



## Project Deliverable

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### **Abstract :**

This document describes the state-of-the-art in the automotive, rail, aerospace, maritime, logistics, power grids, smart buildings and process industries sectors considering implementation of cyber-physical systems of systems and the state-of-the-art of supporting tools. In all areas there is increased physical and virtual connectivity of systems and the use of ICT enables improved capability, capacity, performance, safety and security. The complexity of the systems and their continuous evolution pose new challenges for engineering support as well as to systems management and monitoring. There is a strong need for systems of systems approaches in order to meet the demands of the European citizens for reliable infrastructures, efficient transportation, affordable high quality products, jobs in sustainable production and service industries and energy efficiency and smart living.

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# 1 Methodology and Basic Findings

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## 1.1 Purpose and Intent

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

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

CPSoS, funded by the EC (FP7 programme), is a 30-months Support Action that provides a forum and an exchange platform for systems-of-systems related communities and ongoing projects, focusing on the challenges posed by the engineering and the operation of technical systems in which computing and communication systems interact with large complex physical systems. Its approach is simultaneously integrative, aiming at bringing together knowledge from different communities, and applications-driven.

The project findings will be summarized in a concise strategic policy document "European research and innovation agenda on Cyber-physical Systems of Systems" supported by a set of in-depth technical papers, presented at a symposium "Cyber-physical Systems of Systems Meeting Societal Challenges".

The objective of this deliverable is to present and analyse the current state-of-the-art in engineering and management of cyber-physical systems of systems within the domains of transportation (automotive, rail, aerospace, and marine), logistics, physically connected systems (power grids, smart buildings, and process industries) and tools that support engineering and management of these systems. The report is a result of consultation with around 180 practitioners around the world from key companies and organisations identifying the key issues and needs.

In producing the report it was clear that cyber-physical systems of systems was a major topic in the transport sector and numerous examples of applications could be found. In the report key examples across Europe and beyond are presented along with commercial drivers. Drivers include demands for 24/7 operation, higher availability, improved safety, reduction in cost, reduction in emissions, pressure from competition on the world stage and government regulations. The increased integration of systems using ICT is seen as an opportunity to optimise operation providing potential monetary savings, improve capacity, improve safety and reduce emissions. The use of ICT is seen as critical in achieving industry targets and visions set out for the future.

This report provides a list of research and development topics that are categorized domain-wise as well as in terms of time horizons on which the different domain experts expect the presently identified challenges to be addressed and the corresponding solutions to be deployed.



## 1.2 Data Collection

Data has been gathered by a number of means as shown in Fig. 1. A key aim was to engage strongly with industry to understand the industry pull for cyber-physical systems of systems [1] and also the state-of-the-art in the area. Many industry sectors already build and operate cyber-physical systems of systems and so there is considerable practical knowledge of the challenges that need addressing.



Figure 1. Data Gathering.

The contributors of this document are 35 members (representatives of large industrial companies, SMEs and academic sector) of Working Groups of CPSoS project, participants of the four meetings (including three public meetings) of the Working Groups, 38 domain practitioners across Europe who were interviewed and 94 domain practitioners who contributed with written contributions. In the process of creating this document, 17 SMEs were involved and major networks were involved in the consultations, e.g. European Technology Platforms, IFAC TC on Process Control and EU-funded SoS projects – DANSE, AMADEOS, DYMASOS, LOCAL4GLOBAL, CyPhERS.

From transportation and logistics sectors, around 100 industry practitioners from large companies and SMEs have been contacted to this end. Table 1 gives examples of companies and organisations which contributed to this report.

Table 1. Examples of Companies/Organisations Who Have Contributed to this Report.

