PROPOSAL OF A EUROPEAN RESEARCH AND INNOVATION AGENDA ON CYBER-PHYSICAL SYSTEMS OF SYSTEMS

2016-2025

The CPSoS Project is supported by the European Commission under the FP7-ICT programme (contract no. 611115)

Preface

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This brochure presents the research and innovation agenda for the years 2016-2025 that is proposed by the European Project *CPSoS - Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-physical Systems of Systems* (October 1, 2013 - June 30, 2016). CPSoS has been funded under the 7th Framework Programme of the European Union.

In developing the research agenda, the CPSoS consortium followed a broad trans-disciplinary approach and established three thematic Working Groups on the following topics:

- Systems of Systems in Transportation and Logistics
- Physically connected Systems of Systems (electric grids, processing plants, distribution networks, smart buildings etc.)
- Tools for Systems of Systems Engineering and Management

Members of the Working Groups are representatives of industry (owner-operators and managers of transportation and production systems, solution providers and tool developers) and leading researchers with a variety of backgrounds in computer science, systems engineering, logistics, and systems and control. In these Working Groups, all currently ongoing EU-funded projects on systems of systems were represented. The members of the Working Groups are listed on the following page.

The discussions within the Working Groups and at public workshops were complemented by collecting questionaires and performing interviews with more than 100 domain experts. The experiences and views of the experts were discussed by the CPSoS consortium and have been integrated into this research and innovation agenda proposal.

In summary, the CPSoS team identified three core long-term research challenges that must be addressed in an inter-disciplinary manner and in collaboration of tool and solution providers, end-users, and research institutions:

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

In addition, we defined 11 medium-term research and innovation topics that should receive attention and funding during the next 5 years in order to advance towards meeting the core challenges. You find them at the end of this brochure.

I would like to thank all consortium members, Working Group members and experts for their most valuable inputs, and the European Commission for their support of the CPSoS project. We are grateful if you send additional feedback and comments on our findings and propositions to feedback@cpsos.eu.

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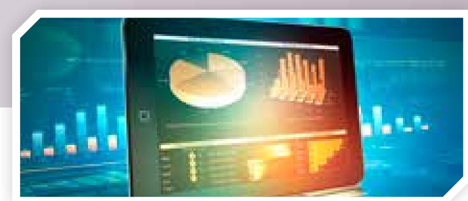

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Introduction

Cyber-physical Systems of Systems (CPSoS) are large complex systems where physical elements interact with and are controlled by a large number of distributed and networked computing elements and human users. Examples are railway systems, air traffic, future road traffic, logistic networks, the electric grid, industrial production sites, and smart buildings. These systems are vital to the competitiveness of the European industry as well as to the quality of living of the European citizens. They are subject to increasingly stringent demands on the reduction of emissions, efficient use of resources, high service and product quality levels and, last but not least, low cost and competitiveness on the world market.

For the satisfaction of these demands, information and communication technology (ICT) plays a major, if not decisive, role. Connectivity of all elements of the cyber-physical system of systems (called the Internet of Things) will provide large volumes of real-time information on the state of the physical system elements, e.g. the locomotives or the tracks of a railway system, on the demands of the customers, and on the performance and quality of service of the system. Connectivity between embedded systems and computing devices is predicted to grow massively over the coming years. Gartner [1], for instance, estimates that there will be 26 billion connected devices (excluding PCs, tablets, and smartphones) by 2020 world-wide, and even higher predictions of 40-50 billion devices are being made by other analyst companies. This equates to a global market value of $1.9 trillion, of which 80% is expected to come from services. Connectivity provides value only if the information is used for improved services, productivity, resource efficiency, and user satisfaction, i.e. if additional functionality is offered and the systems as a whole operate reliably and securely. The field of cyber-physical systems of systems deals with how to engineer and manage such large interconnected and continuously evolving systems and thus is fundamental to the realization of this market potential.

With the support of three Working Groups, the members of which are renowned industrial practitioners and academic experts, and building upon input from more than 100 external contributors, the European project *CPSoS - Towards a European Roadmap on Research and Innovation in Engineering and Management of Cyber-Physical Systems of Systems* (www.cpsos.eu) has developed a proposal for a research and innovation agenda for the field of engineering and management of cyber-physical systems of systems. The agenda identifies three *core challenges*, as well as *11 research and innovation priorities* that should be addressed in the medium term (i.e. within the next 5 years) to progress towards the solution of the core challenges.

The definition of the challenges and priority areas is based on a comprehensive survey of the state of the art and of the research and innovation needs in a variety of industrial sectors that provide and operate cyber-physical systems of systems. A key finding of the CPSoS project is that the identified challenges and priority areas are transversal, i.e. relevant to many different sectors of industry and infrastructure systems.

This brochure first provides a comprehensive overview of the results of this survey in the areas of transportation (automotive, rail, aerospace and ships), logistics, the processing and manufacturing industries, the energy sector and smart buildings. Then, the three core challenges that were identified are outlined:

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

This challenge reflects the fact that cyber-physical systems of systems cannot be managed and operated reliably and efficiently by centralized management and control. Novel distributed management and control methodologies are needed that can deal with partially autonomous systems with human interaction, are resilient to faults, not vulnerable to cyber attacks, and can deal with frequently changing system structures.

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

This challenge is based on the insight that cyber-physical systems of systems pose new challenges for engineering methodologies and software tools. On the one hand, this results from their size and complexity which require divide-and-conquer strategies for model-based design and validation and completely new approaches to deal with emergent behavior. On the other hand, cyber-physical systems of systems are long-living structures that are continuously evolving so that there is no strict separation between the engineering phases and the operational stages. New, fully integrated approaches for their design, validation, and operation are needed for the integrated engineering over the full life-cycle and for modeling, simulation, optimization, validation, and verification.

Challenge 3:
Towards cognitive cyber-physical systems of systems

Cyber-physical systems of systems are large and complex, and their efficient operation requires intense, system-wide monitoring of all system aspects. A consequence is a data deluge, and thus there is a need to handle large amounts of data in real time to monitor system performance and to detect faults and degradation. Cognitive systems should support operators and users, help to avoid information overload, and reduce the management complexity of cyber-physical systems of systems.

The remainder of this document is devoted to the presentation of the 11 medium-term research and innovation priorities that must be addressed to solve the core challenges. These are briefly summarized in the following:

- **System integration and reconfiguration:** Research and innovation is needed in open platforms, easy-to-test interfaces for semantic integration, and methods for describing and handling couplings between elements to enable the fast deployment of new technologies.
- **Resiliency in large systems:** Resiliency is a key issue in cyber-physical systems of systems in which faults are the norm.
- **Distributed robust system-wide optimization:** Cyber-physical systems of systems are too complex for centralized optimization methods and require novel approaches for distributed optimization.
- **Data-based system operation:** Cyber-physical systems of systems produce huge amounts of data that, for the most part, is not yet used to optimize and monitor the system. There is a need for advances in large-scale, real-time data analytics.
- **Predictive maintenance for improved asset management:** Maintenance depends on advances in sensors and novel tools for analysis, visualization, and decision support to provide the right information to the right person at all times.
- **Overcoming the modeling bottleneck:** Model-based methods for CPSoS engineering and management provide large benefits, but the effort needed to build such models often prevents the use of these techniques. New approaches for model adaptation, maintenance, and data-based modeling are needed.
- **Humans in the loop:** CPSoS depend on humans, and novel HMI concepts are required to enable human operators to digest and react to large amounts of data and information quickly and effectively.
- **Integration of control, scheduling, planning, and demand-side management for industrial production systems** will enable to improve efficiency and to reduce the carbon footprint.
- **New ICT infrastructures for adaptable, resilient, and reconfigurable manufacturing processes** are required to adapt to the trend of product personalization, short time-scales, and quickly changing customer demands.
- **Multi-disciplinary, multi-objective optimization of operations in complex, dynamic, 24/7 systems** is needed to improve capacity and efficiency, and to reduce the cost of transportation and logistics systems.
- **Safe, secure and trusted autonomous operations in transportation and logistics:** The increased degree of autonomy in transportation and logistics systems requires new approaches to guarantee safety, security, and trust.

Cyber-physical Systems of Systems

What are cyber-physical systems of systems?

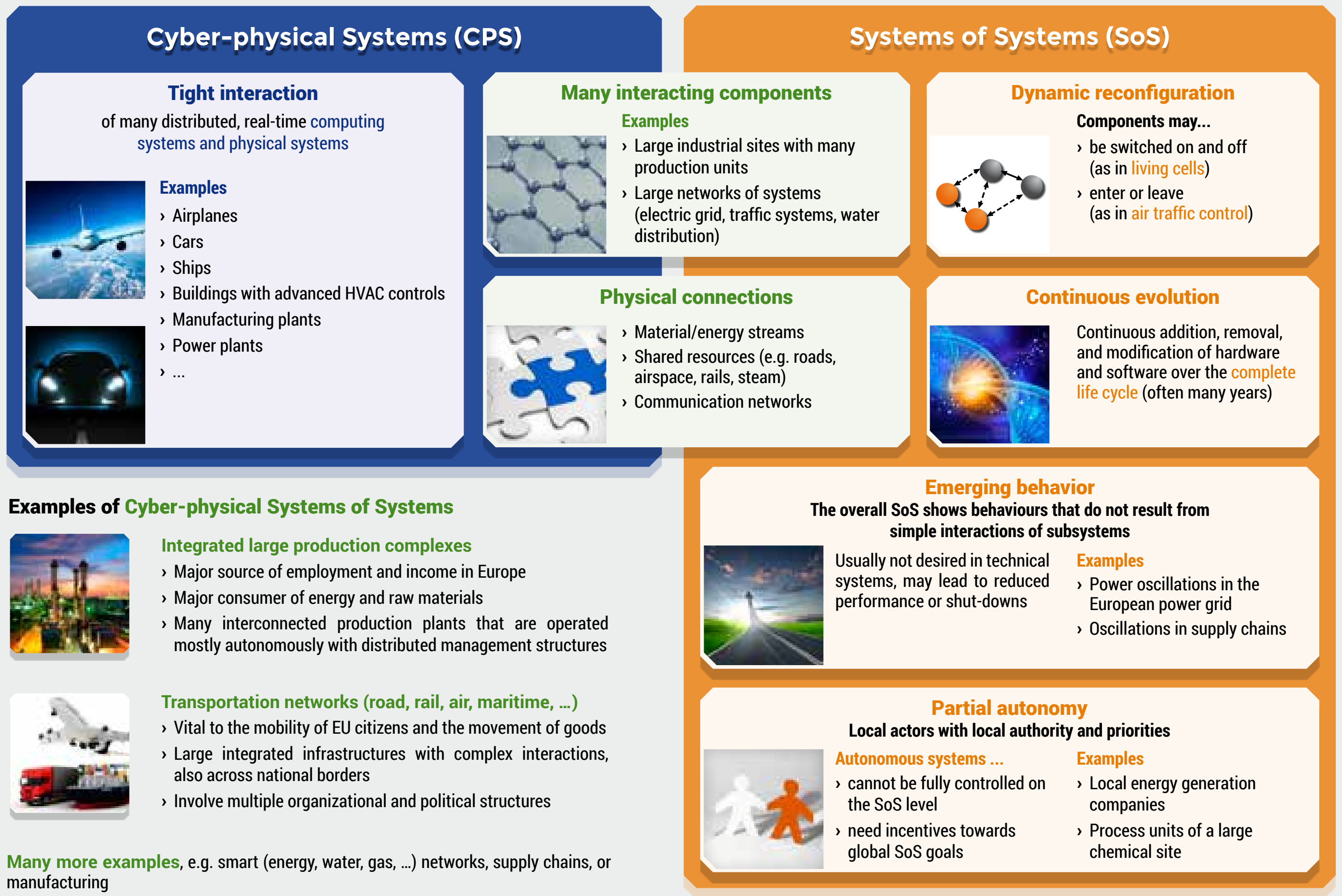
The next generation of energy systems, transportation networks, industrial production systems, and large buildings will consist of many smart elements that are globally networked and respond to the challenges that the world faces today: reducing emissions, improving energy and resource efficiency, and providing better services at a lower cost and in a sustainable manner. These infrastructures constitute *Cyber-physical Systems of Systems (CPSoS)* - they consist of many, often spatially distributed, physical subsystems that tightly interact with and are controlled by a large number of distributed and networked computing elements and human users, and they exhibit the features of *Systems of Systems (SoS)*. These features include partial autonomy of the subsystems, continuous evolution over their life-cycle, frequent and dynamic reconfiguration of the overall system, and the possibility of emerging behaviors.

Systems of systems are not a new phenomenon. Railway systems and electric grids, to name just two examples, have existed for centuries. And for many years, the elements of these systems of systems have been embedded systems in which computing elements and physical system elements interact tightly, e.g. in the locomotives of railway systems. Also, computer-based systems for the support of the operation and management of large systems have been in use for decades, in air traffic, rail, electric grids, power plants, chemical plants, etc.

However, up to now the flow of information in these systems was costly to establish and difficult to change, and their management followed a hierarchical top-down approach. Subsystems, e.g. power plants, units of a chemical plant or manufacturing cells, were managed independently, and coordination was achieved mostly by direct interaction of the operators. With increased connectivity, information will be available from a huge number of sensing devices and will be accessible throughout the system. Also, it will be possible to actuate physical variables and to propose actions to human operators flexibly.

Thus, cyber-physical systems of systems are emerging. They are characterized by consisting of a large number of physical devices and computing elements that are interconnected both physically, by flows of energy and material and by the use or resources, and by highly flexible flows of information. Due to these interactions, the resulting systems become highly complex, and difficult to engineer and to manage. The vastly increased amount of information and the new level of connectivity offer unprecedented potential for more efficient operation, higher flexibility and adaptability, improved levels of reliability, and better quality of products and services.

In the world of tomorrow, there will be a myriad of technical systems that are connected via the internet and can exchange information freely. This is also called the *Internet of Things (IoT)*. Until now, most of the IoT research and development have been focused on wireless sensors and on providing connectivity. In the future, using the information provided by the sensors and networks in a smart fashion and connecting sensing to actuation will be the key points that bring value to the users and to society. The connectivity provided by the Internet of Things will become an enabling technology for cyber-physical systems of systems that close the loop from the sensor information to actions performed by physical systems in transportation, energy systems, production plants, logistics, smart buildings, etc.



Cyber-physical systems of systems (CPSoS) are cyber-physical systems that exhibit features of systems of systems

Key features of cyber-physical systems of systems

Cyber-physical systems of systems are defined by the following features:

Size and distribution

The components of cyber-physical systems of systems are physically coupled and together fulfil a certain function, provide a service, or generate products. Some of the components can provide useful services independently, but the performance of the overall system depends on the "orchestration" of the components. CPSoS may be geographically distributed over a large area, as a railway network, or be locally concentrated, as e.g. a factory with many processing stations and materials handling and transportation systems or a smart building complex.

Control and management

Due to the scope and the complexity of the overall system and often also 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 distribution of authority with partial local autonomy and decision making, where both global and local decisions are not only driven by technical criteria, but rather by economic, social, and ecologic performance indicators, e.g. profitability, environmental impact, and in particular the acceptance and satisfaction of users. CPSoS are managed by humans and have to be addressed as socio-technical systems in which the technical/physical structure determines the possible services of the system.

Partial autonomy

Partial autonomy is essential in the definition of CPSoS and is understood in this context as the fact that the subsystems pursue local goals in a manner that cannot be fully controlled by the central management of the CPSoS. Rather, incentives or constraints are communicated to the subsystem controllers in order to make

them contribute to the global system targets. Often, subsystems are managed and controlled by humans, so there always is a certain degree of autonomy, and their actions are not fully predictable.

Partial autonomy is advantageous and needed because with local autonomy, the subsystems can cope with certain tasks, disturbances, and faults on their own, without intervention from the global CPSoS level. The partly 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 to, and compensate disturbances. This kind of autonomy can lead to self-organizing systems in which the autonomous actions of the agents lead to improved resilience of the overall system.

Continuous evolution and dynamic reconfiguration

Cyber-physical systems of systems are large systems that operate and are continuously improved over long periods of time. While the IT infrastructure and communication architectures in many industrial and infrastructure systems are often replaced or updated frequently, the physical hardware and software infrastructures are in productive operation for decades, and new functionalities or performance improvements have to be implemented with only limited changes of some parts of the overall system. Thus, the separation between the design phase and operational phases blurs in such systems (this is called the design-operations continuum), and the engineering of CPSoS requires methods and tools that can be used seamlessly during design as well as operation.

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 (as in air traffic control) as well as the change of system structures and management strategies following changes of demands, supplies, or regulations. In particular, the detection and handling of faults and abnormal behaviors is a key issue in cyber-physical systems of systems design and operation, since failures are the norm, not the exception in CPSoS due to their large scale and complexity.

Emerging behaviors

The behavior of CPSoS results from the interaction of their components, both by the exchange of signals and information and by physical connections as e.g. in the electric grid. This can lead to the occurrence of oscillations or instabilities on a system-wide level, as e.g. oscillations in large power systems or periodic bottlenecks in transportation systems. Also, self-organization and structure formation may take place. While emerging behaviors are usually seen as problematic in technical systems due to their lack of predictability, the formation of stable structures on a higher level of a CPSoS due to interactions between the subsystems despite their local diversity may enable the design and management of the overall system without precise knowledge of all its elements.

