Core Research and Innovation Areas in Cyber-Physical Systems of Systems

Initial Findings of the CPSoS Project

S. Engell[1], R. Paulen[1], M.A. Reniers[2(✉)], C. Sonntag[3], and H. Thompson[4]

[1] Process Dynamics and Operations, TU Dortmund, Dortmund, Germany
`{sebastian.engell,radoslav.paulen}@bci.tu-dortmund.de`
[2] Control Systems Technology, Eindhoven University of Technology (TU/e),
Eindhoven, The Netherlands
`m.a.reniers@tue.nl`
[3] euTeXoo GmbH, Dortmund, Germany
`info@eutexoo.de`
[4] Haydn Consulting Ltd, Sheffield, UK
`info@haydnconsulting.com`

Abstract. The CPSoS project is developing a roadmap for future research and innovation in cyber-physical systems of systems. This paper presents preliminary findings and proposals that are put forward as a result of broad consultations with experts from industry and academia, and through analysis of the state of the art in cyber-physical systems of systems.

1 Introduction

Cyber-physical systems of systems (CPSoS) are large physical systems as, *e.g.,* railway systems, the electric grid and production plants that consist of many interacting physical elements and of distributed IT systems for monitoring, control, and optimization and interaction with human operators and managers that are interfaced to the physical system elements and are interconnected via communication networks. These systems are of crucial importance for the welfare of the citizens of Europe as they represent some of the most important infrastructures and the backbone of the European economy.

Characteristic features of cyber-physical systems of systems are:

- Complex dynamics,
- Distributed control, supervision and management,
- Partial autonomy of the subsystems,

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- Dynamic reconfiguration of the overall system on different timescales,
- Continuous evolution of the overall system during its operation, and
- Possibility of emerging behaviours.

As cyber-physical systems of systems comprise physical elements as well as computing systems that are tightly coupled, the engineering and operation of these systems 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. Knowledge about the physical aspects of the systems as well as about the application domains 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.

The CPSoS project (www.cpsos.eu) is a Communication and Support Action that acts as an exchange platform for systems of systems (SoS) related projects and communities [10]. One of the main goals of the project is to develop a European research and innovation agenda on CPSoS. 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, led by Haydn Thompson, Haydn Consulting Ltd, United Kingdom,
- Physically Connected Systems of Systems, led by Sebastian Engell, TU Dortmund, Germany, and
- Tools for Systems of Systems Engineering and Management, led by Michel Reniers, Eindhoven University of Technology, Netherlands.

The working groups currently comprise of 36 members, leading specialists from industry and academia, and include delegates from ongoing EU-funded projects in the area of SoS to ensure that as many views as possible are represented. Information about the composition of these working groups can be found via www.cpsos.eu.

Based on input from the working group members, and extensive consultations with domain experts in three public meetings with over 100 participants, and more than 130 written contributions and interviews, a state of the art document was produced (www.cpsos.eu/state-of-the-art, [5]) and the proposals were synthesized into a first research and innovation agenda (www.cpsos.eu/roadmap, [4]). The agenda describes three main areas of research and development:

1. Distributed, reliable and efficient management of CPSoS,
2. Engineering support for the design-operation continuum of CPSoS, and
3. Cognitive CPSoS.

The contents of this paper is based on documents produced in the context of the CPSoS project [3–5]. An abstract of the research challenges has also been published in [11].

Below, these challenges are explained in more detail. First, Sect. 2 gives an overview of the properties of CPSoS. The specific features and challenges of CPSoS in operation and design are analysed in Sect. 3. Building upon this analysis, the three main areas that have been identified as key challenges for future research and innovation are then outlined in Sect. 4. Section 5 provides a summary of the paper.

2 Cyber-Physical Systems of Systems

The concept of *systems of systems* has been developed to characterize large, distributed systems that consist of interacting and networked, but partially autonomous, elements that together can show emergent behaviour [7,9]. Generic approaches to the analysis, design, management and control of SoS 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.

The CPSoS project has refined the above definitions into the following definition [3].

Definition 1. Cyber-physical systems of systems *are cyber-physical systems that exhibit the features of SoS:*

- *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 timescales,*
- *Continuous evolution of the overall system during its operation,*
- *Possibility of emerging behaviours.*

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

3 Features of CPSoS and Industrial Challenges in Their Development and Operation

In this section the key features that characterise CPSoS 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.

3.1 Size and Distribution

CPSoS 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.

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 not a system of systems, as 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.

3.2 Control and Management

Owing 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 CPSoS, 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 CPSoS goes beyond 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"). Research and innovation in CPSoS is about how to use this connectivity for better management and control of the overall SoS. 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 CPSoS, 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, satisfaction of users, and environmental impact. CPSoS are managed by humans, and many performance criteria concern providing services to human users. Thus, CPSoS 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.

3.3 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.

Autonomy is understood 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 and in doing so provides suitable incentives so that the global profit of the site is maximized.

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.

3.4 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 CPSoS design and operation. Due to the large scale and the complexity of CPSoS, failures occur all the time. 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. 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.

3.5 Continuous Evolution

CPSoS 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 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 V-model paradigm with consecutive phases: requirements – modelling – model-based design – verification – validation – commissioning – operation – dismantling, is not applicable in its pure form to SoS where the requirements change during operation. 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 SoS, and should be as simply and clearly articulated as possible. Testing also needs to be thorough in the context of real SoS 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. 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. The engineering of system of systems requires methods and tools that can be used seamlessly during design as well as operation (design-operations continuum).