Airbus France and UK	Emirates Airlines	Martek Marine	SESAR – Air Traffic Control Org
Altran	ERRAC	Mitre Corp.	Sillitto Enterprises
BAe Systems	ESA	NASA	Thales France, UK and Australia
Boeing	Esterel	Network Rail	THHINK Japan Ltd
Car2Car Consortium	FastWave Australia	Peugeot (PSA)	Toyota
Cassidian	FMV	Pratt and Whitney	UPS
CEA-LETI	GE	Rail Infrastructure Technology Ltd.	Vector
Cummins	IBM	Renault	Volvo Trucks
DHL	Jaguar Land Rover	Rolls-Royce Aerospace and Marine	Wartsila
EADS	Lockheed Martin	Safran	Waterborne Technology Platform

There was a high response rate from industry indicating that there was real interest in the topic. Questionnaires have been collected from over 50 companies and telephone and face-to-face interviews have been performed with 12 key actors. Input from academics who have a strong relationship with industry has also been collected. This gives a view of the longer term research issues that need addressing. Already a cluster of EU projects is addressing systems of systems issues and input from these projects has been gathered. A questionnaire was also placed on the CPSoS website [2] and information has been gathered from the Internet to get as broad a picture as possible of activities going on around the world. Finally, the input and feedback from the eleven cross-sectorial members of the Working Group on Transport and Logistics has also been added.

For the state of the art analysis and identification of the future challenges in the domain of physically connected systems of systems, viewpoints of the many domain experts were collected as written contributions or collected by performing a series of interviews. The contributors are listed here with their affiliations:

- Vladimir Havlena (Honeywell)
- Alf Isaksson (ABB)
- Stefan Kraemer (INEOS)
- Francesco Massa Gray (Bosch)
- Karsten-Ulrich Klatt (Bayer Crop Science)
- Gregor Fernholz (Schneider Electric)
- Matthias Roth (BASF)
- Jochen Till (BASF)
- Sachin Arora (BASF)
- Kai Dadhe (Evonik)
- Manuel Remelhe (Bayer Technology Services)
- Felix Hanisch (Bayer Material Science)
- Norbert Kuschnerus (Bayer Technology Services)
- Petr Stluka (Honeywell)
- Santiago Blanco Polo (AYESA)
- Goran Pakasin (HEP-ODS)
- Marek Zima (Swissgrid)
- Ernst Scholtz (ABB Corporate Research)
- Francesco Brancati (ResilTech SRL, FP7 project AMADEOS)
- Gilney Damm (Supelec Paris, NoE HYCON2)
- Elias Kosmatopoulos (Technical University of Crete, FP7 project Local4Global)
- John Lygeros (ETH Zürich, FP7 project DYMASOS/Local4Global)
- Christos Ioakimidis (University of Mons)
- Theodor Sebastian Borsche (ETH Zürich)
- Christian Rehtanz (Technical University Dortmund)
- Cesar de Prada (University of Valladolid)

The majority of contributors comes from industrial sector where physically connected systems of systems (electric power grids, smart buildings, process industries,...) are engineered and managed. The contributors from academic sector, listed above, are actively involved in the research and development projects with industry.

For the state of the art analysis and identification of the future challenges in the support tools, viewpoints of the users and developers of various tools were collected as written contributions or collected by performing a series of interviews. The contributors are listed here with their affiliations:

- L.M.G. Somers (Océ Technologies)
- R. Howe (Verum Software Tools BV)
- J. Voeten (TNO-ESI)
- G. Hilderink (Wazalogic)
- R. Huisman (DAF Trucks NV)
- J.A.C.J. Jacobs (ASML)
- F.P.M. Stappers (Form ICT)
- M. Kuijper (FEI Company)
- K. Pahnke (HTSC)
- R.R.H. Schiffelers (ASML)
- T. Lochow (Airbus Group)
- E.-J. Huijbers (Alewijnse Industrial Automation)
- S. Almagro Frutos (Alten Mechatronics)
- R. Kherrazi (Nspyre)
- P. Mostermann (The MathWorks)
- G. Thomas (The MathWorks)

In the area of tool support, there is a particularly strong involvement of SMEs which focus on the application and deployment of new technologies originating from applied research. The presence of SMEs, among the contributors, is well-balanced by the presence of larger engineering software companies.

Additionally, for the preparation of this document, the 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 domains. The particular attention was devoted to recent projects addressing the research needs for innovations mostly funded under FP7.