Enabling technologies for CPSoS

To build and to operate cyber-physical systems of systems, knowledge and technologies from many domains are needed. The development of new *core technologies* specifically for CPSoS requires contributions from a large variety of *enabling technologies* that are developed independently and for a broad range of purposes. These enabling technologies include:

- Communication technologies and communication engineering
- High-performance and distributed computing
- Big Data
- The Internet of Things
- Advances in sensors
- Human-machine interfaces (HMIs)
- Dependable computing and communication
- Security of distributed or cloud computing and of communication systems

Consultation Process

To gain an overview of the state of the art in cyber-physical systems of systems in the automotive, aerospace, rail, marine, logistics, processing, smart buildings, manufacturing, engineering tools, and energy sectors, a comprehensive consultation process was performed using a number of means. A key aim was to engage strongly with industry to understand the industry pull for cyber-physical systems of systems and also the state of the art in the area.

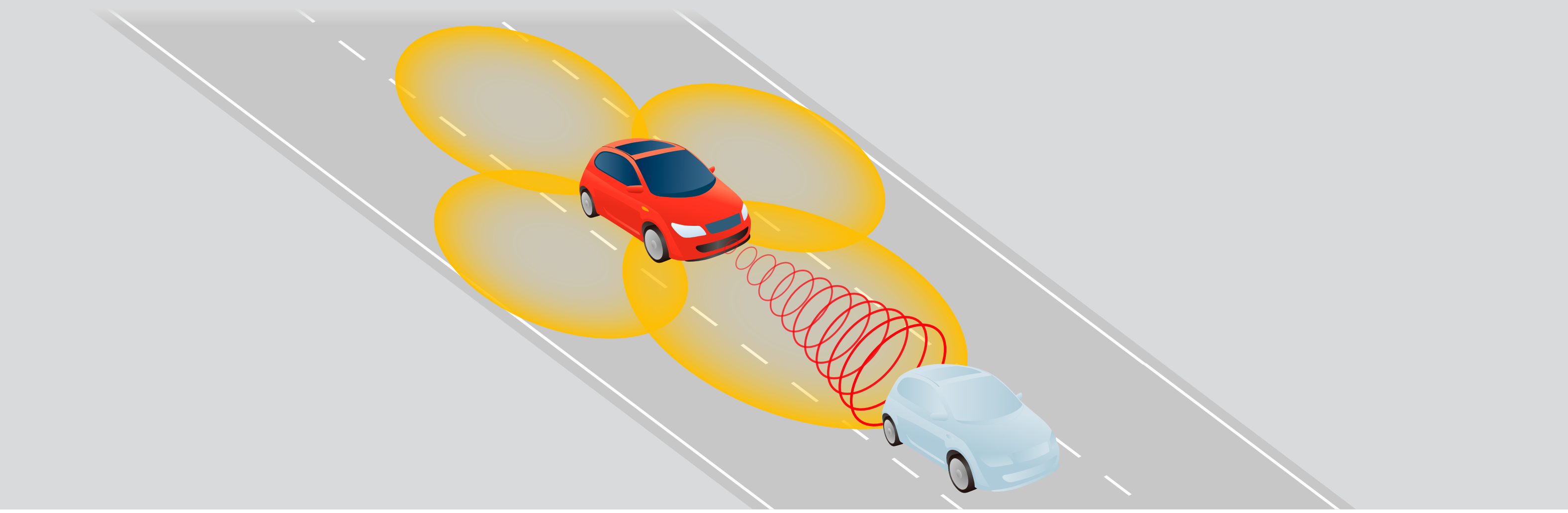
Many industry sectors already build and operate cyber-physical systems of systems, and there is considerable practical knowledge of the challenges that must be addressed. To this end, around 150 industry practitioners from large companies and SMEs have been contacted. The high response rate from industry indicates that there is strong interest in the topic, and the CPSoS project is obliged to the many people who have contributed to this report. Questionnaires have been collected from over 50 companies, and interviews have been performed with 50 key actors. Input from academics who have a strong relationship with industry has also been collected to get feedback on longer-term research issues. A cluster of EU projects is already addressing systems of systems issues, and input from these projects has also been gathered.

Major networks were involved in the consultations, e.g. European Technology Platforms such as ARTEMIS-IA, IFAC TC on Process Control, and EU-funded SoS projects – DANSE, AMADEOS, DYMASOS, Local4Global, and CyPhERS. Additionally, a literature analysis was conducted which was mainly based on survey papers from open literature with particular focus on the industrial application and exploitation of the present technology and some recent reports and innovation guidelines from organizations that include large stakeholders from the investigated sectors. Particular attention was devoted to recent projects addressing the research needs for innovations mostly funded under ICT FP7 and H2020.

A questionnaire was also placed on the CPSoS project website, and information has been gathered from the Internet to get as broad a picture as possible of activities going on around the world.

Last but not least, most valuable inputs and feedback have also been obtained from the 36 members of the CPSoS Working Groups, and from the participants of five public workshops.

Cyber-physical Systems of Systems in Different Technology Sectors



The Automotive Sector

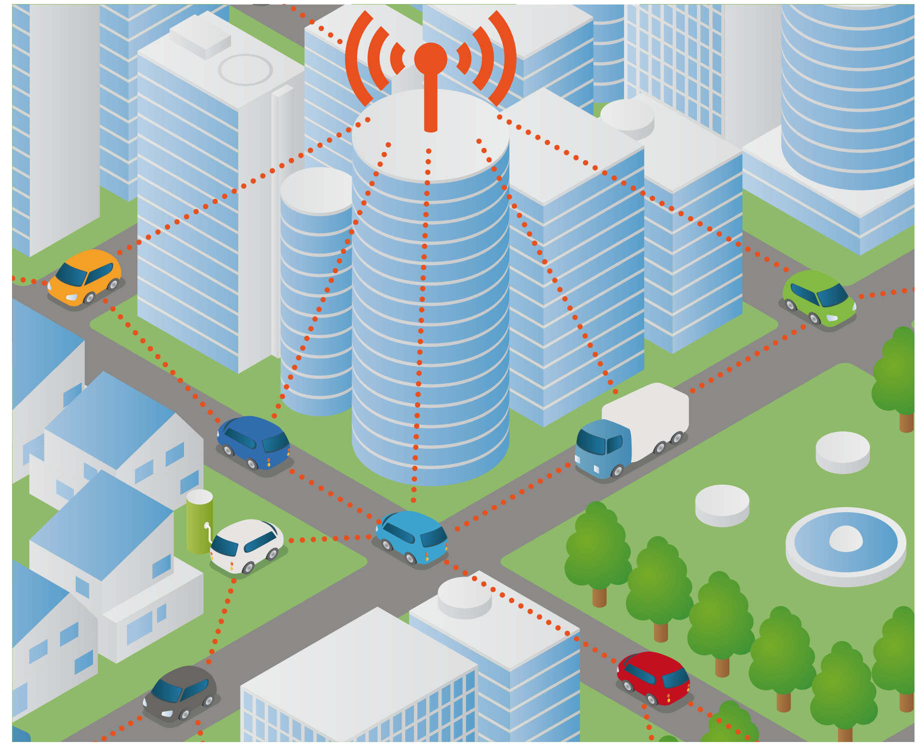
Traffic management [2] represents a highly complex system of systems coming under increasing demands for additional capacity, greater safety, and lower costs while meeting strict environmental regulations [3] . At the same time, the global car fleet is predicted to double from currently 800 million vehicles to over 1.6 billion vehicles by 2030. Without innovative thinking on the integration of information and flow control systems, severe congestion will be a major concern for mobility with long commutes and dramatic implications for road haulage of freight, leading to logistical problems of late deliveries within highly complex scheduled systems. Already embedded intelligence, mobile phone, car-to-car and car-to-infrastructure communication are offering the opportunity for increased awareness, more efficient mobility, and automated driver safety systems.

> The EU is among the world's biggest producers of motor vehicles, and the sector represents the largest private investor in research and development (R&D) within Europe. The sector provides jobs for 12 million people and accounts for 4% of the EU's GDP. Manufacturing accounts for 3 million jobs, sales and maintenance for 4.3 million, and transport for 4.8 million. The automotive industry also has an important multiplier effect in the economy as it generates jobs in upstream industries such as steel, chemicals, and textiles, as well as downstream industries such as ICT, repair, and mobility services.

The industry has been working for 10-15 years already on car-to-infrastructure and car-to-car communications. The technology, which is quite mature, is expected to enhance safety and efficiency and to reduce emissions via enabling a better traffic flow. Even if only a few cars are equipped with the technology in an incremental roll-out, e.g. 2-3%, their modified behavior will have a large impact on general traffic flow. The industry view is that communication between cars and infrastructure is the future, but there is a need for experience from day-one applications which are expected in 2015-2016. A critical issue is the quality of the standard. This needs to work in all the member states and also worldwide, covering Europe, America, Japan, and China. Good progress has been made by the European Car-2-Car consortium [4] in developing a standard for short-range communications, and similar work is ongoing in the US on IEEE 802.11 protocols, e.g. WAVE [5] .

It should be noted that a key requirement in any infrastructure implementation is the ability to be future-proof and to allow for future likely innovations. This is challenging as electronics typically become obsolescent in 18 months and a car in 10 years. An infrastructure investment needs to last 30 years or more, and in order to maintain the system's built-in functionality, it is also required for remote monitoring. There are a number of barriers to adoption, including the difficulty of integrating with legacy equipment, justifying the need for investment to governments, and the slow and bureaucratic decision making process of governments.

The move to greater automation with driver-assist functionality and eventually driverless vehicles is very much the current Zeitgeist, and the whole industry is trying to move in this direction. Autonomous driving is seen as an important technology to make road traffic more secure and more efficient. The majority of the work



is currently concentrated on technical solutions, e.g. processor architectures, sensor technologies, and data processing algorithms. The key challenge here is to make the technologies cheap enough for mass usage. The systems used on the Google Car [6] , for instance, currently cost $150,000. More of a concern, however, is that little is being done presently considering how a population of such vehicles, mixed with more traditional vehicles, will actually behave, especially under fault conditions. Designers will not be able to anticipate all possible eventualities and put in place necessary and sufficient mitigations as the scope of the system is effectively unbounded and the number of eventualities is very large. Additionally, no one will feel responsible for all aspects of the whole population, rather they will limit their scope to their own commercial interests. Emergence will thus be a key issue.

As a consequence, there is a need for intensive real-time monitoring of the performance of the systems to spot potential issues arising before they develop into accidents. This raises concerns over privacy. There are needs for protection from unscrupulous companies and state surveillance, and also security to provide protection from criminals and terrorists. This is something that needs to be addressed at the European level as different countries have different views on privacy with different regulatory and political interests. For instance, at a political level in Germany privacy is a very important topic, and technology cannot be used for tracking cars. In France, there is a different point of view and so car tracking is possible.

Another key issue for autonomous cars is risk. Accidents are inevitable, and what process is adopted when accidents happen is important. Here, there are issues of how responsibility is apportioned among the myriad suppliers and sub-suppliers, and what victims have to do to get support for their loss and/or recovery, i.e. they should not need to battle through the courts for 10 years. Some research in this area is needed.

> Road traffic represents a highly complex cyber-physical system of systems that is coming under increasing demands for additional capacity, greater safety, and lower costs while meeting strict environmental regulations, as the global car fleet is predicted to double from currently 800 million vehicles to over 1.6 billion vehicles by 2030. To avoid severe congestion in the future, there is a need for intelligent traffic systems, and there is also a move to greater automation with driver assist functionality and autonomous driving being seen as important technologies to make road traffic more secure and more efficient.
>
> Key CPSoS challenges are the coordination of a huge number of independent systems under the control of human drivers, to use the massive amount of data that arises in these systems for coordination and monitoring, to make traffic systems resilient to errors and faults, to find new ways to deal with emergence in these systems, and to develop methods to integrate new components and functions into the existing, heterogeneous infrastructures.

The key enablers for the successful development of cyber-physical systems of systems in the automotive sector in the medium term are advances in sensors, wireless communications, and much better theory/algorithms/data. In the longer term from a research perspective, there is a need to fuse disparate sensor data. Here, there are control/communication/computing trade-offs. A key issue is that there is no theoretical framework for systems of systems at present. There is also a need for tools to support quick prototyping of heterogeneous hardware and software for deployment.

The Rail Sector

The European rail infrastructure, a highly complex cyber-physical system of systems, is facing increasing congestion due to unprecedented numbers of passengers requiring innovative ways to increase capacity on existing infrastructure

> The overall rail sector in the EU, including the rail operators and infrastructure managers, employs approximately 1.8 million people with an estimated 817,000 dependent individuals. The European rail supply industry employs nearly 400,000 people and is a top exporter, accounting for nearly half of the world market for rail products with a market share of 84% in Europe and a total production value of €40 billion (2010). The rolling stock and locomotives market is the most important market employing 160,000 people, but there are also large markets for rail infrastructure (around 50,000 employees) and a smaller market for signalling and electrification. The world rolling stock industry market is dominated by three major players which are (partly) based in Europe: Bombardier (Canada/Germany), Alstom (France), and Siemens (Germany).

(faster scheduling of passengers through stations and shorter stopping times at stations) and demanding levels of punctuality never before seen with more people and improved journey times. The commercial drivers in the industry are for 24/7 operation, high availability, low cost, safety, increased capacity for both passengers and freight, recovery from disturbance, and low carbon emissions. There is also a drive to attract more customers, and to achieve this, there is a need to improve customer satisfaction and customer service. Customers are becoming more sophisticated and will demand a door-to-door service from public transport in the future. Here, the management, control, and sociological aspects need to be considered in unison.

The interoperability regulations and the 2011 Transport White Paper [7] require that the European railway system behaves as a single system of systems. Within the EU, the Commission requires a level playing field without barriers to competition, and already trains operate across the European continent. The 2011 Transport White Paper also requires that in the future, the majority of medium- to long-distance journeys (freight and passengers) are to be by rail. This is driven by congestion costs (1.5% of EU GDP) and the need for greatly reduced transport emissions. This is challenging as the rail network has stiff competition from other modes of transport, and in order for the railway to be the preferred transport mode, the industry must offer a guaranteed door-to-door or factory-to-point-of-sale service 24/7. Currently, capacity is severely restricted due to controlling train movement through a system of blocks. The use of moving blocks would improve this, and autonomous train-to-train communications and new infrastructure components could increase capacity by more than 100% and have an asset value of billions. To achieve this, there is a drive for automatic train control and automated maintenance to increase capacity and reduce costs to the point where rail operations do not require subsidy from the government.

The industry aims for a more resilient infrastructure, and some of this resilience can be obtained by better systems to route traffic in an optimal manner responding to an incident. Via a central coordination system, operators and managers should have a better overview of the whole system rather than the more localized view of the individual control centres or signal boxes. Key improvements expected from a systems-of-systems approach are increased capacity through improved planning and operation by optimizing the timetables at peak periods to maximize traffic flow, and reduced emissions by optimized driving to reduce stopping and starting. Additionally, systems of systems technology may provide the planning necessary to allow hybrid rail vehicles to just run the combustion engine when outside of stations and urban areas, reducing noise and urban pollution.

Existing railway control centres already act as a cyber-physical system of systems, where the individual railway sections are subsystems that are controlled by signalling interlocks utilizing information from track circuits or axle counter methods of train detection. Control centres act as higher-level systems that plan traffic routes and respond to delays and incidents. Each control centre covers a regional area, and therefore the intercommunication between control centres is vital. The introduction of the European Railway Traffic Management System (ERTMS) [8] will provide a much more centralized traffic management system that will remove many of the operational problems of running trains between countries. The system is being trialled currently at different levels in different countries, with full roll out expected by 2024.

In the rail industry, there is confidence that a systems-of-systems approach will be better, with metrics already being gathered to support this argument. The rail industry has many years of experience of rolling out systems of systems and also of maintaining networks. An issue is that traditionally, railway infrastructure maintenance and operations have been subject to a silo mentality with just a few engineers having the job title of "railway systems engineer". To convince management that there is a need to invest in systems of systems, research effort is required, and there is a need for leadership at the European level to do more than incremental change. There is, however, general industry support for change, as if there is no investment in modernization, the railway will become obsolete. With investment capital limited, investment decisions must be weighed against the benefits of other schemes.

The migration to a new approach is complex as there is a need to maintain the present level of services while the migration takes place. Key enablers are thought to be a well-prepared implementation scheme with the benefits clearly mapped out. The key research needs are support for determining the design and validation of such a scheme and proving that it is secure and safe and ready to be used on the railway system. Underlying this, there is a need for assessment tools and methods to prove the benefits. Modeling capability is thought to be critical here for optimizing the components (operations, maintenance, etc.) within the system. There is also a need for commitment from the top, i.e. from government. There will inevitably be some disruption to passengers and freight, and a need for large investment.

Increased automation is a key feature of future systems, and there is a need to carefully consider the sociotechnical issues of how humans will interact with automatic control on trains and in control centres. Here, there is a need to understand which aspects and systems should be controlled automatically, which should be controlled by humans, and which in combination. It is also important to consider how decision support tools can help human operators, and to design the HMIs between humans and technology.