3.6 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. 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.

3.7 Enabling Technologies and Methodologies

In order to build and to operate CPSoS, knowledge and technologies from many domains are needed. We distinguish between enabling technologies that are required to realize CPSoS but are developed independently and for a broad range of purposes, and core technologies that are specific and have to be specifically developed for CPSoS. The following are examples of enabling technologies/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 CPSoS, but have broader applications and includes investigating how to best make use of these technologies and to trigger and jointly perform specific developments related to CPSoS.

4 Key Research and Innovation Challenges in CPSoS

In this section, the identified key research and innovation challenges in the engineering and management of CPSoS are introduced.

4.1 Distributed, Reliable and Efficient Management of CPSoS

Due to the scope and the complexity of CPSoS 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 CPSoS, there is a significant distribution of authority with partial local autonomy. An illustrative example of such a system is a self-organizing automation system for coordinating smart components within the grid as presented in [1]. See Fig. 1 for an illustrative example. 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 CPSoS.

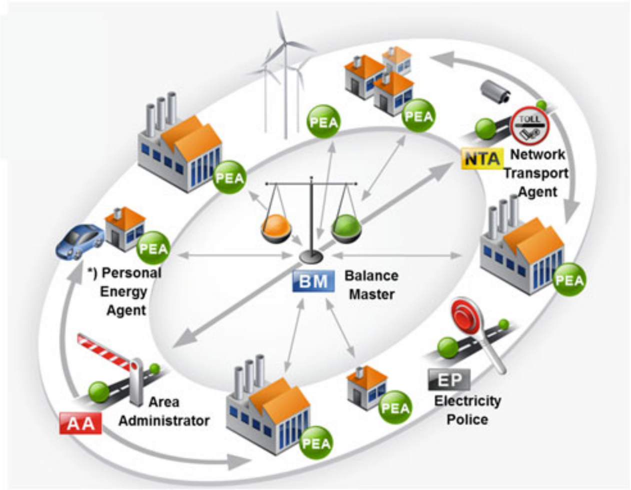

Fig. 1. Self-Organizing energy automation systems: coordinating smart components within the grid, from [1].

The following sub-topics should be addressed:

- Decision structures and system architectures,
- Self-organization, structure formation, and emergent behaviour in technical SoS,
- 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, and
- Trust in large distributed systems.

Decision Structures and System Architectures. The interaction and coordination of dynamic systems with partial autonomy in SoS, 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 SoS. Due to local autonomy and dynamic interactions, CPSoS 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.

Real-Time Monitoring, Exception Handling, Fault Detection, and Mitigation of Faults and Degradation. Due to the large scale and the complexity of CPSoS, the occurrence of failures is the norm. 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 downtime. 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. CPSoS 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 CPSoS. A specific 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 insecure states, suitable isolation procedures and soft (partial) shut-down strategies must be designed.

4.2 Engineering Support for the Design-Operation Continuum of CPSoS

While model-based design methods and tools have been established in recent years in industrial practice for traditional embedded systems, the engineering of 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

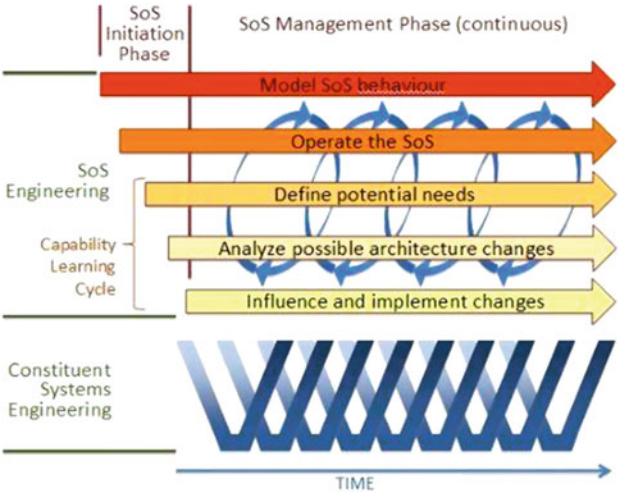

Fig. 2. DANSE system engineering life cycle, from [6].

specification, adaptation, evolution, and maintenance of requirements, structural and behavioural models, and realizations not only during design, but over their complete life cycle.

An example of such a life cycle is the DANSE system engineering life cycle shown in Fig. 2 which features a continuous SoS management phase [6]. The challenges in rolling out SoS are the asynchronous life cycles 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.

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 CPSoS, 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 SoS 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-criterion 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 CPSoS, 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.

4.3 Cognitive CPSoS

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 [2,8]. 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 CPSoS 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 socio-technical 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.

Learning Good Operation Patterns from Past Examples, 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. CPSoS are socio-technical systems and as such humans are an integral element of the system. SoS 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 CPSoS 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.

5 Summary

After a thorough investigation of the state of the art in the domains of transportation and logistics, electrical grids, processing plants, smart buildings, distribution networks and methods and tools for the engineering and management of CPSoS and discussions and consultations with stakeholders in the domains from industry and from academia, the project CPSoS has identified three core research and innovation areas for the next decade:

1. Distributed, reliable and efficient management of CPSoS,
2. Engineering support for the design-operation continuum of CPSoS, and
3. Cognitive CPSoS.

Important long-term research topics in these domains have been described above. CPSoS will continue to raise awareness about cyber-physical systems of systems and their importance for the welfare of Europe and will propose also shorter term research and innovation topics for national and European research and innovation funding.

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