## 1.3 Main Findings

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

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

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

Cyber-physical systems of systems cannot be designed and managed using theories and tools from only one single domain. The behaviour of the large coupled physical part of the system must be modelled, simulated and

analysed using methods from continuous systems theory, e.g. large-scale simulation, stability analysis, and design of stabilizing control laws. Also methods and tools from computer science for the modelling of distributed discrete systems, for verification and testing, assume-guarantee methods, contract-based assertions etc. are indispensable to capture both the behaviour on the low level (discrete control logic, communication, effects of distributed computing) and global effects, in the latter case based on abstract models of complete subsystems. Logistic models as well as models and tools for performance analysis of discrete systems will be useful for system-wide performance analysis. Finally, theories from physics, e.g. structure formation in large systems, and from economics and social science (market mechanisms, evolution of beliefs and activity in large groups) may also prove to be useful.

### 1.3.1 Identified Commonalities

The analyses of the engineering and management of cyber-physical systems in the domains of transportation, logistics, electric power grids, smart buildings, and process industries shows that there are common issues that need to be addressed in these sectors. The main challenges involve the engineering of systems of systems over their full lifetime, coordination and optimization of autonomously managed subsystems, modelling, simulation and model management, tools and methods for validation and verification on the systems level, humans in the loop, and systems integration.

Cyber-physical systems of systems are large systems that operate and are continuously improved over long periods of time. In many systems, from railways to chemical plants, the hardware (real physical hardware) infrastructure “lives” for 30 or more years, and new functionalities or improved performance have to be realized with only limited changes of many parts of the overall system. Management and control software as well usually has long periods of service, while the computing hardware base and the communication infrastructure change much more rapidly. Components are modified, added, the scope of the system may be extended or its specifications changed. So engineering to a large extent has to be performed at runtime.

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

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

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

When a new system is developed and deployed, the two activities of design and operational management usually can clearly be distinguished and often different groups of people are responsible for them. But later, the distinction is blurred, the experience gained in (day-to-day) management must be taken into account in revisions, extensions etc., and the operational management must also take care of the implementation of engineered changes in a running system. Validation and verification has to be done “on the fly”. This integration strengthens the role of models in both engineering processes. Up-to-date (because continuously updated) models of the running operation can be used for both purposes. If they are adapted to the real operational practice, they reflect

reality better than the original engineering models and can be used to investigate options for modifications as well as improved operational policies without modifications. The engineering of system of systems requires methods and tools that can be used seamlessly during design as well as operation (design-operations continuum).

A commonality across the sectors is the increased use of ICT for optimization and management of operations. The introduction of ICT and remote connectivity to assets also introduces the ability to perform improved condition monitoring of assets through the deployment of sensors everywhere. This is expected to bring huge savings in maintenance of the systems. A challenge here is the generation of big data and the need for tools to data mine large data sets to extract useful information. There is an opportunity to introduce new service industries in this domain. In the aerospace and marine domains maintenance service contracts are already being offered commercially by manufacturers.

Communication is seen as a key enabler in all sectors between subsystems (vehicles, smart buildings, chemical plants) and management systems (intelligent infrastructure, integrated power grid and supply chain). Here there will be increased communication between cars, aircraft, ships, and trains to allow safer operation and also operation of more vehicles. The increased communication rate is expected as well while building future smart grids and establishing optimal electricity management. Linked with this is the need for security of communications and also a need for guaranteed levels of Quality of Service. Safety and reliability is paramount in all operations of systems of systems in transportation, industrial production and distribution of electric power, gas and water.

Increasing levels of autonomy are being pursued in all sectors. The aerospace sector is currently leading in this field with autonomous vehicles already deployed for many years driven by military applications and enabled by the controlled nature of airspace. Cars are expected to introduce autonomous features by 2015 and many systems of systems challenges are predicted. The rail and maritime industries are also pursuing more autonomy to increase safety. For the rail industry plans are already well underway with roll out by 2024. In the maritime industry ships are becoming increasingly more autonomous but there is still quite a lot of work to do before ships can become completely autonomous. In the domain of physically connected systems, the main concern lies in the coordination of systems that are physically tightly interconnected but are governed by different authorities, pursue local goals (e.g. the maximization of local power generation from renewables) or are operated using local control policies. It was clearly pointed out by the representatives of the industry that such decentralized decision-making system must be coordinated but there exist very few automated solutions for doing so.