Underlying this, there are key issues with respect to data gathering and management, considering how is data to be sensed, collected, communicated, processed, and stored. Standards are required here. Security and integrity also needs to be guaranteed to deal with vulnerabilities and threats as systems become more interconnected and autonomous.

> The rail system is a huge and vital cyber-physical system of systems with enormous management and engineering challenges. The introduction of automated train control via the European Railway Traffic Management System (ERTMS) will allow more autonomous operations that could increase capacity by more than 100% and have an asset value of billions. Likewise, automated maintenance can be used to provide more resilient infrastructures. Resiliency to unexpected events and management of their consequences so that users are least affected are key challenges as well as the introduction of new technology while maintaining existing operations. Optimization of operations and maintenance based upon models must increasingly be used to ensure a high quality of service and low cost of operations.

The Aerospace Sector

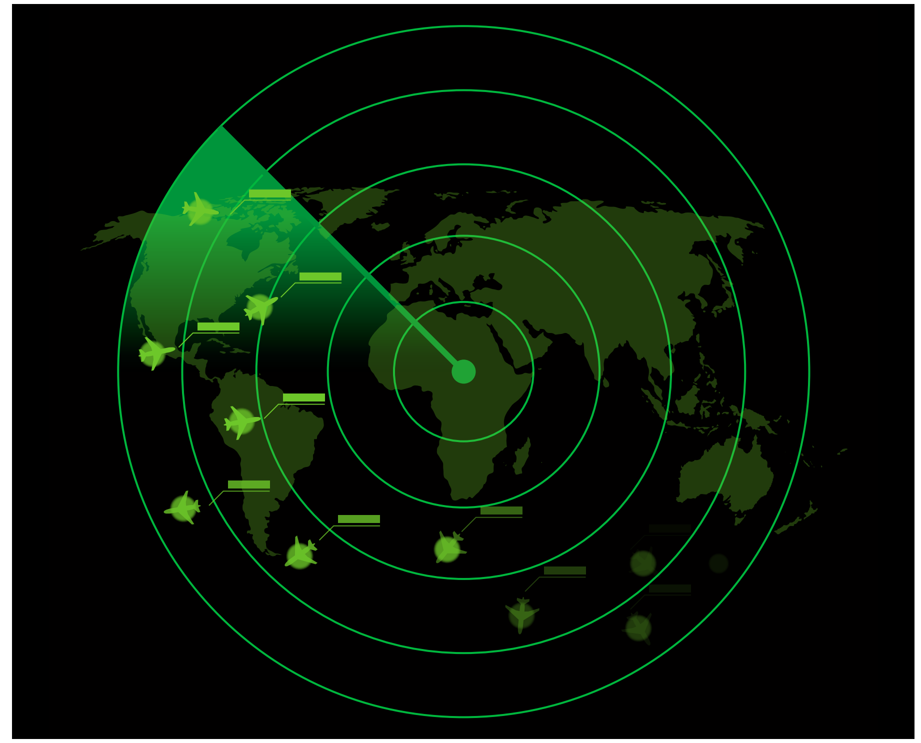
In the aerospace sector, air passenger volume is predicted to double air traffic density over the next two decades in an already congested airspace. On key routes and large airports within Europe, there are over 50 million passengers a year, and on the majority of other routes, there are 10-50 million passengers. Air traffic is increasing, and the number of aircraft is expected to double by 2020. As a global aviation industry, the biggest and most important challenge is to continue to safely accommodate ever-increasing air traffic in support of global economic growth and prosperity, whilst protecting the environment. Movement of increasing numbers of passengers requires a complex cyber-physical system of systems across the world that integrates airport operations, baggage handling, and air traffic control to maximize flow. Air traffic control systems by themselves integrate numerous functionalities that enable semi-automated operations in the en-route airspace. Tools and methods that partially automate some of what is manually performed by air traffic controllers today is currently an active area of research. At the same time, the need for unprecedented high levels of aircraft availability is driving the use of sophisticated information and communication technologies for predictive health monitoring, integrated with worldwide maintenance and logistics systems to ensure that aircraft are always fit to fly.

> The European aerospace industry is a world leader in the production of civil and military aircraft, helicopters, drones, aero-engines, and equipment, exporting them all over the world. It also provides support services, such as maintenance and training. Aerospace within the EU provides more than 500 000 jobs and generated a turnover of €140 billion in 2013. Employment in the aerospace sector is particularly significant in the United Kingdom, France, Germany, Italy, Spain, Poland, and Sweden. A sizeable share of value added is spent on research and development (R&D) within Europe.

From a systems-of-systems perspective, air traffic management is a major topic, especially in Europe where separate systems will have to be integrated. The challenges here are not only technological, but also legislative/ political and need to be tackled at a European (and even world-wide) level. Already air space is congested, and better coordination of aircraft will allow for increases in capacity and real-time deconfliction of flight paths. The expectation is that systems-of-systems approaches will provide a better integrated end-to-end passenger journey experience and reduced emissions. Improved air traffic control will reduce costs and delays, and better integration of systems offers the opportunity to optimize gate-to-gate transits without on-the-ground delays or stacking before approach (with consequent reductions in emissions).

There is a lot of military experience in the operation of aircraft within systems of systems, and it is well known that military capability is enhanced through the synchronization of force elements across time and space. In a civilian context, the same approaches can be employed for a more effective and focused use of information and existing assets to increase capacity. This tends to result in better performance and also monetary savings due to a reduced need for capital equipment and more efficient utilization of assets and resources.

Autonomous aircraft operations are not a new concept in the aerospace domain. There are already deployed systems, e.g. for homeland security, that indicate that there is maturity in methods, processes, skills, and competencies. The actual differentiators between companies developing the systems of systems in this field are knowledge and the usage of architecture frameworks, systems engineering norms and standards. In the military domain, it is commonplace to operate autonomous vehicles in controlled military airspaces, and the three-dimensional separation of vehicles is also an enabling factor. The sector is thus a leader in terms of implementation of autonomous vehicles. Future programmes such as ASTRAEA [9] are looking at the technological, legislative, and political challenges of how unmanned aerial vehicles can also be integrated with the civilian ATM network.



The experience of the sector highlights a number of key issues. Here, it is noted that systems engineers are often stuck in a "requirements first" clean sheet design paradigm and are used to having a level of control over the system elements. This is not available in systems-of-systems engineering. The key perception is that there is a need for a scientific foundation to handle multi-layer operations and multiple life-cycle management. Supporting this, there is a need for modeling and simulation. The biggest problem in modeling is to access accurate enough "as built", "as tested", and "as configured" information. Often, this information is jealously guarded by individual contractors, and not everyone who needs it can easily get access to it. There is also a need for widely accepted validation and verification procedures to allow cyber-physical systems of systems to be adopted in the public domain. Justifying investment in systems-of-systems development is also a challenge as there is a problem putting a value on the (potentially large) marginal improvement in capability that will come from a (potentially relatively small) marginal investment in systems-of-systems capabilities. Financial systems do not know how to put a value on "better capability", and so usually the running costs are considered as these are more visible.

For interoperability and integration, there is a need for communication standards between systems, however it is difficult to judge at what level this should occur (e.g. is one standard for all system types viable, or are several standards for different system types a better choice). The system should have sufficient autonomy to deal with the times when communication is not possible. It should be noted that the aim is not to have strong integration, but to have dynamic integration along the life-cycle of the system of systems in order to take into account addition and suppression of constituent systems, their evolution, and the emerging effects. For systems of systems that do not operate in a strictly controlled environment, dynamic reconfiguration is key.

> Air traffic control is a prototypical example of a cyber-physical system of systems where elements enter and leave the system all the time. The key challenge is to continue to safely accommodate ever-increasing air traffic in support of global economic growth and prosperity whilst protecting the environment. Movement of increasing numbers of passengers requires a complex system of systems across the world that integrates airport operations, baggage handling, and air traffic control to maximize flow. Tools and methods that automate air traffic control are needed, and modeling, integration, and the handling of emerging effects are key issues. At the same time, the need for unprecedented high levels of aircraft availability is driving the use of sophisticated technologies for predictive health monitoring, integrated with worldwide maintenance and logistics systems to ensure that aircraft are always fit to fly.

The challenges in rolling out a system of systems are the asynchronous life-cycles of constituent parts and also the fact that many components are developed independently. The key is to make sure that the integration is loosely coupled so that integration can happen in any order, or at least such that useful capability is achieved by many different partial systems-of-systems configurations. This ensures that everyone is incentivized to join the systems-of-systems perspective because they get benefits for each integration step. Once rolled out, operating and maintaining a system of systems requires good knowledge of the "as-deployed-and-configured" physical, functional, and behavioral configuration of the system.

The Maritime Sector

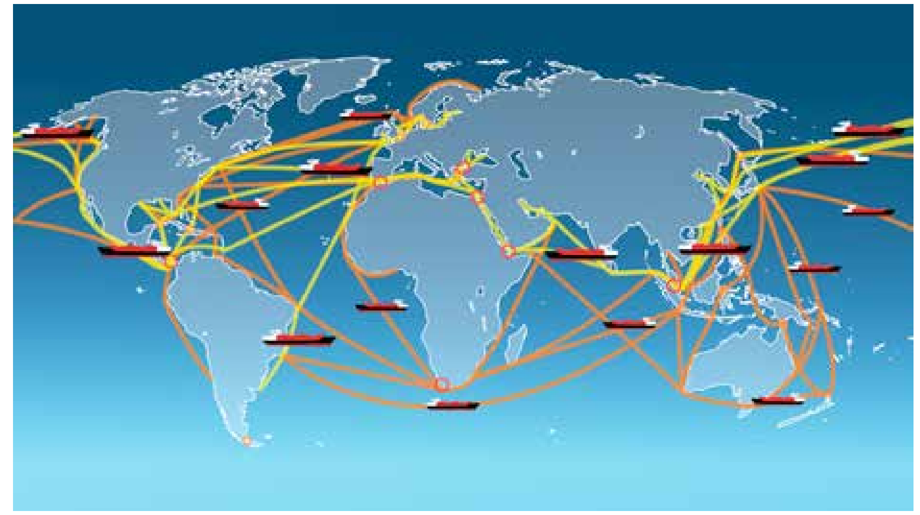
By far the most efficient mode of transport for the movement of goods, the shipping sector is expected to grow by 150-250% over the next 30 years. European shipbuilders are world market leaders by turnover. In particular Europe produces nearly all the high-value cruise ships in the world, around 50% of all equipment suppliers' products are exported outside Europe, and almost 100% of the dredging technology and know-how is European. From a fleet management perspective, around 40% of the world merchant fleet is controlled by European companies, and approximately 25% are flying the European EEA flag. Of the top 5 world ports, 3 are European, and the European oil & gas service industry is also a world technology leader, exporting 70% of products. The European maritime industry is spearheading environmentally friendly technologies. For example, European equipment suppliers have provided on-board total waste management systems ahead of future environmental regulations.

Over 90% of world trade is carried by ships, making them pivotal in the world economy. It is the most economical and the least environmentally damaging form of transport. Without ships, the transport of raw materials and the import/export of affordable food and manufactured goods would not happen. The growth in seaborne trade has averaged 4% per annum since the 1970s. The estimated number of active seafarers in maritime EU Member States in 2010 is 254,119 (143,967 officers and 110,152 ratings). It is estimated that 4.78 million people are employed in maritime-related activities in ports and logistics that support the movement of goods.

In the industry, systems-of-systems thinking is leading to integrated world-wide ship management systems being linked with ship fouling efficiency metrics and navigation systems to optimize performance to reduce shipping costs, fuel consumption, and emissions. This is being addressed through the introduction of ICT technologies and algorithms to optimize shipping movements and port operations. There is also a big push to improve safety across all types of shipping due to high-profile accidents. The increasing size of passenger ships and their operation in remote and inhospitable locations is also leading to concerns about safety. In recent years, emissions have become a major issue at the local port level and also at an international level with legislation, e.g. IMO Tier III [10] , driving for increased monitoring of emissions. The introduction of emissions monitoring has led to new operational approaches such as "slow steaming" for products that are not time-critical. Logistically, there are complex interactions in the movements of containers around the world to ensure that shipping and handling costs are minimized, with tight linkage into the appropriate rail or road haulage networks to move the goods onwards as quickly and efficiently as possible.

The commercial requirements are for high performance, fuel cost reduction, reliability, safety, lower capital expenditure, and lower operating expenses (maintenance). In discussions with the maritime industry, it is apparent that the concept of systems of systems is not a known term. There is more an idea of operations, fleet management, and logistics of moving containers and goods. It is clear that systems of systems exist in the industry, but currently there is a fairly low level of use of ICT and little connection between systems.

The industry believes that the introduction of new ICT technologies for maritime traffic management will be a key for safer and more secure operations. There is great interest in optimized shipping operations and voyage optimization, condition-based maintenance, reducing costs, and reducing emissions. The drivers are for reduced maintenance, enhanced asset life, reduction in crewing levels through increased automation and fleet optimization via shore-based decisions. Key enablers in the industry are the introduction of VSAT systems that provide connectivity to ships and much greater data rates for data transfer. Presently, however, there is not a clear view of what data should be transferred and how this should be used.



There is also a drive for a more integrated transport chain. To reduce congestion in ports and port fairways, port traffic guidance systems need to be at the same time cost efficient and easily deployable. Synergies with existing systems should be ensured, with the aim of integrating the use of port traffic guidance tools by all relevant authorities and ensuring the full interoperability between ICT systems, which monitor vessels, freight and port services. Actions such as Waterborne and e-Maritime [11] are helping drive technologies here. The introduction of data exchange standards would be a major move forward, allowing currently installed systems to become interoperable. The increasing use of ICT within the industry and the new internet-savvy crew and operators offer great potential for improvements in efficiency.

The maritime industry has very good system integration engineers as ships are highly complex systems, but they may not think in a systems-of-systems way. The ship builders produce the ships and their systems, but the operators are the ones who would benefit from a systems-of-systems approach. The fact that ships are regularly sold to other ship owners makes investment in on-board technology such as monitoring more difficult, as installation of expensive equipment may be lost within a few years. As a consequence, the suppliers of equipment are now building in monitoring for their own equipment which is used internally. The ship owners are then offered the option of purchasing monitoring and management services by the suppliers, e.g. in power-by-the-hour contracts.

In the area of safety-improved navigation systems, traffic management algorithms for busy sea ways and ports will improve safety, and looking to the future, there will be a gradual reduction of crew levels leading to fully autonomous ships once regulatory authorities are convinced that this is safe. Already Rolls-Royce is proposing autonomous container ships that are operated from shore-based simulators as a means of reducing cost and increasing capacity through the removal of the bridge and hospitality infrastructure required to support the crew [12] .

Monitoring of the oceans is seen as a major opportunity for deployment of systems of systems. As systems become more interconnected, it will be possible to combine mixtures of autonomous underwater, surface, and aerial drones to monitor accidents at sea, pollution spills, ocean acidification, wildlife, and also the relationship between the oceans and climate change. This is an area that is still in its infancy, but already fairly large-scale deployments are being trialled, identifying systems-of-systems issues. Much of the technology push here is on the development of vehicles that can operate for long periods as this is a prerequisite for cost-effective deployment. It is interesting to note that monitoring of the oceans is seen as a new commercial opportunity and this is supported by Google's interest in being a central player in this area.

In world-wide ship management systems, ship efficiency metrics and navigation systems will be combined to optimize performance and to reduce shipping costs, fuel consumption, and emissions. Advanced planning and control technology is seen as key to the optimization of shipping movements and port operations. To reduce congestion in ports and fairways, port traffic guidance systems are being introduced. Safety is a major driving factor, and in recent years, emissions have become a significant issue which has led to the introduction of emission monitoring. There are increasing demands for condition-based maintenance across ship assets, for overarching planning and optimization tools, and for a more integrated transport chain which calls for the introduction of data integration and data exchange standards to allow interoperability with the multiple systems in use today. Looking to the future, autonomous container ships are being proposed that could be operated from shore-based simulators as a means of reducing cost.

The Logistics Sector

Logistics is a global business, and Europe has some of the largest logistics companies in the world with highly developed and efficient delivery networks. Logistics contributes nearly 14% to the European GDP (900 billion Euros) and has a significant impact on the service sectors it supports. Within warehouses the market for logistics robots currently accounts for 9% of the total sales of professional service robot systems. This is expected to grow in the future, driven by the increasing cost of labour and higher demands for efficiency.

The consumer marketplace is becoming increasingly volatile, fragmented, and dynamic, being dominated by extreme service-level requirements, multi-tier distribution networks, and a myriad of high- and low-volume stock keeping units. Order-to-delivery excellence is now a key requirement for demand management that drives new business models and collaborative transport management. Customers expect on-time delivery with an eco-conscious approach, driving supply chain sustainability initiatives to reduce fuel consumption and lower emissions. Information provided by modern ICT systems is available at all levels of the supply chain, offering unprecedented opportunities for optimization. Successful supply chains rely on complex cyber-physical systems of systems for accurately forecasting market demand, formalizing vendor-managed inventory consignment, reducing stock levels, and focusing on buying/manufacturing inventory only when it is needed.

