management burden from increased interconnectivity and the data deluge presented by increasing levels of data acquisition. This requires research in a number of supporting areas to allow vertical integration from the sensor level to supporting algorithms for information extraction, decision support, automated and self-learning control, dynamic reconfiguration features and consideration of the sociotechnical interactions with operators and users. The following key subtopics have been identified as being necessary to support a move to Cognitive CPSoS.

- Situation awareness in large distributed systems with decentralized management and control
- Handling large amounts of data in real time to monitor the system performance and to detect faults and degradation
- Learning good operation patterns from past examples, auto-reconfiguration and adaptation
- Analysis of user behaviour and detection of needs and anomalies

Situation awareness in large distributed systems with decentralized management and control

In order to operate a system of systems efficiently and robustly there is a need to detect changes in demands and operational conditions (both of the equipment and outer factors) and to deal with anomalies and failures within the system. This can only be achieved via the introduction of much greater levels of data acquisition throughout the CPSoS and the use of this data for optimization, decision support and control. Here a key enabler is the introduction of novel, easy to install, low cost, sensor technologies and monitoring concepts. If wireless monitoring is to be used there is also a need for ultra-low power electronics and energy harvesting technologies to avoid the need for, and associated maintenance costs of, battery change. An increase in data gathering will also require robust wired and wireless communication protocols that can deal with efficient transmission of individual data values from a multitude of sensors to streaming of data at high data rates, e.g. for vibration and video monitoring.

Handling large amounts of data in real time to monitor the system performance and to detect faults and degradation

A challenge for the future will be the physical system integration of highly complex data acquisition systems and the management of the data deluge from the plethora of installed sensors and the fusion of this with other information sources. This will require analysis of large amounts of data in real time to monitor system performance and to detect faults or degradation. Here there is a need for visualization tools to manage the complexity of the data produced allowing managers to understand the “real world in real time”, manage risk and make informed decisions on how to control and optimize the system.

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Learning good operation patterns from past examples and auto-reconfiguration and adaptation

There is a great opportunity to aid system operators by incorporating learning capabilities within decision support tools to identify good operational patterns from past examples. Additionally, to deal with the complexity of managing system faults, which is a major burden for CPSoS operators, auto-reconfiguration and adaptation features can be built into the system.

Analysis of user behaviour and detection of needs and anomalies

Finally, it must be remembered that CPSoS are socio-technical systems and as such humans are an integral element of the system. Systems of systems thus need to be resilient to the effects of the natural unpredictable behaviour of humans. There is thus a need to continuously analyse user behaviour and its impact upon the system to ensure that this does not result in system disruption.

The end result of combining real world, real-time information for decision support with autonomous control and learning features will be to provide *Cognitive Cyber-Physical Systems of Systems* that will support both users and operators, providing situational awareness and automated features to manage complexity that will allow them to meet the challenges of the future.

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Appendix – List of CPSoS Working Group Members

WG1: Systems of Systems in Transportation and Logistics

Haydn	THOMPSON	Haydn Consulting Ltd (WG Chair / Consortium member)
John	AMOORE	Rail Infrastructure Technology Limited
Carlos	CANUDAS DE WIT	CNRS GIPSA-Lab
Uwe	CLAUSEN	Fraunhofer IML
Judith	DAHMANN	MITRE Corp.
Charles	DIBSDALE	OSyS (Rolls Royce)
Philippe	LIATARD	CEA – Leti
Antonio	PASCOAL	IST, Instituto Superior Tecnico
María Victoria	CENGARLE	fortiss GmbH – Delegate FP7 Project CyPhERS
Christina	DIAKAKI	Technical University of Crete – Delegate FP7 project Local4Global
Hermann	KOPETZ	TU Wien – Delegate FP7 project AMADEOS

WG2: Physically Connected Systems of Systems

Sebastian	ENGELL	Technische Universität Dortmund (WG Chair / Project Coordinator)
Göran	ANDERSSON	ETH Zürich
Vladimir	HAVLENA	Honeywell Prague Laboratory
Alf	ISAKSSON	ABB AB Västerås
Patrick	PANCIATICI	RTE - Réseau de Transport d'Electricité
Francesco	BRANCATI	ResilTech SRL – Delegate FP7 Project AMADEOS
John	FITZGERALD	Newcastle University – Delegate FP7 project COMPASS
Elias	KOSMATOPOULOS	Technical University of Crete – Delegate FP7 project Local4Global
Stefan	KRÄMER	INEOS in Köln – Delegate FP7 Project DYMASOS
John	LYGEROS	ETH Zürich – Delegate FP7 project DYMASOS and Local4Global
Radoslav	PAULEN	TU Dortmund (Consortium Member)

WG3: Tools for Systems of Systems Engineering and Management

Wan	FOKKINK	Technische Universiteit Eindhoven (WG Chair / Consortium member)
Alberto	BEMPORAD	IMT Lucca
Alessandro	CIMATTI	Bruno Kessler Foundation
Marika	DI BENEDETTO	University of l’Aquila
Peter	FRITZSON	Linköping University
Stefan	KOWALEWSKI	RWTH Aachen
Erwin	SCHOITSCH	AIT - Austrian Institute of Technology

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Wil	VAN DER AALST	Technische Universiteit Eindhoven
Peter Gorm	LARSEN	Aarhus University – Delegate FP7 Project COMPASS
Martin	TÖRNGREN	KTH Stockholm – Delegate FP7 project CyPhERS
Christian	SONNTAG	euTeXoo / TU Dortmund (Consortium member)
Michel	RENIERS	TU Eindhoven (Consortium member)
Bertrand	COPIGNEAUX	inno TSD (Consortium member)

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