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

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

The challenges in modelling include the high cost for building and maintaining models and the difficulty of model re-use, modelling, simulation and analysis of stochastic behaviour, coupling tools of different strengths without

the need for re-modelling, the consistency of detailed and abstract models, and the effort needed for setting up models that include failure states and the reaction to these for validation and verification purposes.

Analysis of the behaviour of humans in the loop stresses the need of the identification of the capabilities of humans and machines in real-time monitoring and decision making and results in a challenge of optimal cooperation between human and machine decisions. Acceptance of advanced solutions by human users or operators is often a problem. If systems are sold in large numbers, like cars, a high development effort can be invested to make them completely automatic and/or robust against wrong behaviours of the human users and operators. This is not possible in domains where solutions are one of a kind and human intervention is needed to react to unforeseen situations and faults and to monitor the behaviour of the overall system. Humans may introduce an additional nonlinearity and uncertainty in the system and future research on the monitoring of the actions of the users and anticipating their behaviours might be a promising direction of progress.

### 1.3.2 Issues Identified

Underpinning development of the future systems of systems there is a need for a fundamental methodology to be developed for systems of systems engineering. Much of the infrastructure already exists so approaches to development are needed that can deal with legacy integration. A significant challenge is in developing new approaches to dealing with requirements engineering and model-based systems engineering that support systems that continually evolve and can never be considered to be finished. There is a need for comprehensive interdisciplinary heterogeneous, multi-scale modelling at different levels of resolution. This is needed for methodology development, multi-objective optimisation of performance, and for proving the economic benefits of increased integration/system-wide control as a means of unlocking investment. A key challenge here is gaining access to data and models which may be commercially sensitive/valuable. Modelling is also seen as key to giving confidence in safety and in identification of any emergent behaviours. For safety-critical and safety-related applications certification is required and this is complicated by the fact that the automotive, aerospace, rail and maritime industries have their own industry standards. Certification for a system of systems is particularly challenging as they are not predictable and predictability is a fundamental requirement for many certification standards. There is thus a need to think differently about validation and verification and come up with new standards/techniques for the different transport sectors.

Approaches to system wide control and coordination are required to deal with autonomy and increased interconnectivity. Increasingly autonomous decision making will be introduced and this introduces sociotechnical issues about what systems should be made autonomous and what should be left to the human operator, and the need for homogeneous HMIs that allow users to interact easily and effectively with the system.

The maintenance of systems is an issue and a complex system of systems will require a high degree of monitoring. To support this there is a need for low cost smart sensors, self-powered sensors and exploitation of the Internet of Things (IoT) to provide information and create new services. It is clear that 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. This highlights the pragmatic need for a loose integration of systems rather than a tight integration.

The ability to deal with the situations such as malfunctions and abnormal operations strongly depends on real-time availability of high-quality data and on efficient data processing. Thus a key challenge for the future is data management. This needs to address the data deluge problem via large-scale online data integration and analysis of heterogeneous data sets to extract information. Visualization tools are also needed to present a view of the “real-world in real-time”. Supporting this there is a need for data exchange standards that allow the seamless

integration of systems and provide interoperability. Challenges here are heterogeneity in the data but again also in maintaining security and privacy.

Across domains there are differences in the views in the readiness levels for development of CPSoS. In the aerospace sector the view is that engineers already have the capability to think and develop systems in a systems of systems way. In the automotive sector planned implementations of systems of systems technologies are currently underway but much of the concentration is on technical innovation at the hardware level and cost reduction rather than the issues of systems operation. Although in the rail sector systems of systems are the norm, engineers are not thought to think in a systems of systems way presently. In the marine sector systems of systems have evolved over the years but the concept of systems of systems is not a known term. In the area of logistics systems of systems is a very well-known concept. In domains of electric power grids, smart buildings and process industries, systems of systems solutions are rarely deployed. Many decisions that would require a systems of systems approach are done manually, conflicts between the constituent systems are solved via negotiations of managing personnel.