The challenges in this sector are that transport volumes keep growing globally, but the sizes of individual shipments are not increasing, and indeed there is a move towards shipments of smaller loads. Customer service expectations are high with demands for fast and efficient on-time delivery. In order to execute transport tasks efficiently, transport service networks play a vital role. These networks are dedicated e.g. to parcel, express or less-than-truckload-shipments and related logistic services. Analysis and optimization of their structure can provide great benefits in terms of efficiency and also fuel cost and emission reductions. More efficient operation of nodes (depots, hubs, terminals) provides greater throughput and lower latency. To support this, operators are increasingly turning to simulation models to achieve robust solutions that improve their efficiency, reduce handling costs, and increase the performance of their terminal operations. A key challenge is to link between material-flow simulation and arriving and departing traffic. The task of delivery in urban areas increasingly is leading to congestion, and ways of bundling deliveries at local hubs to reduce the numbers of vehicles making deliveries are being sought.

Systems of systems are not a new concept in the logistics domain, with worldwide distribution systems being in place already for many years. The industry is facing new challenges in the shift from large individual shipment sizes to shipments of smaller loads. The transport volumes are thus growing rapidly, introducing challenges in cost, emission reduction, and increased congestion on roads and in cities. The universal nature of interconnectivity is allowing the design of co-operation networks to deliver goods. Here, there is a need to create synergies and incentives, and to develop new service concepts. Data and knowledge are becoming key competitive criteria, with tracking of items through the logistics chain the norm and companies competing to provide efficient and cheaper services.

A problem with increased interconnectivity in logistics systems of systems is that it exposes them to external risks, such as natural disasters and organized crime. Security and flexibility to reconfigure are thus key prerequisites and concerns. Congestion is a growing problem, and there is a need for incentive schemes that produce a more balanced use of the vehicle, facilities and traffic infrastructures. The key aim here is to drive demand and reduce traffic bottlenecks. Schemes that allow bundling of deliveries from different companies would have a significant impact, and there is a need to move more transport to off-peak hours. At a system level, there is a need to understand how much centralized planning is needed versus the use of decentralized self-organized flexible delivery.

Currently, there is a drive towards tighter time limits on delivery. This makes it more difficult to implement energy-minimal logistics to reduce emissions. This is a systems-of-systems problem, but at present, customers are not demanding information on the carbon footprint of goods transportation. However, this may well be a factor in the future as customers become more eco-conscious.

The use of autonomous vehicles in the logistics domain is already an established concept, with autonomous picking machines being commonly used in large warehouses. There is a drive towards more distributed autonomy for these vehicles to provide greater flexibility in operations, and this, coupled with the use of smart communication technologies in intelligent bins, is leading to greater efficiencies.

Moving out of the warehouse, the industry is beginning to think about automated delivery systems. An example of this is Amazon Prime Air [13] which is a drone concept for delivering small packages to customers within 30 minutes. This is still many years away from deployment and needs to gain certification acceptance from the FAA before it can be reality, however, again it shows synergies with the move towards autonomous aircraft operations.

A key challenge in logistics is that the transport volumes are growing but the individual shipment sizes are getting smaller. Customer service expectations are high, with demands for fast and efficient on-time delivery. There is a need for optimization of parcel, express or less-than-truckload-shipments to be more efficient, to reduce fuel cost and emissions. Different approaches to planning are needed, combining traditional centralized planning with the use of decentralized self-organized flexible delivery.

More efficient operation of nodes (depots, hubs, terminals) allows greater throughput and lower latency. The couplings of the different elements in the logistics chain must be considered, and real-time feedback must be integrated into automated planning systems that also can deal with problems of congestion on roads and in cities. Here, there is a need for incentive schemes that produce a more balanced use of the vehicle, facilities and traffic infrastructure. Increased interconnectivity is allowing the design of co-operation networks to deliver goods, but increased interconnecity also requires more security to avoid criminal activity and malicious disruption.

The Process Industry

Industrial sites in the process industries host a considerable number of production plants, nowadays often owned by different companies, with complex interconnections by streams of energy and materials to ensure resource and energy efficiency, operational excellence, and competitiveness of production. Different plants may belong to competing value chains inside one company, or even to different owners in an industrial park. The ecological and economic viability of the production depends crucially on the careful management of the ensemble of different plants which are interconnected by several networks of carriers of energy and of various intermediates and are operated to make the best possible use of energy, materials, and by-products.

The process industries, including biotech, cement, ceramics, chemicals, minerals and ores, non-ferrous metals, and steel, employ more than 6.8 million European citizens and generate an annual turnover of over € 1,600 billion. These industries operate large, integrated production complexes that are major consumers of raw materials and account for one fourth of the energy consumption in Europe. They transform feedstock to produce end-user products and virtually all raw materials for convenience products in modern industrial society and thus play a significant role in the value chains. The challenges the process industries face arise as a synergy of environmental movements, promoting reduced carbon and energy footprints and growing competition from emerging extra-EU markets.

The flexibility of the production is limited by many constraints on individual units that must not be violated in order to prevent safety-critical operation modes or accelerated equipment degradation. Each plant aims to operate most efficiently in terms of economics and energy and resource consumption under specific conditions and targets which often are not fully in line with the global need of the production system. The main goal of site-wide management must be to achieve an optimal overall performance.

Orchestrating management decisions
Significant challenges exist for the computation and implementation of an optimal site-wide production regime which is a complex optimization problem that spans multiple time scales and layers of decision making.

The upper management layer conducts the planning of the production and supply chain optimization that allocate production targets to respond to the market conditions and to meet the contracts with the customers and suppliers, for example electricity contracts. The decisions are communicated to the lower layers that adjust the production plans and the operation of the specific plants. A critical aspect of the integration among these layers lies in the different conceptual views employed along this decision pyramid. A too coarse representation of the physical plants by the upper-level decision making processes affects the feasibility of the decisions, as dynamic effects and uncertainties might not be taken into account. The arising conflicts are currently resolved by communication of the operators.

Challenges of vertical integration of the systems emerge from the increased focus on efficient energy management that requires process designs that are often more integrated and as such intrinsically harder to manage. The plants possess the ability to vary the production intensity in order to compensate for changing utilities supply and market prices. Each plant operates autonomously to some extent and tries to reach its production objectives as part of the value chain. A suitable coordination among the independent decisions of plant managers would in many cases result in improved economic and ecological performance of the whole site. Processing plants are also active players in the electric grid, as they can significantly influence the balance of power loads in the network. The vertical integration with utility providers to achieve optimal demand-side response would result in a significant step towards sustainability and a more resilient power grid.

One possible way to overcome the management challenges is to influence the prices of utilities and materials that are used in the local optimizations of the different plants according to availability and demand. Market-based mechanism can be employed, and an automatic coordination of the site can be established in order to steer the site performance towards the global optimum.

Handling exceptional situations
The plants on a site can be driven into abnormal operating regimes by faults and disturbances, causing a snow-ball effect of deterioration of the site performance and a decrease of safety. Such situations occur as consequences of the malfunction of the components of some system but might happen also during shut-downs of some plants or during the start-up procedures and changes of operating points of the major plants. An early recognition of unplanned events and their thorough diagnosis could lead to a better handling of these situations without performance deterioration. Many abnormal situations can be avoided by predictive maintenance of the assets.

Handling of abnormal situations is currently based on the experience of the operators and negotiations between plant operators and managers. In severe cases, a set of rules may exist and be followed which can, for example, define the order in which the plants are shut down on the site such that safety is guaranteed. Automatic solutions that result in optimal responses to faults are rarely implemented because of the complexity of the problems and missing solutions that exploit past experiences gained during the handling of abnormal events.

Towards cognitive plants
One of the drivers for technological development of management in the process industries is the reliability and availability of modern sensing hardware and software. Many sensors are deployed in the industry that can provide useful information about the actual plant behaviour and large amounts of data can be stored that records past operating scenarios.

This data should be a useful asset to plant operators who should be informed, ideally on a real-time basis, about the best operation scenarios extracted from past events, and should be assisted by a decision-support system to make the best possible decision in a given situation. In case of abnormal operation of some plant, a root-cause analysis should be performed to automatically detect the occurrences that led to the event, and to propose remedies for its mitigation.

Such cognitive features of information systems are not yet realized, as the current technology is not able to handle large amounts of data in real time automatically to identify the trends and patterns and to extract useful features and information. Solutions of this type provide a great opportunity for seamless and safe management of the industrial sites.

Model-based solutions will play a crucial role in the future management of processing sites. By making better use of data and models, planning and management will be based on more up-to-date and more accurate predictions, leading to improved sustainability and cost efficiency.

Industrial production systems are complex dynamic nonlinear systems. Their engineering and management are challenging given the integrated, tightly-coupled nature of the production sites, their dynamics on multiple time scales and distributed authorities. The pressure on the industry to be sustainable and competitive in high-wage countries requires better vertically and horizontally integrated management and control structures, fast and optimal responses to abnormal situations and their thorough analysis to prevent their occurence in the future, and advanced decision-support systems. This will secure the job opportunities in the process industries in Europe for the next decades.

The Manufacturing Industry

While manufacturing is traditionally defined as a production process that transforms raw materials into products and goods, manufacturing systems are currently evolving into global, highly integrated cyber-physical systems of systems that go beyond pure production and that cover other parts of the value chain, such as research, design, and service provision.

With more than 30 million employees, a turnover of € 6,410 billion, and a value added of € 1,590 billion in 2010 [14], the European manufacturing sector represents a major part of the European economy and is one of its largest sources of employment. It generates a vast range of products, from food and beverages to textiles and furniture to metal-based products and heavy machinery, on a large range of scales, from small enterprises that manufacture e.g. musical instruments to very large enterprises at the top of a large pyramid of parts and components suppliers, collectively manufacturing complex products.

This evolution, which is accelerated by the availability of new ICT technologies, is driven by a quicky changing world in which business and private customers are thinking globally, are more aware of environmental impact, ask for a high degree of product customization and configurability, and require efficient, yet sustainable production. In the face of increasing complexity of products, processes, and supply networks, modern manufacturing systems must strive for ever higher efficiency and quality while staying competitive in a global market.

The European support action Road4FAME (www.road4fame.eu) in which several CPSoS consortium members were involved has analyzed the manufacturing sector in detail and has identified a number of key needs and recommendations for the engineering of modern manufacturing systems that will help European manufacturers solve today's challenges [15]. These needs and recommendations correlate strongly with those identified in CPSoS which we summarize in the following.

Smart, flexible manufacturing

To face the increasing trend towards customization and short times from order to delivery and the resulting large degree of flexibility and quick adaptability of manufacturing processes, the German industry initiative Industrie 4.0 advocates smart factories that consist of intelligent, self-adapting, and resilient components. Key components to make smart factories a reality include novel ICT platforms for the seamless and low-effort reconfiguration of manufacturing systems, new methodologies for multi-disciplinary, context-aware modeling of flexible manufacturing environments, and new real-time coordination, control, monitoring, and optimization solutions.

Open data and system integration

The IT landscape in today's manufacturing plants is highly heterogeneous, with many different systems from different vendors that cannot easily be connected, which makes the introduction of novel ICT solutions expensive. Consequently, their introduction is a slow process. The threshold for the deployment and integration of such innovative solutions in existing infrastructures must be reduced to speed up the innovation and to make them affordable also for smaller companies.

Open data and system integration platforms are needed that include harmonized and standardised interfaces to enable "one-click" plug-and-play integration of new manufacturing components and ICT solutions. They must provide low-effort integration for different kinds of engineering and operations entities, such as unstructured data, models, and documentation. In addition, they must ensure consistency of data and other design artefacts across the complete engineering and operations infrastructure, and they must address security and privacy concerns (today's number one show-stopper for manufacturing ICT innovation).

Engineering support for the design/operation continuum

Many manufacturing companies describe flexibility as the need that has most strongly increased in importance in recent years. The need for flexibility is driven by the trend towards shorter product life-cycles which is caused by increased competition due to global markets, as well as by the demand for customized products and the need to quickly adapt production to changes in demand.

This flexibility is currently very difficult to achieve, not only because of the lack of easy integration and reconfiguration facilities in today's heterogeneous IT infrastructures, but also because the need for flexibility triggers constant evolution in manufacturing environments, which dissolves the separation between the design and engineering phases and the operational stage in modern manufacturing processes. New, integrated engineering platforms are needed that support the complete design/operation continuum of highly flexible and reconfigurable manufacturing processes.

Real-time big data analysis and use for quality control, monitoring, and optimization

Stricter quality margins, more complex customized products, flexible processes, and shorter time-to-market are putting increasing requirements on production efficiency and quality control in the manufacturing sector. More efficient and high-quality production requires more detailed knowledge about the production process. Greater levels of data acquisition throughout the manufacturing system are needed and can be realized by the integration of novel, easy-to-install, low-cost sensor technologies and monitoring concepts.

Due to the ongoing integration of embedded, intelligent sensors and components into production systems and products, manufacturing companies often have large amounts of data available, but they struggle to derive useful information from it, in particular when decisions are needed in real time. What is needed is large-scale real-time data analytics that can provide the detailed knowledge needed to increase production efficiency and quality.

Such analytics must be able to detect changes in demands and operational conditions in real time, must support the user in spotting performance gaps, and must be able to deal with anomalies and failures within the system. To achieve this, new architectures as well as data transmission, collection, storage, and security systems must be developed, demonstrated, and implemented on a broad scale.

Context-centric visualization of crucial information

The increase in complexity of manufacturing processes and the deluge of data in future manufacturing environments will necessitate new, context- and problem-centric approaches to the visualization of real-time information. These visualizations must be able to distill useful and crucial information from the data torrents that allow managers to understand the "real world in real time", to manage risk, and to make informed decisions on how to control and optimize the system.

Manufacturing systems are currently evolving into global, highly integrated cyber-physical systems of systems that go beyond pure production and that cover all parts of the value chain, including research, design, and service provision. This evolution is driven by quicky changing customer requirements that are more aware of environmental impact, ask for a high degree of product customization and configurability, and require efficient, yet sustainable production. To meet these requirements, new ICT-driven solutions are required that include engineering support for highly flexible manufacturing environments, big data applications for quality control, monitoring, and optimization, and context-centric visualization of crucial information.

The Energy Sector

Power grids form spatially distributed networks that encompass multiple nodes of electricity generation and consumption and the infrastructural interconnections, such as lines and transformers, between the nodes. Their management is presently undergoing a transformation from integrated, top-down-operated, state-owned systems to systems that are operated by independent and competing companies who are active players in the real-time electricity (spot) markets. This change creates new opportunities for better load balancing in the network, but it also introduces a tight interaction between physics, ICT technology and economics, and new needs for communication and real-time control.

> Electric power grids are systems that are engineered, built and operated to ensure the uninterrupted transport of electrical energy from the places of production (supply side) to places of consumption (demand side). Today, the European power grid spans 29 countries on three continents with more than 10 million kilometers of power lines, transferring over 3,500 TWh of electrical energy annually [16]. The electricity consumption in Europe is expected to increase by 2050 to 4,300 TWh, while the ratio of energy produced from renewable sources will increase to 50-80% from the current value of approximately 14%. Together with the planned liberalization of the EU electricity market, these drivers lead to enormous changes and emerging challenges for the development and management of the future smart power grids in Europe.

The operational goals of power grids are to ensure a reliable and quality power supply to all consumers by adherence to grid codes, i.e. the network specifications for the operation of the grid such as voltage level references at different transmission and distribution lines while maximizing the economic benefits (e.g. by minimizing power losses) of the distribution and transmission grid operation. Operational constraints are posed on the grid frequency and voltage amplitudes at all connection points. Furthermore, power flows through individual grid segments and transformer stations are constrained to prevent excessive power dissipation and equipment damage. From a societal point of view, the operation of the power grids should make the best possible use of all sources of renewable energy [17].

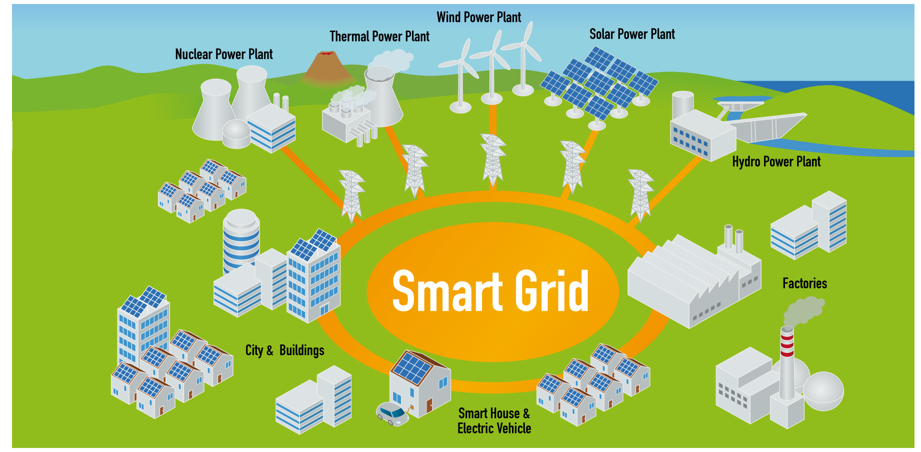
Emerging behavior

Because of the nature of the system, even the smallest imbalance in the produced and consumed power has immediate effects on system stability (frequency and voltage magnitude) that usually is absorbed by the systems due to their large scale [18]. This positive effect of systems integration, very similar to the creation of the human conscious mind by the networking of myriads of neural cells of human body, is a kind of emerging behavior of the system.