A key issue that was highlighted across a number of sectors was the need to provide convincing evidence that a new systems of systems approach will deliver the benefits expected. This is needed for investment and to convince companies to engage in systems of system activities. Proving that a systems of systems solution is “better” is challenging when the modelling of the systems is not possible and so the return on investment is difficult to justify. In many cases industry is funding systems of systems research activities because it is thought to be the “right thing to do”. Other challenges for industry are in coordinating implementation, rolling out a systems of systems, validation and verification, and operating and maintaining a systems of systems.

The size of cyber-physical systems of systems and their “multimodality” or hybrid nature consisting of physical elements as well as quasi-continuous and discrete controls, communication channels, local and system-wide optimization algorithms and management systems, implies that hierarchical and multi-domain approaches to their simulation, analysis and design are needed that are currently not available. In the individual domains, e.g. dynamic modelling and simulation, verification of discrete systems, design of controllers for guaranteed system stability on different system levels, and optimization of flows across a system, further progress can be expected that will have a high impact on the engineering of systems of systems. However the simultaneous use and the integration of heterogeneous models and tools to capture system-wide properties reliably and with firm guarantees are currently completely open issues. The critical properties of cyber-physical systems of systems reside in between what can be analysed and designed systematically today: dynamic reconfiguration of complex systems, large-scale dynamics, waves of events or alarms, interaction of autonomous, selfish systems, and coupling of physical and computational elements via communication channels.

### 1.3.3 Identified Research Challenges

The research challenges in the different domains of systems of systems and in methods and tools were discussed at several meetings with of the Working Groups of CPSoS, including public meetings with participation of domain experts and also discussed in interviews with external experts. The research challenges for the different domains and their prioritization are listed in the subsequent chapters of this report. The overarching challenges that were identified by the CPSoS consortium are described below.

It is recommended that these research topics are addressed in a European research agenda for development, deployment and maintenance of systems of systems in order to increase the quality of products and services, the sustainability of production, transportation and infrastructure services, and to secure employment opportunities in Europe in future. Defining a European research agenda on cyber-physical SoS, enhancing awareness, building constituencies are important steps for competitiveness and the impact of future European developments.

## Challenge 1: Engineering support for the design-operation continuum of cyber-physical systems of systems

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

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

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

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

### Integrated engineering of CPSoS over their full life-cycle

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

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

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

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



## Modelling, simulation, and optimization of CPSoS

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

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

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

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

## Establishing system-wide and key properties of CPSoS

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

## Challenge 2: Distributed, reliable and efficient management of cyber-physical systems of systems

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

management systems for reliable and efficient management of the overall systems poses a key challenge in the design and operation of cyber-physical systems of systems.

The following sub-topics should be addressed:

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

### **Decision structures and system architectures**

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

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

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

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

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

### **Adaptation and integration of new or modified components**

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

### **Humans in the loop and collaborative decision making**

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

### **Trust in large distributed systems**

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

## **Challenge 3: Cognitive cyber-physical systems of systems**

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

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

### **Situation awareness in large distributed systems with decentralized management and control**

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

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

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

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

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

### **Analysis of user behaviour and detection of needs and anomalies**

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

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

## 2 Cyber-physical Systems of Systems in Transportation and Logistics

### 2.1 Transport Infrastructure Innovation at the European Level

The European Commission supports a number of transport Technology Platforms that includes ERRAC [3], ERTRAC [4], ACARE [5] and WATERBORNE [6]. In 2001 the Commission issued a White Paper [7] setting a 10 year agenda for the European transport policy which was updated in the mid-term review of 2006 [8]. This highlighted that transport is a complex systems of systems that depend on multiple factors, including the pattern of human settlements, the organisation of production and the availability of infrastructure. Transport is an essential component of the European economy accounting for about 7 % of GDP and for over 5 % of total employment in the EU. Although the European transport system compares well in terms of efficiency and effectiveness with most advanced regions of the world, it is still not on a sustainable path. The open markets in Europe have led to more efficiency and lower costs which can be particularly seen in air transport, however, in other transportation areas there is a need to harmonise differences in taxation and subsidies. To coordinate the planning of infrastructure projects across Europe the Trans-European transport networks (TEN-T) policy has provided many benefits with an investment program of EUR 400 billion.

The TEN-T Guidelines [9] are the European Community’s instrument for policy definition and network planning. Adopted in 1996 and amended in 2004, the guidelines include two planning layers: a comprehensive network layer including outline plans for rail, road, inland waterway, combined transport, airport and port networks and a second layer of 30 priority projects. The TENs have already gone a long way in linking EU markets and peoples. Progress has been achieved in reducing air pollution and road accidents. Air quality in European cities has significantly improved through the application of stricter Euro emission standards addressing fine particles (PM10) which are particularly damaging for human health. The guidelines are also addressing expansion of transport infrastructure which result in habitat loss and landscape fragmentation.



Figure 2. Cross-Modal Transport Infrastructure Innovation Roadmap [10] and Key Routes Identified [11].

Key transportation routes have been identified across Europe covering road, rail and marine transport [10, 11] (See Fig. 2). Sustainability is a key issue and there has been a dramatic increase in both freight (35%) and passenger transport (20%) between 1995 and 2006. Along with this increase in traffic there has been an increase in emissions and within Europe transport accounts for a quarter of all emissions. The expectation is that traffic will increase further in all sectors and the infrastructure needs to support continuing increase in demand. Linked

with this is a drive to improve safety. There is an objective in the 2001 White Paper to halve casualties with respect to 2001 levels in road transport. Although not achieved in practice significant progress has been made. With still over 39 000 deaths in the EU in 2008, transport by road is still costly in terms of human lives. In the maritime sector, marine pollution and maritime accidents were considerably reduced and the EU has established one of the most advanced regulatory frameworks for safety and for pollution prevention (most recently with the third maritime safety package). In aviation, a comprehensive set of common, uniform and mandatory legislation has been adopted covering all the key elements affecting safety (aircraft, maintenance, airports, air traffic management systems, etc.). Safety agencies have been set up for aviation (EASA), maritime affairs (EMSA) and rail transport (ERA).

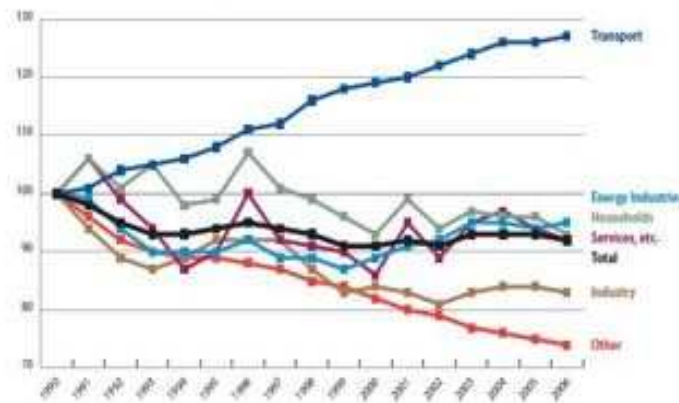


Figure 3. Data from the European Environment Agency [11] for total greenhouse gas emissions in different sectors.

The growth of transport activity raises concerns for its environmental sustainability. According to data from the European Environment Agency [11], transport accounted for close to a quarter (23.8%) of total greenhouse gas emissions and slightly more than a quarter (27.9%) of total CO<sub>2</sub> emissions in the EU-27 in 2006. No other sector has the growth rate of greenhouse gas emissions as high as in transport (See Fig. 3). As the transport sector relies on fossil fuels for 97% of its needs, the fight against climate change in this sector is also synergistic with energy security of supply. Europe’s roads have become safer in recent years: the number of road accidents involving personal injury fell by some 12% between 1991 and 2007. More importantly, the number of road fatalities dropped by more than 44% over the same period.

Freight transport follows trade activity and in recent years this has grown more than GDP. Passenger transport, excepting aviation, has undergone a less dramatic rise. These trends can only be sustained, however, if transport radically improves its energy efficiency and reduces its greenhouse gas emissions.

## 2.2 State-of-the-art in the Automotive Sector

Traffic management represents a highly complex System of Systems coming under increasing demands for additional capacity, greater safety and lower costs while meeting strict environmental regulations. 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, 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



Figure 4. Intelligent Transport Systems [12].