It is generally not known to what extent the disturbances occurring in the power grid can be mitigated by the system, and tight integration may turn out to cause negative effects on the system performance and stability. Several ill-understood phenomena, in particular oscillatory cross-continent behaviors, appeared in the past and may again be encountered with the growth and evolving nature of the system. Such situations are hard to overcome with today's technology because of the lack of online information and the difficulty to analytically model the system, taking into account its continuously evolving nature, heterogeneity, and the partial autonomy of the constituent elements.

Optimal decision making under incomplete information

Due to the largely local character of the electricity generation from renewable energy sources, an increasing number of non-negligible local oscillations in the power flow can be expected with the larger penetration of renewables. Their inherent volatility, e.g. in wind and solar power generation, must be instantaneously compensated on a system-wide level by the generation of power from non-volatile energy sources, for example by biomass, fossil-fuel or nuclear generation, while the consumed power also constitutes a time-varying load [19].



Variances in renewable power generation may appear on time scales of minutes and hours while the response to these variations is usually not as flexible. For example, it will take several hours for a large coal-fired power plant to ramp up its generation level to counterbalance an energy outage caused by variations in wind or radiation intensity due to weather conditions. A frequent use of counterbalancing techniques is not economical, and it would even require strengthening Europe's dependence on fossil fuels whose import accounts for € 300 billion annually today and which contribute strongly to CO_2 emissions.

A remedy to this situation lies in decision support and automated decision systems that calculate the optimal loads for different parts of the generation side of the network and are able to cope with the uncertainty in day-ahead predictions about the availability of renewable energy and peak load consumption taking into account weather forecast and correlations on the evolution of the electricity price on the spot market. Another important aspect is to integrate demand-side response so that the consumption of electric power is adapted to its generation, and to possibly use large industrial production units as regulating or even storage elements.

Distributed management

With the expected establishment of the electricity spot market in all the member states of the European Union in the future, market aspects will play a key role in the future. Producers and consumers of electricity will coordinate with each other to provide smart grid functionality only if forced by the introduction of a legal framework, or if the right market mechanism makes it mutually beneficial for them to do so. Determining the benefits and costs of different behaviors and allocating them to the different participants fairly will be crucial for the latter approach. If a certain power consumption is requested (e.g. because load aggregation provides ancillary services by bidding into the reserves markets), the market participants should distribute the requested loads among them. This would require the development of novel distributed optimization and distributed control methods, depending on how many loads participate in the aggregation, the economic relation between them, privacy issues, etc.

When the solutions building on two-way communication and control systems are implemented into the management systems of power grids, several security threats must be addressed due to increased amount of data transfers [20]. These include consumer privacy, data integrity, network-jamming attack detection, and maintaining continuity of service [21].

The smart electricity grids as envisioned today are only a part of the future energy landscape. There is a bidirectional interconnection of electricity with other energy carriers, for example with gas networks, heat/steam networks, etc. These interconnections need to be taken into account when designing the next-generation electricity grids and optimizing their performance. This is relevant not only at the level of micro-grids, which combine electricity generation and consumption with other energy sources, for example combined heat and power generation, but also for major prosumers such as industrial production facilities and big power plants. Additional information on the topic can be found in [22]-[29].

> Investments of several billion Euro are planned annually in the next years to convert the current power grids and their functionalities into a smart cyber-physical system of systems. These investments concern the development of the grid infrastructure, for example transmission power lines with direct current flow, or reinforcements of the distribution system that will receive increasing amounts of injections from locally distributed generation. These developments must be supported by the development of systematic approaches for the engineering and management of future power grids that support the sustainable development of society and meet climate and energy regulations. The most pressing needs are in the areas of system-wide robust operation, system resiliency, integration, and reconfiguration, taking into account the huge scale of the power grid as well as uncertainties connected with the penetration of renewables-based power injections and the possibility of structural changes of the system along its operation.

Smart Buildings

The concept of smart buildings was created to bring the benefits of modern technological developments to the everyday life of people through their experience of indoor environments such as homes, offices, shopping malls, etc [30]. Smart buildings are engineered to meet the, possibly time-varying, comfort criteria of their occupants by taking into account the weather conditions and the number and the behavior of the occupants. The changing conditions are often not known accurately in advance, which makes the engineering and operation of smart buildings a challenging task.

> Smart buildings are among the high-priority energy management topics in the EU. The building sector consumes around 40% of the energy used in Europe and is responsible for nearly 40% of greenhouse gas emissions. A smart building represents a system where its environment, the power grid with its subsystems, as well as other external material and energy networks (e.g. gas and water) interact by exchanging energy while providing comfort services to humans. The goal is to establish a reliable and sustainable technology for deploying green and zero-energy buildings that use all the available sources of energy efficiently and that, even proactively, assist to stabilize the resource and energy networks (in particular the electric power grid).

With the increased focus on energy efficiency, the deployment of renewable energy sources, and the development of smart grid technologies, a growing number of buildings and multi-building facilities (campuses) will also become active participants in the electricity market. From a systems point of view, such next-generation facilities will be autonomous entities with capabilities to sell or to buy electricity to/from the power network and to flexibly shift or reduce electrical loads when needed.

The energy system of a building or a campus of buildings can include any type of local energy generation, distribution, consumption, and storage elements. Frequently, a central combined heat and power (CHP) plant is a key generation element, and this means that a heat distribution network – and possibly also thermal storage – must be considered in addition to the electricity network for efficient energy management strategies.

The overall system management can be seen as a complex optimization problem formulated as a balancing between energy generation (supply side) and energy consumption (demand side), which are interconnected by distribution subsystems with carriers for commodities such as hot water, chilled water, and electricity. The renewable sources of energy, for example solar radiation or wind power, play a particularly significant role on both the supply and the demand side. This makes proactive energy balancing challenging, as optimal management tools use the predictions on the future availability of the renewables-based energy whose quality depends mainly on the accuracy of the weather forecast.

Humans in the loop

Occupants of buildings play a critical but poorly understood and often overlooked role in the building environment. Several studies [31] show that smart metering technology that is deployed to household users of the power grid, together with variable-pricing policies, shape the behavior and increase the situational awareness of the users. Questions such as how to influence users to use building equipment more rationally and how to affect the occupants to become more energy-aware are still open.

Personal behavioral strategies need to be further studied, and the factors and incentives affecting user behavior need to be better understood. Only then can the efforts for system approaches to proactive energy balancing be successful.

Privacy is an important matter in this respect. There is a need to respect the privacy of occupants and to avoid exposing details about their habits or lifestyles to third parties in order to increase the trust in the systems and to make human-building interaction effective.

Integrated engineering over the full life-cycle

The present state of the art of building management is to control and to optimize the system such that the daily demand for heating or cooling inside the building is met. The flow rates and supply temperatures are maintained around fixed set points that were specified during the system design. The current standard is to apply control schemes that are employed with rule-based control that defines supply set points using the current ambient and internal temperatures, and that are adjusted dynamically. These techniques in many cases do not take into account changing conditions, such as sunshine intensity, updates in the forecast of the evolution of ambient temperature, the daily expectations on number and behavior of occupants, and the evolving nature of the system (introduction of new and ageing of present components), in an automatic and optimal fashion.

The fact that the system behavior is subject to frequent changes, due to weather, human behavior, incidents, or changes in the system infrastructure, renders the transformation of human expectations about the conditions in the building into an effective response of the system a difficult and complex task.

Future research should aim at integrated, inexpensive, standardized, straightforwardly deployable application software which will embed the conventional cheap infrastructure into a highly intelligent mechanism for assisting the customers in significantly reducing their energy bills and environmental footprints and will enable the human operators to control and adjust the systems of high complexity, scale, and heterogeneity in a simple yet efficient manner.

Modeling, simulation, and optimization

Recent studies [32] have shown that for substantial savings in building energy consumption, no static assumptions should be made about the state and the operation of the building, and that dynamicity is an essential property to achieve energy efficiency in buildings. In parallel to optimizing energy consumption and performing automated adaptations, user comfort of course is the essential success criterion for ICT-based solutions.

The majority of today's advanced automatic management and control technologies require an elaborate model of the system to be available. In real-life applications, these technologies often turn out to be inapplicable due to absence of such system models, inappropriate modelling assumptions of the available models, computing limitations, and complexity trade-offs [33]. It is therefore recommended that the future developments of smart building technology are oriented towards increased fidelity of modeling, simulation, and optimization via standardization of models and their adaptation mechanisms, and via the creation of schemes that are robust to model insufficiencies.

Smart building technology promises a revolution in the role that buildings play in people's lives. The uptake of this technology can only come hand in hand with availability and reliability of data, the ability to make an effective use of the available data (via advanced management solutions), and the demonstration of benefits and sustainability through new business models and when ensuring intuitiveness for use by human users.

> Smart buildings should be engineered to be operated in a flexible and proactive way, considering the time-varying demands of the inhabitants, their interaction with the system, weather conditions, electricity prices/tariffs, and other external parameters. The ratio between local generation and purchased electricity should be optimized with respect to dynamic electricity prices and CO_2 footprint, using storage capabilities to accommodate variations. Novel technologies and methodologies are needed for optimal management that provide adaptability, flexibility, and stability, and that reflect the distributed nature of the system, taking into account uncertainty in the models of the system, variability of external and internal conditions, and the interaction with the power grid.

The Importance of Cyber-physical Systems of Systems for European Society and Industry

Innovation, productivity, growth, and competitiveness

Despite the fact that many technological innovations originate in the US or Japan, Europe is a true spawn of ICT technologies, many of them being crucial for the development of technologies needed in the engineering and management of cyber-physical systems of systems. This is evidenced by the European origin of many global market players in areas such as business management applications, cyber security, computing, telecommunications, automation, intelligent building technologies, e-commerce solutions, cloud-based management software products, etc. The position of Europe as a technological innovator and an incubator of successful ICT business models is, however, not secured when taking into account demographic changes and established and emerging markets in Asia, America, or Africa. Europe should build upon its successful technological developments and provide opportunities for CPSoS innovations that are necessary and vital for transportation, the process industries, the energy sector, manufacturing, and smart building technologies. This way, new jobs are created, and a competitive economy is expanded, which is a prerequisite for sustainable growth.

Europe needs to capitalize on its expertise, and the successful exploitation of ICT in cyber-physical systems of systems generates opportunities to provide efficient, environmentally friendly, autonomous, and safe mobility in the automotive, aeronautics, rail, maritime, and logistics sectors; greater efficiency in management and operations for the process industries, manufacturing, conventional/renewable power plants, energy conversion, smart grids and smart metering; greater benefits to citizens via smart, safe, and secure cities, energy-efficient buildings, and green infrastructure (traffic management, lighting, water and waste management); and smart devices and services for smart home functionality, home monitoring, health services, and assisted living.

Green economy and energy efficiency

The European Union has identified energy and resource efficiency as a key step on the path towards a sustainable and green economy. The targets on this path for 2030 are a 40% cut in greenhouse gas emissions compared to 1990 levels, a 27% to 30% share of renewable energy generation, and 27% to 30% energy savings compared with the business-as-usual scenario. These targets cannot be reached within this short period of time only via building new and more efficient infrastructures and more efficient cars, power plants, processing sites, and buildings, but must be accompanied by the improved management and the re-engineering of already existing infrastructures and traffic, power, and production systems, e.g. by establishing tighter energy integration.

Transport accounts for a quarter of all emissions within Europe, and the expectations suggest that traffic will increase further and become a dominant source of pollution and consumption of fossile fuels in Europe. The building sector uses around 40% of the energy consumed in Europe and is responsible for nearly 40% of greenhouse gas emissions. The process industries and the energy sector are the biggest consumers of energy and raw materials.

These sectors must radically improve their energy efficiency and reduce their greenhouse gas emissions. In the energy-and resource-intensive industries as well as in transportation, there is large potential for efficiency improvements by improved management, operation, and control. Optimal planning and scheduling of production and of utilities such that the efficiency is maximized will lead to significant savings and greener economy.

The Importance of CPSoS for employment

Europe has a strong position in the ICT market with an ecosystem of world-leading suppliers and systems integrators. The embedded systems industry alone creates 50,000 new jobs every year, and Europe accounts for 30% of the world production of embedded systems, with particular strengths in the automotive sector, aerospace, and health. Today, the worldwide ICT market has reached € 2,000 billion and is still growing at 4% per year. Europe represents 34% of this market. The embedded ICT market is currently € 850 billion, with a fierce competition and strong players in the US aiming at the expanding market. Over the past ten years, a quarter of the EU GDP growth and 50% of the EU productivity growth were due to ICT developments. Differences in economic performance are closely related to the level of ICT investment and use. The ICT sector currently represents 12 million jobs in Europe and generates 6% of the EU GDP. It has been estimated that each worker in the sector contributes €105,000 to the economy each year, more than twice the EU average across all sectors. Thus, the European ICT sector is a powerful driver of sustainable growth and employment. It plays a major role in boosting innovation, creativity and competitiveness across all industry and service sectors.

The **automotive industry** is crucial for Europe's prosperity. The sector provides jobs for 12 million people and accounts for 4% of the EU's GDP. Manufacturing accounts for 3 million jobs, sales and maintenance for 4.3 million, and transport for 4.8 million. The EU is among the world's biggest producers of motor vehicles, and the sector represents the largest private investor in research and development (R&D) within Europe. The automotive industry also has an important multiplier effect in the economy, generating jobs in upstream industries such as steel, chemicals, and textiles, as well as in downstream industries such as ICT, repair, and mobility services.

The European **aeronautics** industry is a world leader in the production of civil and military aircraft, helicopters, drones, aero-engines, and other systems and equipment. It also provides support services, such as maintenance and training. The EU has a trade surplus for aerospace products, which are exported all over the world. Aeronautics is one of the EU's key high-tech sectors on the global market. It provides more than 500,000 jobs and generated a turnover of € 140 billion in 2013. The industry is highly concentrated, both geographically (in particular in EU countries) and in terms of the few large enterprises involved. A sizeable share of value added is spent on research and development.

The **rail** sector in the EU, which includes the workforce of the rail operators and infrastructure managers, employs approximately 1.8 million people with an estimated 817,000 dependent individuals. The European rail supply industry employs nearly 400,000 people and is a top exporter, accounting for nearly half of the world market for rail products with a market share of 84% in Europe and a total production value of € 40 billion (2010). There are large markets for rolling stock, locomotives, and infrastructure, and a smaller market for signalling and electrification.

Over 90% of world trade is carried by **ships**, the most economical and the least environmentally damaging form of transport. The growth in seaborne trade has averaged 4% per annum since the 1970s. The estimated numbers of active seafarers in maritime EU member states in 2010 are 254,119, but it is estimated that 4.78 million people are employed in maritime-related activities in ports and logistics that support the movement of goods.

The total number of direct jobs provided by the EU **energy sector** in 2011 is estimated at between 1.5 million (DG Energy) and 2.2 million (Eurostat, LFS). The electric power generation, transmission, and distribution

sector is by far the largest employer, providing around 55-60% of all direct jobs in the energy sector. The extraction of fossil fuels accounts for around a quarter of all direct jobs, while other activities (including oil refining, manufacturing, and distribution of gas) account for around 20%. The renewable sector is a growth area with jobs being created in wind turbine manufacturing and in biomass fuel supply. It is estimated that 417,000 additional jobs will be needed to meet the 20% renewable energy target.

With more than 30 million employees and a turnover of € 6,410 billion in 2010, **manufacturing** represents a major part of the European economy and is one of its largest sources of employment. It generates a vast range of products, from food and beverages to textiles and furniture to metal-based products and heavy machinery, on a large range of scales, from small enterprises that manufacture e.g. musical instruments to very large enterprises at the top of a large pyramid of parts and components suppliers collectively manufacturing complex products.

The **process industries**, including biotech, cement, ceramics, chemicals, minerals and ores, non-ferrous metals and steel, employ more than 6.8 million European citizens in more than 450,000 individual enterprises and generate an annual turnover of over € 1,600 billion. As such, they represent 20% of the total European industry, both in terms of employment and turnover.

Advanced techniques for the management and for the engineering of cyber-physical systems of systems will be crucial in making these systems perform better, to provide better services and better products at a higher efficiency. This will contribute to the sustainability goals of the European Union and to economic competitiveness.

Growth opportunities exist for the European industry especially as systems providers in all areas discussed before: transportation (road, rail, air, maritime), logistics, manufacturing, and process industries, electricity grids, water and gas, smart buildings. The performance of the systems and the quality of their engineering and deployment, in-time startup, and continuous operation without breakdowns and support of continuous improvement processes are major selling points to which better CPSoS management and engineering methods will contribute significantly. By high long-term performance, the vendors of systems and the suppliers of components from physical hardware to software solutions and integration services will secure and increase their global market share and the employment in Europe.

The users and operators of cyber-physical infrastructure systems (traffic systems, rail and air transport, buildings, electric grids, gas and water distribution systems) will profit from the even higher reliability and system efficiency, and from the continuous addition of new functionalities and improved system elements and replacement of outdated elements without interruption of service.

Better engineered and managed production plants in the manufacturing and process industries are crucial for the competitiveness of the producing industry in Europe, and thus cyber-physical systems of systems engineering and management methods will secure and increase the number of jobs in this extremely competitive sector.