In the automotive sector Intelligent Transport Systems (ITS) [13] are being developed to provide innovative services relating to different modes of transport and traffic management (See Fig. 4). These will enable various users to be better informed and make safer, more coordinated, and 'smarter' use of transport networks. The aims are to increase journey efficiency, reduce congestion, improve road safety and reduce air pollution. An EU Directive (2010/40/EU) was issued on the 7 July 2010 [14] defining the framework for deployment of intelligent transport systems in the field of road transport. Here ITS are defined as “systems in which information and communication technologies are applied in the field of road transport, including infrastructure, vehicles and users, and in traffic management and mobility management, as well as for interfaces with other modes of transport”. Air pollution and congestion are issues in areas of high population density and integrated approaches exploiting combinations of walking, bicycle, buses and trains are advocated.

In the US similar ITS activities are being proposed, however, here a key driver is homeland security. There is a desire to provide surveillance of roadways and also a means for mass evacuation of people in urban areas as a result of natural disaster or threat. Among the technologies being explored under ITS are car navigation, traffic signal control systems, vehicle message signs, automatic number plate recognition and speed cameras. Opportunities to link with parking guidance and with weather systems are also being considered. For congestion avoidance advanced modelling techniques are being explored against historical baselines to predict and redirect traffic.

Another trend which is enabling ITS is a fundamental change in vehicle control systems. A typical vehicle in the early 2000s had between 20 and 100 individual networked microcontrollers using non real-time operating systems. The current trend is towards fewer, more capable microprocessor modules with hardware memory management and Real Time Operating Systems. This increased capability allows potential for more sophisticated software applications to be implemented based on model-based control and artificial intelligence.

Already a lot of work is being performed on "floating car" or "probe" data collection for obtaining travel time and speed data for vehicles traveling along streets and motorways [13]. This can be done from triangulation from mobile phones (which periodically transmit their presence to the mobile phone network), vehicle re-identification using sets of detectors mounted along the road to track a unique vehicle serial number (provided by Bluetooth MAC addresses or RFID serial numbers, e.g. from toll tags) as it travels down a road to give travel times and speed, or from in-vehicle GPS (satellite navigation) systems that have two-way communication with a traffic data provider. A key advantage of floating car data technology is that it is less expensive than sensors or cameras, it provides greater coverage, is faster to set up and maintain and works in all weather conditions including heavy rain.

Cameras are a common sight on today's roads and have been used for many years for traffic enforcement to detect and identify vehicles disobeying a speed limit (normally combined with radar detection), detect vehicles that cross red traffic lights, identify vehicles traveling in bus lanes, vehicles crossing railways, crossing double

white lines or incorrectly utilising high occupancy vehicle lanes (reserved for car pooling). Number plate recognition systems can be used to automatically issue tickets to offenders. However, more recently cameras are also being used for traffic flow measurement and automatic incident detection.

Cameras are considered to be "non-intrusive" as there is no need to install components into the road surface but they do require some configuration, e.g. input of known measurements such as the distance between lane or the height of the camera above the roadway. The typical outputs from a video detection system are lane-by-lane vehicle speeds, counts, and lane occupancy readings. Some systems provide additional outputs including gap, headway, stopped-vehicle detection, and wrong-way vehicle alarms. These systems have been successfully combined with variable speed limits that change with road congestion and other factors such as weather conditions. One example is the M25 Motorway that circumnavigates London. On the most heavily travelled 14-mile (23 km) section (junction 10 to 16) of the M25 variable speed limits combined with automated enforcement have been in force since 1995 [13]. The results indicated savings in journey times, smoother-flowing traffic, and a fall in the number of accidents, so the implementation was made permanent in 1997.

Inside of the car emergency vehicle notification systems (eCall) [15] are becoming more common driven by EU regulation and also insurance companies who are interested in driver behaviour tracking functionalities. In an emergency the vehicle occupants can manually eCall or the vehicle can automatically call via activation of in-vehicle sensors after an accident. The eCall device establishes an emergency call carrying both voice and data directly to the nearest emergency point. The voice call enables the vehicle occupant to communicate with the eCall operator. At the same time, data is sent containing information about the incident, including time, precise location, the direction the vehicle was traveling, and vehicle identification. The pan-European eCall system aims to be operative for all new type-approved vehicles as a standard option. Depending on the manufacturer of the eCall system, it could be mobile phone based (Bluetooth connection to an in-vehicle interface), an integrated eCall device, or a functionality of a broader system like navigation, telematics device, or tolling device. Going one stage further the EC funded project SafeTRIP [16] is developing an open ITS system that will improve road safety and provide resilient communication through the use of S-band satellite communication. This would allow greater coverage of the Emergency Call Service within the EU.