Finally, software for cyber-physical systems engineering and management will be a growing field. Industrial-quality software solutions are crucial for the transfer of research results into real applications to improve the performance of the engineering processes and of the systems themselves. Opportunities exist here both for large vendors and for small and new specialized companies that provide independent solutions that can be integrated in and are integrating software platforms from the large vendors.

Core Challenges in Cyber-physical Systems of Systems

Core Challenge

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 and management structures, 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 management systems for reliable and efficient management of the overall system poses a key challenge in the design and operation of cyber-physical systems of systems. The following sub-topics must be addressed by future basic and applied research:

- Decision structures and system architectures
- Self-organization, structure formation, and emerging behavior in technical systems of systems
- Real-time monitoring, exception handling, fault detection, and mitigation of faults and degradation
- Adaptation and integration of new or modified 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 that constitute cyber-physical 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 constrained resources. The partial autonomy of the components from the overall systems-of-systems perspective leads to uncertainty about the behavior of the subsystems. Therefore, system-wide coordination must take into account uncertain behavior 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 emerging behavior 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 or, in short, emerging behavior. 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 behavior. Inputs from the field of dynamic structure or pattern formation in large systems with uncertain elements should 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 so that 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 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 down-times. Faults may propagate over the different layers of the management and automation hierarchy. Many real-world systems of systems 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).

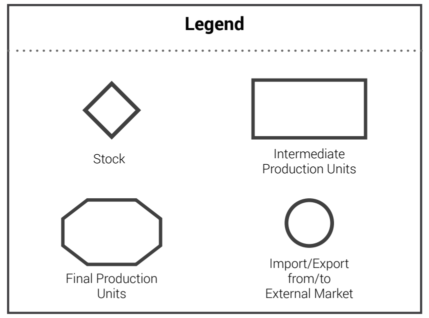
Humans in the loop and collaborative decision making

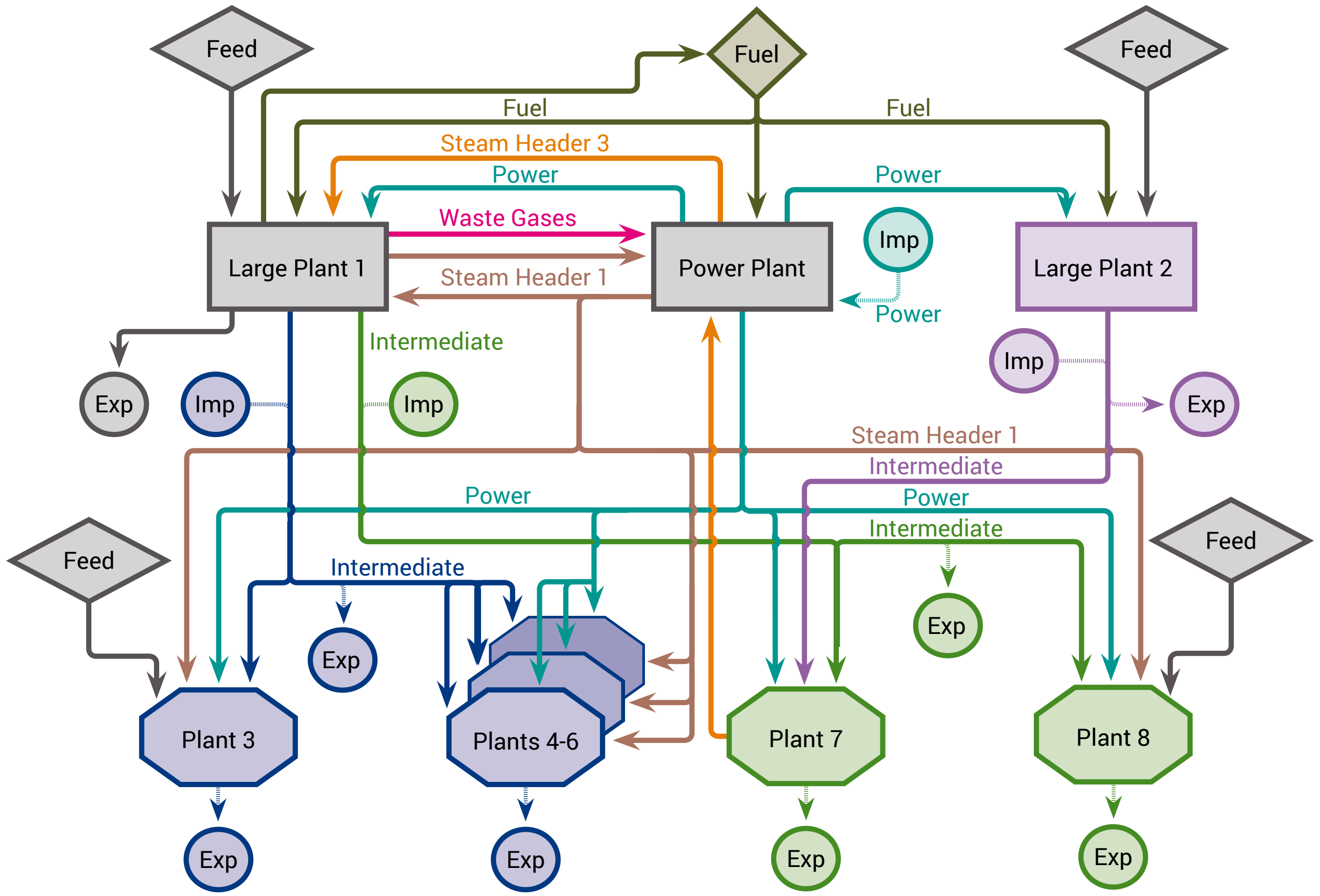
Human operators and managers play a crucial role in the operation of cyber-physical systems of systems because of their ability to understand the global behavior of the system and to react to previously not encountered situations. On the other hand, the interventions of humans introduce an additional 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, anticipating their behaviors, and modeling their situational awareness is needed. Social phenomena (e.g. the dynamics of user groups) should 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, shut-downs, or accidents, on the system level, e.g. power outages. The detection of such attacks requires taking into account both the behavior 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 and executed.

Example: Management of the Shared Resources in an Integrated Petrochemical Production Site





Integrated chemical production sites rely heavily on their interconnected infrastructure to exploit economies of scale and to ensure anoptimal use of energy and materials. These sites host a large number of autonomously operated production plants with complex interconnections by streams of energy and materials. The plants share limited resources (utilities, material streams, energy streams). The different plants may belong to different business units or even to different companies having their own individual economic goals and contractual obligations.

An example of an interconnected petrochemical site is schematically represented in the figure. Here a power plant is employed to burn off-gas and other waste from production units that can be incinerated to produce electric power and steam on different pressure levels that are needed by the production plants. Further complexity is added by production plants that feed different steam grades into the headers that are produced by auxiliary boilers or by reactor cooling. Thus, the management of the plant has to take into account continuous degrees of freedom such as the load and the distribution of the flow rates of the different types of fuels to the boilers and discrete degrees of freedom such as switching boilers on and off. The

Cyber-physical systems of systems are spatially or physically distributed systems that involve multi-layered decision processes. Thus, they cannot be managed and operated reliably and efficiently using traditional techniques, e.g. optimization that considers only one decision layer or control strategies that do not take into account the coupling between distributed entities. Distributed management and control methods must be designed to establish efficient, reliable, and robust distributed management through multi-domain and multi-layer coordination of decision processes of partially autonomous systems while considering humans aspects, built-in resiliency to faults, invulnerability to cyber attacks, and seamless reconfiguration for accommodation of new or changing components.

production rates of the plants as well as the steam production of the central power plant can only be changed at certain rates due to their inherent dynamics and equipment constraints.

The steam networks need to be run in a resource-optimal way in order to avoid the loss of energy by e.g. steam let-down or the loss of production due to steam shortages. The production plants are strongly coupled by flows of material, so their production rates cannot be changed individually. Load reductions of one unit will cause severe restrictions to other units, and in particular the cracker products must be used on the site or fed into pipelines at the contractual rates to avoid economic losses. The individual units strive at optimizing their operation economically and ecologically for given production targets. The connections to the other units to the steam network present complications in this endeavour that constraint the decisions of the units.

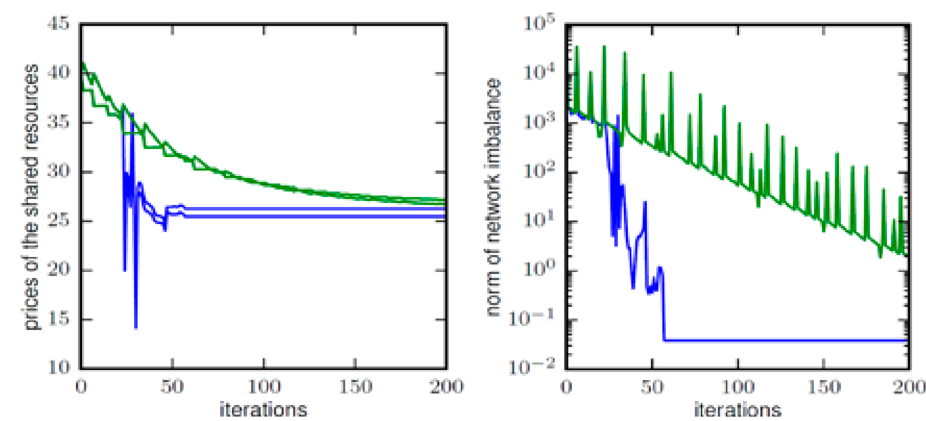
Characteristic features of such integrated production sites are:

- Complex networks of energies and chemicals are operated to enable the interaction of integrated production facilities, aiming at wasting as little of the energy, the raw materials, and the intermediate products as possible.
- The balance of the different units for changing throughputs is delicate and requires a careful coordinated operation of all units, as especially gas networks have only very small buffer capacities.
- The flexibility of production is limited by many different constraints on individual units which must not be violated in order to prevent accelerated equipment degradation, plant trips or similar events.
- An overall operational optimum can only be achieved by coordination of individual production units.

The basic task is the dynamic balancing of the production rates and the optimal operation of all the production units while fulfilling the requirements of the production planning within a certain horizon and while efficiently distributing the available shared resources. The industrial state of the art is the use of static planning tools and network balancing in meetings and phone calls between the different operating teams and the use of buffers in the system to smoothen short-term variations. Dynamic variations are only addressed on an ad-hoc basis.

Establishment of an automated solution to this problem results in the energy-optimal operation of a large petrochemical site which is a major step towards reducing the energy needs of existing chemical plants and can be extended to the planning of future integrated chemical sites.

One possible approach to management of the shared resources is based on the price-based coordination, which was explored in [34] and [35]. The coordination is based on market-equilibrium principle where the consumers and producers of utilies in the production complex are regarded as participants of the market which buy and sell the goods. The coordination among the managers of constitutive plants is then realized via a price-setting mechanism that automatically issues the prices of the shared resources based on their imbalance. The prices of these utilities are then reflected in the optimal production or consumption of the constitutive plants. This process is repeated until the market equilibrium, i.e. balance of shared resources on the site, is achieved. The distinct advantage of this coordination principle is that no transfer of internal information about the plants operation is required, only the consumption and production of shared resources is disclosed.



Core Challenge

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 poses 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.

In contrast to traditional systems, CPSoS are continuously evolving which softens, or even completely removes, the traditional separation between the engineering / design phases and the operational stages. They are highly flexible and subject to frequent, dynamic reconfiguration, and their high degree of heterogeneity and partial autonomy requires new, fully integrated approaches for their design, validation, and operation. These new approaches must also take into account that failures, abnormal states, and unexpected/emerging behaviors are the norm in CPSoS, and that CPSoS are socio-technical systems in which machines and humans interact closely.

New engineering support methodologies and software tools must be developed that are tailored to handle CPSoS with all their constitutive properties in the following areas:

- Integrated engineering of CPSoS over their full life-cycle
- Modeling, 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 stages necessitates new engineering frameworks that support the specification, adaptation, evolution, and maintenance of requirements, structural and behavioral 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, modeling and simulation tools, execution and runtime systems, …).

CPSoS usually are not designed and maintained by a single company, but instead many providers of components and software may be involved. Thus, collaborative engineering and runtime environments that enable providers to jointly work on some aspects of the CPSoS while competing on others are essential. 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 introduction of model-based design techniques does not come for free. It requires an initial investment and also constrains the freedom of the engineers to proceed in an ad-hoc manner. The advantages of new tools for CPSoS engineering may therefore not be immediately apparent to the end-users, in particular in smaller companies. Thus, the demonstration of industrial business cases and applications that illustrate the benefits of these technologies is important and should be supported.

Modeling, simulation, and optimization of CPSoS

Challenges in modeling and simulation are the high cost for building and maintaining models, modeling of human users and operators, simulation and analysis of stochastic behavior, 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. Model management requires meta-models that can describe models and modeling formalisms so that models can be transformed and connected automatically.

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 modeling and simulation of CPSoS is necessary, including stochastic phenomena and the occurrence of abnormal states.

The model-based development of cyber-physical 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 will lead to a situation where for all 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 over 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-criteria optimization in order to explore the design space.

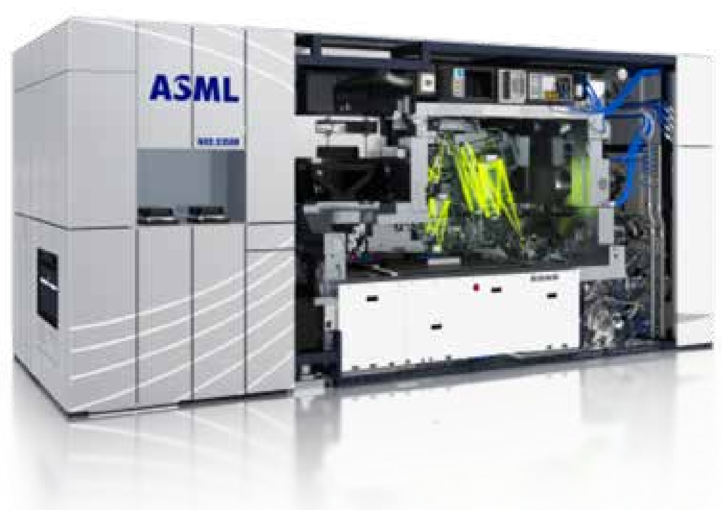
Establishing system-wide and key properties of CPSoS

Establishment, validation, and verification of essential properties of CPSoS are important challenges. 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 systems-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 connected, and the joint use of assume-guarantee reasoning and simulation-based (Monte Carlo) and exhaustive (model checking) verification techniques.

The engineering of cyber-physical systems of systems poses new challenges for engineering methodologies and software tools since CPSoS are continuously evolving and do not have a strict separation between the engineering and design phases and the operational stages. New, fully integrated approaches for their design, validation, and operation are needed for the integrated engineering over the full life-cycle and for modeling, simulation, optimization, validation, and verification.

Example: Ecosystems for Lithography Machine Development

Contributed by Jeroen Voeten, TU Eindhoven and TNO Embedded Systems Innovation, and Ramon Schiffelers, ASML, Eindhoven, Netherlands



ASML is the world's leading provider of complex lithography systems for the semiconductor industry. ASML is driving the exponential computer chip shrinking process as articulated in Moore's law in 1965. Lithography machines are highly complex Cyber-physical Systems of Systems, designed to be extremely accurate, deliver very high throughput and operate 24/7 to deliver exceptionally reliable results. Moore's law dictates a challenging roadmap of ever tightened performance and functionality requirements. Lithography systems have very long life times and are continuously customized to deliver the latest features to the customers.

Problem

The design process of these high-tech cyber-physical systems involves different engineering disciplines, each of them using a specific set of loosely coupled engineering methods and tools. As a result engineering conventions are easily disobeyed leading to errors that show at the moment when the subsystems are integrated. In addition it hampers the ability to reason about the realisation of system-wide KPIs (e.g. throughput versus accuracy) sufficiently early in the development process.

Solution

To keep up with the increasing requirements on performance, evolvability and predictability, ASML uses models for different parts of the system. Information that needs to be shared between disciplines are formalized in Domain Specific Modeling Languages that are used (i) by domain experts to specify their designs very precise and unambiguously, (ii) as input of synthesis algorithms for refinement and artifact generation, (iii) by model interpreters at runtime; and (iv) as inputs for various diagnostic purposes after deployment.

The use of Domain Specific Languages increases the understandability for domain experts by tailoring languages to express the essential domain concepts and only those concepts. Incorporating different levels of abstraction enables the disentanglement between the various pieces of information that originate from the several disciplines involved, supporting a seamless parallel multi-disciplinary development process. The languages serve as input for various analysis and exploration techniques during the design process. The analysis results are used as inputs to support key decisions where it has to be proven that a design based upon these decisions will work. In addition, these models are the starting point for automated synthesis and artefact generation and they are used to interpret diagnostic data from systems deployed at the customers.

MDSE ecosystems

Since there is not a single language, method and tool to address all these use cases, the realization of an intuitive integrated system development environment leads to an Model Driven Systems Engineering (MDSE) ecosystem consisting of several dedicated (modeling) languages and tools, and automatic transformations between them. It combines different formalisms and tools to specify and to analyse different kinds of properties such as timing (worst/best case, stochastic) and correctness (such as absence of deadlock, safety and progress properties). Examples of such ecosystems can be found in the domains of high-end motion control [36], (material) logistics [37], software design, supervisory control, and machine learning.

Challenges

Language ecosystems have proven to deliver effective design support, improving system quality and reducing development time. However, a number of challenges are still to be overcome to match the complexity increase. They concern design-patterns to support efficient analysis and synthesis, improved language support especially regarding language evolution, and support to deal with legacy systems.

To allow effective prediction and trading-off of key system aspects concerning performance, correctness, reliability and evolvability, a grand challenge concerns the identification and formalization of the semantic relations between domain models, across different levels of abstraction.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Core Challenge

Towards Cognitive Cyber-physical Systems of Systems

Systems of systems 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. A challenge here is the sheer complexity of systems of systems. Already, operators are struggling with the data deluge that has resulted from the explosion in the use of monitoring enabled by the increased interconnectivity and low-cost sensor technologies for data acquisition. In addition, gaining an overview of the entire system of systems is inherently complicated by the presence of decentralized management and control, which also introduces difficulties in understanding the potentially large number of interactions and consequences of operator interventions.

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. 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 four key subtopics have been identified as being necessary to support a move to cognitive cyber-physical systems of systems in the future:

- Situational 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 operational patterns from past examples and auto-reconfiguration and adaptation
- Analysis of user behavior and detection of needs and anomalities

Progress in all these areas and integration of activities between these areas is required in order to advance towards cognitive cyber-physical systems of systems.

Situational awareness in large distributed systems with decentralized management and control

In order to operate a cyber-physical system of systems efficiently and robustly, there is a need to detect operational changes in demand and to deal with anomalies and failures within the system. This can 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. There is a need for communication standards and also for agreement on data formats to improve interoperability of subsystems.

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 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. This will require significant processing capability as provided by the cloud and large-scale data management. There is a need for visualization tools to manage the complexity of the data produced, allowing managers and operators to understand the "real world in real time", to manage risk, and to make informed decisions on how to control and optimize the system.

> Cognitive systems are needed to help operators and users of complex cyber-physical systems of systems to deal with information overload and management complexity. This requires installation of sensors throughout large distributed systems to provide monitoring information to give situational awareness. These need to provide key information across the decentralized management and control system. A consequence of this monitoring will be a data deluge, and there is a need to handle large amounts of data in real time, not only to monitor system performance, but also to detect faults and degradation. Here, cognitive features can be added to learn good operational patterns from past known "good" operation and provide auto-reconfiguration and adaptation if failures or performance degradations are detected. Humans are also part of the control loop, and there is also a need to analyze user behavior, detect the needs of the operators, and recognize anomalities in operation.

Learning good operational 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. By introducing self-learning capabilities, systems can recognise normal "good" operation of a system and also detect when a system moves away from the norm. A challenge here is to relate the changes in the norm to known fault cases. This may require significant modeling of different fault scenarios or connection to relational databases of known previous failures. Additionally, to deal with the complexity of managing system faults, which is a major burden for CPSoS operators, auto-reconfiguration and adaptation features should be built into the system.

Analysis of user behavior and detection of needs and anomalities

Finally, it must be remembered that CPSoS are socio-technical systems and as such, humans are an integral element of the system. Cyber-physical systems of systems thus need to be resilient to the effects of the natural, unpredictable behavior of humans. There is thus a need to continuously analyze user behavior and its impact upon the system to ensure that this does not result in system disruption. This may come from misuse or unusual behavior of personnel who interact with systems at lower levels and also from misundertandings from poor interpretation of data and actions by operators.

A truly cognitive system requires the combination of all the subtopics highlighted. 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.

The Way Forward

Medium-Term Research & Innovation Priorities

Research & Innovation Priorities

Overview

The following pages describe 11 medium-term research and innovation priorities that should receive attention and specific targeted funding on all levels during the next 5 years in order to advance towards meeting the three core challenges in cyber-physical systems of systems engineering and management.

These priorities comprise seven cross-sectorial topics that are highly relevant and pressing in all domains.

In addition to these overarching topics, we have defined four research and innovation priorities that target specific domains, i.e. the manufacturing sector, the process industry, and transportation and logistics.

Cross-sectorial research and innovation priorities

- System integration and reconfiguration
- Resiliency in large systems
- Distributed robust system-wide optimization
- Data-based System operation
- Predictive maintenance for improved asset management
- Overcoming the modelling bottleneck
- Humans in the loop

Sector-specific research and innovation priorities

- Integration of control, scheduling, planning, and demand-side response in industrial production systems
- New ICT infrastructures for adaptable, resilient, and reconfigurable manufacturing processes
- Multi-disciplinary, multi-objective optimization of operations in complex dynamic 24/7 systems
- Safe, secure and trusted autonomous operations in transportation and logistics

Research & Innovation Priority

System Integration and Reconfiguration

Cyber-physical systems of systems consist of a multitude of physical components, computer hardware and software modules that are provided by a variety of different vendors. Today, many of the systems and software solutions in such complex systems are vendor-specific islands, and the integration of new components is expensive and time-consuming.

This state of the art severely hinders the deployment of novel technologies that can improve the performance and efficiency of CPSoS. These new technologies include real-time-capable Big Data applications for optimization, management, and decision support that rely on easy access to data from many different systems, as well as novel integrated engineering frameworks for the complete CPSoS life-cycle that allow engineers to design fault-resilient management and control architectures by an integrated cross-layer design that spans all levels of the design and automation hierarchies. The latter requires easy integration of the deluge of different design documents, data, and in particular models that are generated during the design and operation of a CPSoS. Easy integration of new components is also a prerequisite for dynamic reconfiguration (i.e. the live addition, modification or removal of components), which is a widespread phenomenon in CPSoS.

Reference architectures, open platforms, and easy-to-test interfaces for semantic integration of systems, data, and models must be developed. To enable dynamic reconfiguration, new mechanisms and tools for the plug-and-play integration and live removal of components are needed that support an incremental live validation of modifications to the system. These developments must be based on open (new or existing) standards and must be developed and demonstrated on industrially relevant business cases.

First steps in this direction are taken by the project *ARROWHEAD [38]*, which is funded by the *ECSEL Joint Undertaking* and develops collaborative automation architectures for several domains, including industrial production.

> The integration of systems, data, and models in today's proprietary CPSoS infrastructures is too expensive and time-consuming and hinders the deployment of cutting-edge technologies. Reference architectures, open platforms, and easy-to-test interfaces for semantic integration must be developed that enable the live, plug-and-play addition, removal, and validation of CPSoS components and the rapid and affordable deployment of new technologies.

Research & Innovation Priority

Resiliency in Large Systems

When an event or situation occurs in a large-scale system which does not correspond to its normal, designed behavior, this is referred to as an unforeseen event or abnormal state of the system. In large systems with many components, such faults and exceptions will almost always be present in some part of the system. While the safety of the overall cyber-physical system of systems usually can be guaranteed by local protection mechanisms, the performance of the overall system may degrade very quickly when unforeseen events occur. Often the system performance and the satisfaction of its users are more strongly influenced by the reactions to the unforeseen events, upsets, faults, and disturbances than by the carefully optimized performance in the nominal state.

Fault detection
There is a large need for detecting abnormal situations quickly, and for fail-soft mechanisms and fault tolerance on the local and on the systems level. By appropriate analysis of the frequency of abnormal events, countermeasures against frequently occurring faults must be triggered. Advanced data processing on the local and on the systems level should lead to early warnings of degradations so that appropriate countermeasures can be taken in time before abnormal situations occur.

System-wide fault mitigation
From a system point of view, the critical aspect of abnormal situations in some components is that their effects may propagate to the systems level and affect a large number of components and the overall system performance. To support continued operation, cyber-physical systems of systems need to be resilient, and mechanisms for trans-layer fault handling and mitigation must be engineered and validated. This is more easily achieved if there is a loose integration of the constitutive systems rather than a tight interaction, as can be achieved e.g. by storage elements between the elements of a production system or by the presence of unused resources. However, this leads to additional cost in normal operation, so the two aspects have to be balanced carefully.

Humans vs. machines
Automation systems have strategies in place to deal with many eventualities, from redundant devices to fault detection systems to safety shutdown systems, but there is a qualitative difference between how expert human operators will respond to an unforeseen event and how today's automation systems respond. Partly as a result of training, often using training simulators, pilots and process plant operators can continue the operation of an affected complex system in situations that would be beyond the scope of a fully automated system. Research is needed to develop automation systems that can exhibit human-like capabilities in such situations.

Fault detection and handling of errors or abnormal behavior is a key issue in cyber-physical systems of systems design and operation. The handling of faults and abnormal behavior 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. The sharing of tasks between humans and automatic systems in handling abnormal sitations must be investigated in detail.

Research & Innovation Priority

Distributed Robust System-wide Optimization

Given the managerial complexity of cyber-physical systems of systems, a fully centralized management architecture where a single entity precisely controls all system elements is not adequate. Rather, distributed, multi-agent architectures where decisions are made in the constituent systems in a semi-autonomous fashion are needed. The local decisions must of course be influenced by the information received from other agents (subsystems) or by signals from a coordinating entity. An example is the spatial and managerial distribution of the European power grid into country- or region-wise decision entities. This distribution is established historically and maintained because of the spatial distribution of the system and legislation reasons. Decentralization may occur also due to privacy and confidentiality issues where exemplary cases are traffic control, where human drivers refuse to give away information about their routes, or the coordination of production systems in industrial parks, which will not share information about their production levels or cost structures.

Distributed architectures
Architectures must be developed that perform effective distributed management, optimization, and control where the global problem is divided into a set of smaller local problem formulations. It must be studied how optimal, or close-to-optimal, decisions from a system-wide perspective can be obtained and which influence the decision architecture has on global optimality and robustness, and on the effort to compute them. Promising architectures may involve principles that are adapted from market theory, game theory, and population control.

Robust optimization
The partial autonomy of the components from the overall systems-of-systems perspective leads to uncertainty about the behavior of the subsystems. Moreover, model predictions always differ from the real behavior of a physical system as they do not involve all couplings, stochastic effects, and user interactions. Therefore, robustification of the distributed decision processes is needed. This can be realized, for instance, by a scenario-based approach that takes into account a set of disturbance models with extreme values of some important parameters (scenarios) and employs recourse actions to avoid conservative results.

Multi-criterial optimization and human decisions
In cyber-physical systems of systems there are often many competing decision criteria, e.g. quality of service vs. cost of operation. These should be tackled in a multicriterial fashion and adequate decision support for human managers or operators must be provided.

Due to partial autonomy, privacy issues, and spatial distribution, the overall optimization of CPSoS must be distributed into smaller local problems whose decisions are coordinated using a specialized architecture. The decision architectures must be capable of driving a CPSoS into the overall optimum despite the uncertainty that is present in the system, and external influences and restricted sharing of information.

Research & Innovation Priority

Data-based System Operation

Two major approaches exist in the engineering and research community for the management and control of cyber-physical systems: model-driven and data-driven approaches. In model-driven approaches, data is used in conjunction with a model to pre-process data (filtering, data reconciliation), to determine the state of the system (state and parameter estimation), and to improve the model (adaptation, system identification). Actions (e.g. optimal planning, scheduling, and advanced control) for maximizing system performance or fault detection are based on mathematical models, and on feeding real-time data to the models.

Purely data-driven approaches either fit general model structures (e.g. neural nets, Kriging models) to data to obtain predictive models or derive actions directly from observed system responses. With the increasing availability of real-time data that is collected during operation and the increasing computing power available, the idea that purely data-based techniques can complement or even replace model-based approaches in order to capture more information and to reduce the modeling effort seems attractive and should be explored.

Combining data-driven and model-driven approaches

One way to make effective use of data-driven techniques is to enhance physics-based models with correction elements that are computed from the data gathered from the system in real time. This way, the physics-based models can be adjusted online to improve the quality of the predictions of the model. Clearly, open issues are how to keep track of the validity region of the data-based model elements and how to control the speed of adaptation or forgetting of past data.

Data-based management and optimization of CPSoS

Another promising option is the direct use of collected data either to predict system behavior or to retrieve promising patterns of operation from the recorded data. Reliability, accuracy, and security of data are challenging issues that need to be resolved before such techniques can be implemented in real applications. Autonomous driving acts as a spearhead of technology development towards data-based autonomous operation of technical systems. However, cars and trucks are produced in large numbers while production systems or power plants are usually one or a few of a kind, so the effort for hardening the data-based operation schemes cannot be as high here, and most likely, the responsibility for the acceptance of the proposals of data-based management systems will rest with human operators. As a basis for data-based operation, data exchange standards that allow the seamless integration of systems, as well as engineering systems that propagate information on changes of the configuration as they happen frequently in cyber-physical systems of systems, are needed.

The rapidly increasing amount of data gathered and stored in cyber-physical systems of systems must be put to use in their operation and also when engineering changes of the systems. Real-time analytics of data from various sources must be combined with knowledge and models based on physical laws in an optimal fashion in order to steer the systems towards efficient use of resources, upset-free operation, and high quality of service levels at low cost.

Research & Innovation Priority

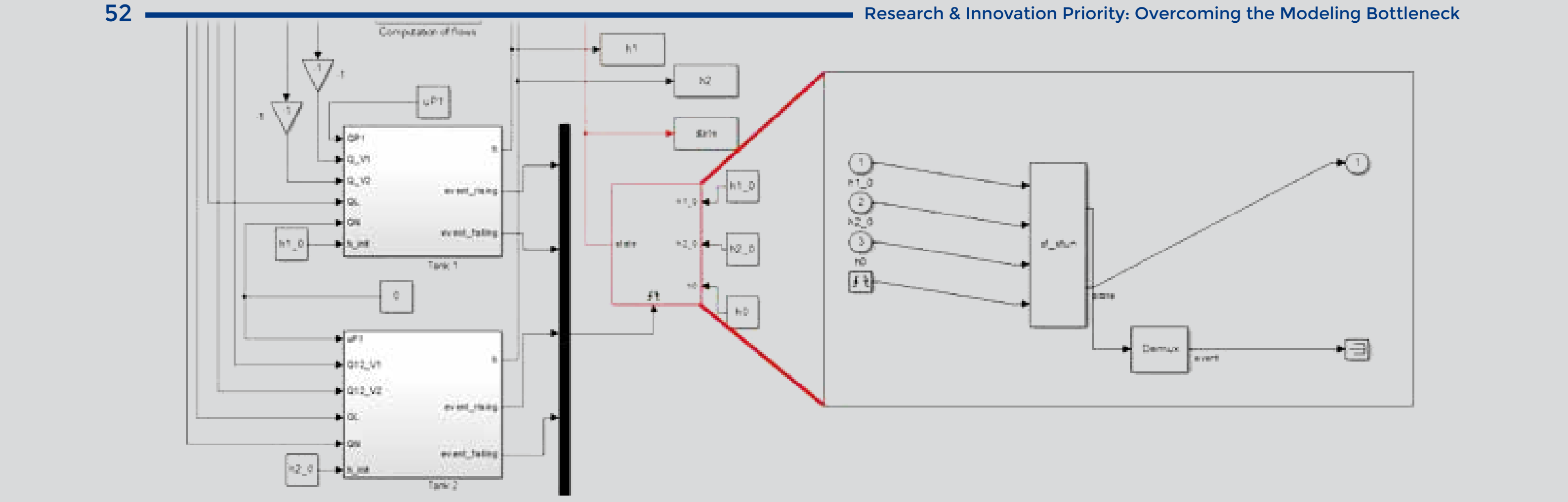
Predictive Maintenance for Improved Asset Management

Traditional maintenance procedures are based on schedule-driven manuals that rely on laboratory data and analytical predictions that were developed during design and manufacturing. Since the in-service conditions and failures modes experienced are generally complex and unknown, conservative calendar-based or usage-based scheduled maintenance practices are frequently used. These are time-consuming, labour-intensive and expensive. Also, as systems age, maintenance service frequency and costs increase whilst performance and availability decrease.

Increasing connectivity can be used to create a step change in asset management to continuous monitoring of assets in the field. On-line health monitoring offers the promise of a shift from schedule-driven maintenance to condition-based maintenance. Built-in sensor networks can be used to provide information on the condition, damage state and/or service environment of the system. The key change will be from diagnostics to prognostics. Information from sensor data can be used for prognosis of the health of the system. This will allow informed decision processes for inspection and repair. In future asset management will be performed based on the actual health and performance of the system, therefore minimising failures and maintenance costs, while maximising reliability and readiness. Real-time feedback will drastically reduce the person-hours currently expended in collecting data, better condition assessment and improved safety.

There are, however, a number of challenges that need addressing. In order to get reliable and sufficiently early information on impending failures it is necessary to install a myriad of sensors close to the source of failure, e.g. in bearings, actuators, etc. There is also a need to record a variety of data at different sample rates, from discrete positions, to e.g. high bandwidth vibration monitoring. There is a need for low cost, easy to install sensors. Wireless battery-less, self-powered sensors scavenging heat and vibration energy are expected to have great impact. Increasing amounts of data will be collected with the need to gather, store and analyse terabytes of data in real time every day. There is a need for supporting tools and techniques to scan across the assets looking for impending problems, data analysis and visualisation tools for interpreting data and decision support tools for notifying maintenance engineers when failures are predicted to occur and suggested courses of action to allow for a fast and prompt response.

The overall aim of predictive maintenance is to provide the right information, to the right person, in the right place at the right time. In order to do this there is a need for advances in sensors, tools and techniques to scan across the assets looking for impending problems, data analysis and visualisation tools for interpreting data, and decision support tools for notifying maintenance engineers when failures will occur. The final stage is to suggest the best course of action for a fast and appropriate response.



Research & Innovation Priority

Overcoming the Modeling Bottleneck

Models are the basis for systematic engineering processes, for improved management and operation, and for the realization of cognitive systems. Currently, the application of advanced methods for engineering and operations is severely slowed down by the effort that is needed to develop the required models, to maintain them when the system that is described changes, and to assess the quality of models and their adequacy for a specific purpose.

Model heterogeneity and re-use

In the foreseeable future, it will not be possible to describe a cyber-physical system of systems by one single monolithic model that covers all system elements and all system aspects. Rather, modeling, analysis and optimization will focus on the critical elements of the system for which detailed models are developed while other aspects are only represented coarsely. Different aspects, e.g. computing the expected throughput and safety analysis, require different model depths and formalisms. Furthermore, different models of different accuracies often exist for the same element and aspect of a system. This poses two challenges: Integration of heterogenous models in simulation, analysis and optimization, and documentation and management of a large variety of models and their relationships, underlying assumptions etc. The latter is also the prerequisite for the re-use of models based upon modular, object-oriented modeling.

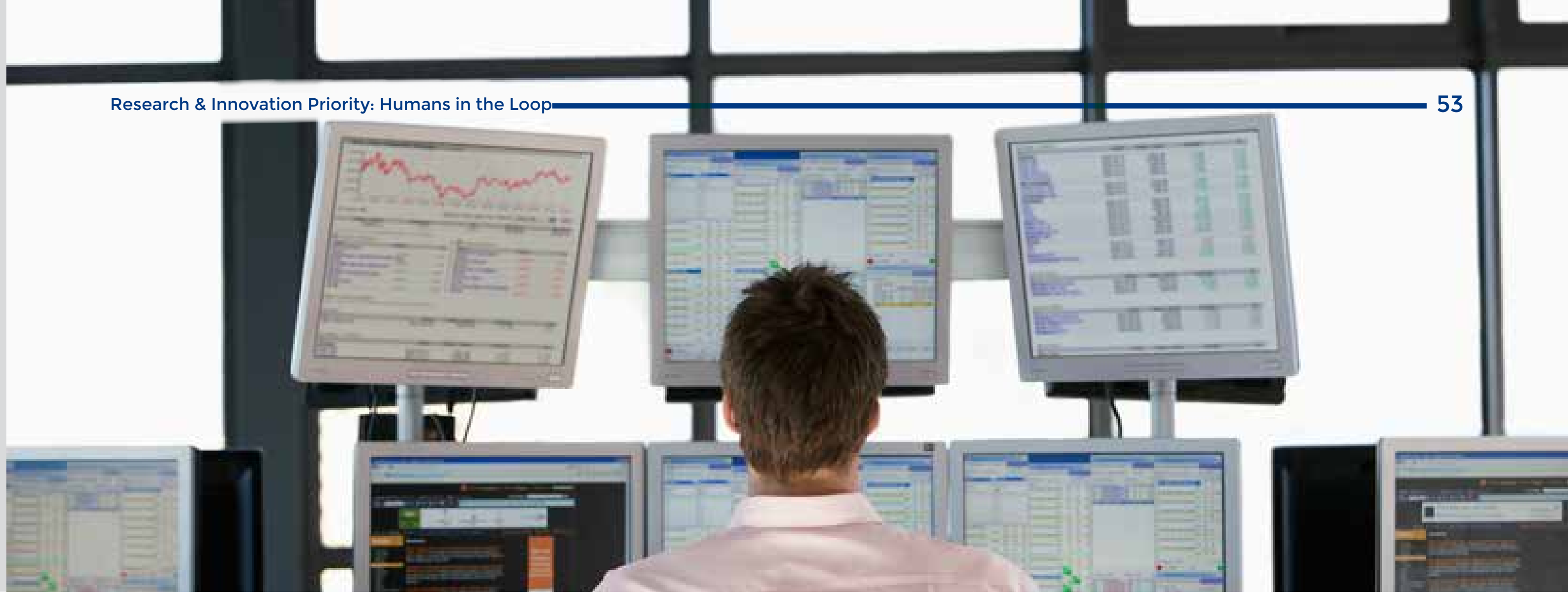
Combining rigorous and data-based models

When modelling physical system elements, two approaches are generally followed: Rigorous modeling based on the laws of physics and chemistry, and data-based modeling. Both have their strengths and disadvantages. In the future, it will be essential to combine both approaches into efficient modeling techniques. Basic relationships between the variables, e.g. mass balances, can easily be represented by rigorous model elements and need not be learned from data, but the effort for modelling all effects in detail can be prohibitive so that data-based models for the detailed behavior are easier to obtain.

Model adaptation

Even if a model initially provides a faithful description of the behavior of a system element, this may change over time due to quantitative and structural changes of the system or changes of the operating regime. The model quality, i.e. its predictive capabilities, must be maintained during the whole life-cycle of the system. For this purpose, the data gathered during operations must be used, and the key parameters of the model, where the influence is the largest, must be continuously adapted. This adaptation process will also provide information on the model reliability such that the uncertainty can be quantified and taken into account when using the model.

> The cost and effort involved in modelling cyber-physical systems of systems must be drastically reduced. This can be achieved by employing heterogenous modular models and combining data based models with rigorous ones. Models must be maintainted and adapted continuously over their lifetime so that he modelling effort will be paid off by long-term reliable and efficient system operation.



Research & Innovation Priority

Humans in the Loop

Cyber-physical systems of systems usually are not operated fully automatically, but the decision process is distributed among teams of operators and managers who may make use of available decision support systems if available. Usually, the operators act above automatic control systems that provide stability and reference tracking. The way in which the system is managed and operated is the result of the interplay of humans and computerized systems and is influenced by many socio-technical factors. If a computer-based solution is not intuitive or not presented transparently, humans tend to intervene and alter the decision suggested by a computer according to their past experiences. Thus, while being able to recognise problematic or abnormal situations early and reacting to them based on knowledge and experience, humans may introduce also an additional source of unpredictable behaviour in the system.

The role of humans in the management and operation of complex systems and their interplay with computer-based decision support systems or optimization algorithms is an area that urgently needs deeper investigation. Additionally, it must be studied how human attention evolves if humans are, on one hand, facing similar situations and must make similar decisions too often and, on the other hand, they can mostly rely on the correctness of the actions of an automated system.

Situational awareness

Operators and managers should be confronted only with relevant information that makes them aware of the current situation of the system and of possible courses of action. Overloading them with information must be avoided, adequate filtering and presentation of information must be established, and reliable early warnings must be issued.

Collaborative decision making

Cognitive models must be investigated to anticipate human decisions and to realize computer-based systems learning from experienced operators storing and retrieving good patterns of reacting to events when human intervention proved being beneficial for system performance and stability. This will lead to the creation of collaborative human-machine environments where the combination of the capabilities of humans and algorithms in real-time monitoring and decision making is realized to provide safe and near-optimal system operation under all circumstances and pleasant and rewarding working conditions.

Human Machine Interfaces (HMIs)

Innovation of HMI concepts and designs is required where new forms of interaction, enabled by e.g. 3D visualization and virtual reality technologies, are developed for the effective presentation of multi-dimensional information. Identification of the root causes of safety or performance issues, assessment of new operational scenarios based on historical data, and for influencing systems in an intuitive and interactive way will enable managers and operators to perform effectively and efficiently with minimal training.

> Operators and managers play a key role in the operation of CPSoS and take many important decisions. A symbiosis is needed between computer-based systems and human managers and operators. Selecting the information that is presented to the managers and operators well, and designing well-structured and easy to comprehend human-machine interfaces for the visualization of complex data and relationships are crucial.

Research & Innovation Priority

Integration of Control, Scheduling, Planning, and Demand-side Response in Industrial Production Systems

Currently, control, production scheduling, and production planning are performed separately top-down in a layered approach. The different decision layers operate on different time scales, follow different objectives, and use different models to represent the responses of the managed entities. Planning in large plants is based upon linear models for the behavior of the units of the plant. Scheduling often is performed manually on the plant or unit level based on experience or on standard operation data. On the control layer, the given set-points or sequences are implemented. There is little feedback and no tight integration between the layers, so potential for optimization is lost. As an example, the control layer should prioritize throughput optimization in high-load situations, and energy efficiency when utilization is low. Durations of operations or yields that are assumed on the planning and scheduling layer should be updated using information from the control layer.

A real-time information flow has to be established between the layers by synchronizing the communication across enterprise-resource planning (ERP), manufacturing execution system (MES), and advanced process control (APC) information systems.

Demand-side response

A crucial element of the present-day operation of industrial production systems is the utilization and local generation of electric power. In large production complexes, electric power usually is a by-product of the generation of steam, and the split between steam production and electric power generation can be varied. In addition, there is often a net import of electric power. With respect to the overall sustainability of the process industries in Europe and also to take advantage of the changing electricity prices with respect to the economics of the plants, coordination between the production planning and execution and the procurement of electric power and the internal generation is of high importance.

Procurement of electric power and production scheduling are usually dealt with as two distinct planning problems and addressed separately. Strategies to solve the overall problem jointly making use of the individual solutions must be investigated and integrated into the site-wide scheduling and optimization of large production complexes. This requires the integration of models used in different layers, such that these exchange relevant information, as well as integration of different software tools used at different levels.

> Production planning, scheduling and control and demand side response must be integrated more tightly in the future. The process industries may use surpluses of electric power from renewables to reduce their carbon footprint and stabilize the grid by demand side response.

Research & Innovation Priority

New ICT Infrastructures for Adaptable, Resilient, and Reconfigurable Manufacturing Processes

The increasing trend towards more personalized products that must be produced on shorter time scales and that are subject to quickly changing customer demand requires a large degree of flexibility and quick adaptability in manufacturing processes. This severely increases production complexity and the likelihood of errors.

Novel ICT infrastructures are needed that facilitate easily reconfigurable and resilient production environments that contain self-adapting smart componentst. These environments will have numerous benefits over existing systems in scenarios where flexibility and adaptability is required, such as down-time reduction, quicker replacements of tools and machine components, and increased production capacities due to higher utilization of the production hardware. In addition, they must be able to autonomously detect and resolve abnormal situations by adapting to the specific circumstances that caused an issue, or by giving early notice and information that helps human operators to find and resolve the problem quicky.

Research and innovation efforts are needed to develop ICT infrastructures that support a seamless and low-effort reconfiguration of manufacturing systems for fast adaptation to changing demands. Production machinery must be equipped with a high degree of autonomy and the capability for self-adaptation in response to changing requirements. In the end, some degree of self-organization in production systems may be achieved.

These ICT architectures will have to rely on architectural patterns that provide consistency and simplicity for re-use, and they must provide semantic, "plug-and-produce" integration and reconfiguration capabilities. Standardization is essential to facilitate interoperability and vertical integration of smart components.

Other important challenges are to develop new modeling approaches for such flexible systems, where models will have to be multi-disciplinary, context-aware, and must account for human interaction, and to develop novel real-time coordination, control, monitoring, and optimization solutions.

> To adapt to the trend of product personalization, short timescales, and quickly changing customer demands, novel ICT infrastructures are needed that facilitate easily reconfigurable and resilient manufacturing environments that contain self-adapting smart components. These infrastructures must support low-effort system integration and reconfiguration, based on semantic interface standards.

Research & Innovation Priority

Multi-disciplinary, Multi-objective Optimization of Operations in Complex, Dynamic, 24/7 Systems

Many of the challenges within Europe in the area of transportation and logistics arise from the fragmented infrastructure that has evolved over many years. There are many borders within Europe, and in order to operate transport across borders, there is a need for cross-border, cross-organisation cooperation leading to a natural need for systems-of-systems approaches in order to meet the pan-European transport flow of goods and people. In these 24/7 systems, there are the needs to improve capacity and efficiency, to reduce cost, to maintain continuous operation, and to provide resilience to disruption and failures.

To increase capacity and avoid congestion, there is a need to use existing infrastructure more efficiently by forecasting, coordinated control, and multi-objective optimization among subsystems, and optimal routing for dynamic traffic networks where there is an increasing need to be able to model multi-modal traffic and also the passengers as they move between transport modes.

ICT and remote connectivity to assets introduce the ability to perform increased "on condition" monitoring through deployment of sensors. This is expected to bring huge savings in infrastructure maintenance. Component systems will inevitably fail, may be unavailable for periods of time, or only offer degraded performance. To support continued operation, the systems of systems need to be resilient with requirements for dynamic and self-configuration. The ability to deal with these situations depends on the management and processing of real-time, high-quality data.

Consumer demand and government regulation are driving the transportation and logistics sectors to use less energy overall, emit fewer harmful emissions, and utilize an increased mix of sustainable energy sources. Countries around the world have agreed to CO_2 emissions targets that have been spelled out in the Copenhagen accord of 2009, with the EU offering to increase its emission reduction to 30% (from 1990 levels) by 2020. With the transportation sector emitting over 25% of CO_2 globally, this represents a significant challenge. To achieve greater efficiencies and reductions in emissions, operators are now turning to systems-of-systems thinking to optimize the use of assets to minimize fuel costs and emissions. This needs to be achieved while at the same time delivering increasing levels of service.

> Multi-disciplinary, multi-objective optimization is needed to improve capacity and efficiency to reduce the cost of transportation and logistics systems, and environmental concerns are driving the minimization of emissions. Transportation and logistics systems need to be available at all times and cannot fail as they are vital to the mobility of Europe. There are critical requirements to provide resilience to disruption and more efficient operation.

Research & Innovation Priority

Safe, Secure and Trusted Autonomous Operations in Transportation and Logistics

In the transportation and logistics domains, the increased use of ICT is seen as the answer to allow better scheduling of traffic flow, enabling increased communication with infrastructure and between vehicles, to reduce congestion and avoid accidents, and as a central element for future autonomy within systems to improve efficiency and increase safety.

Increasing levels of automation and autonomy are being pursued in all transport sectors. The aerospace sector is currently leading in this field, and autonomous features are expected in all other sectors as well, with many associated systems-of-systems challenges. In addition, safety is paramount in all transport operations and is a key driver in all related sectors.

In the future, there will be a much higher reliance on communication technologies between vehicles leading, in the longer term, to the integration of both manned and autonomous vehicles being operated in the same airspace, rail networks, maritime environments, and on the roads. Here, there is a need for interoperability, guaranteed quality of service, and security of communications.

Autonomous decision making will introduce socio-technical issues about what systems should be made autonomous and what should be left to the human operator. Here, there is also a need for homogeneous HMIs that allow users to interact easily and effectively with the system. Societal acceptance will be a key challenge, as will be trust. If a malicious entity managed to break into the system and cause an accident, there would be a total loss of public confidence. Systems thus need to be secure, but also need to fail safely even in the presence of a security breach.

Privacy is also a key issue as increasing interconnectivity results in a potential loss of privacy, and liability needs to be carefully considered to ensure that citizens, manufacturers, and operators have a clear framework in which to legally handle the consequences of the inevitable accidents when they happen.

> Across all transportation and logistics sectors, there is increased autonomy driven by safety and efficiency requirements. In order for autonomous systems to be accepted, they will have to be safe and secure to generate trust. Security is required to avoid disruption, and fail-safe mechanisms are needed to maintain safety. Monitoring will be required to maintain safe operation, but this will be at the expense of privacy. Inevitably, there will be accidents, requiring a liability framework to be in place, with interfaces that are easy to understand.

Conclusion

As we have described in this brochure, cyber-physical systems of systems have been emerging in many areas, from railway systems to industrial production and smart buildings. They are characterized by consisting of a large number of physical devices and computing elements that are interconnected both physically, by flows of energy and material and by the use of resources, and by flows of information between different computer systems and computers and humans. Due to these interactions, the resulting systems become highly complex, can exhibit emerging behaviour and are therefore difficult to engineer and to manage. The vastly increased amount of information and the new level of connectivity ("internet of things") offer unprecedented potential for more efficient operation, higher flexibility and adaptability, improved levels of reliability, and better quality of products and services.

To realize these potentials and to master the complexity of the cyber-physical systems of systems of the future, **new tools and methods for their engineering over the complete life-cycle and their efficient, safe, and reliable operation** are needed. Based on a thorough investigation of the state of the art in the application domains and in tools and methods, The CPSoS project has summarized three core challenges in engineering and management of cyber-physical systems of systems and proposed 11 topics on which research and innovation should focus during the next years. **Special attention should be paid to the interaction of cyber-physical systems of systems with humans**, as operators and managers who use computer-based systems to access the available information and to manage and control the systems, and as users who want to interact with the systems in an easy manner so that it satisfies their demands in a reliable and timely fashion.

The proposed research and innovation topics are **highly interdisciplinary** and must be tackled by teams from research institutions, solution providers, and end users with different backgrounds, from computer science, systems and control theory, software and systems engineering to HMI design and the theory of cognition and perception. Such joint efforts will ultimately lead to even more sustainable, safe and reliable production and infrastructure systems that are economically viable and provide excellent products and services, satisfy the demands of the users and provide satisfaction at work.

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