Work on the eCall standard has been ongoing for a number of years and currently it is targeted for implementation in 2017. This has been slowed by lack of support for it from some member states and currently other technologies are overtaking it combining the same functionality with congestion and traffic management information. In general telematics in the automotive sector, even for fleet and insurance operations, has a low uptake because of the cost of retrofitting it to vehicles which is far higher than for factory installed equipment. Customers are not currently asking for connectivity. The younger generation who are more interested in connectivity tend to live in big cities and have children later in life. The car sales to younger people are thus decreasing. Presently the interest is in providing in-car WiFi so that passengers can connect to services such as Apple CarPlay [17] and those being provided by the Android Open Automotive Alliance [18]. Going one step further Apple is producing wearable computing that connects with cars. The future could well be a "Google Dashboard" and Google are very interested in the automotive industry as collecting information from cars gives them free mapping information.

With the rise of communication technologies there is interest in "communication cooperation": car-to-car, car-to-infrastructure, and infrastructure-to-car. This can be used for warning drivers of upcoming hazards. An example of this is in Japan where installed sensors on highways are used to notify motorists that a car is stalled ahead. Transmission of car data to infrastructure opens up the opportunities to centrally fuse and process data to detect events such as rain (wiper activity), congestion (frequent braking activities) and ice detection (from ABS activations). Transmission from infrastructure to car can be used to provide driver recommendations to avoid



traffic or warn of hazards increasing road safety. The European Commission defines communication cooperation as

"Road operators, infrastructure, vehicles, their drivers and other road users will cooperate to deliver the most efficient, safe, secure and comfortable journey. The vehicle-vehicle and vehicle-infrastructure co-operative systems will contribute to these objectives beyond the improvements achievable with stand-alone systems."

A Network of National ITS Associations was officially launched on 7 October 2004 in London [19]. This Network is a grouping of national ITS interests formed in order to ensure that ITS knowledge and information is transmitted to all actors at the local and national level. The Network currently consists of 27 member organisations. The Network Secretariat is at ERTICO-ITS Europe and is a multi-sector, public/private partnership pursuing the development and deployment of Intelligent Transport Systems and Services. It connects public authorities, industry players, infrastructure operators, users, national ITS associations and other organisations together and works to bring "Intelligence into Mobility". The ERTICO work programme [20] focuses on initiatives to improve transport safety, security and network efficiency whilst taking into account measures to reduce environmental impact. The vision is of a future transport system working towards zero accidents, zero delays with fully informed people, where services are affordable and seamless, the environment is protected, privacy is respected and security is provided.

In the United States, a similar activity is being pursued but here each state has an Intelligent Transportation Systems chapter that holds a yearly conference to promote and showcase ITS technologies and ideas. Representatives from each Department of Transportation (state, cities, towns, and counties) within the state attend this conference. At a worldwide level the ITS World Congress [21] is an annual event to promote and showcase ITS technologies organised by ERTICO – ITS Europe, ITS America and ITS Japan. This event attracts over 8,000 people.

MIRA in the UK operates Europe's most advanced ITS test track, innovITS-Advance [22] dedicated to research and development of intelligent transportation systems (ITS). This utilises modern communication technologies, private GSM and cellular networks, fully configurable wireless networks and state-of-the-art vehicle-to-vehicle communications based on the draft 802.11p WAVE standard [23]. Work is investigating transport information, intelligent vehicles, and intelligent infrastructure, looking at a range of topics including OEM/aftermarket applications for congestion, hazards, tracking and fleet management, data management and modelling, real-time data sharing, integrated in-vehicle multimedia applications, aftermarket and integrated HMI solutions, secure communication networks, pedestrian safety, vehicle positioning and sensor systems, co-operative control systems and autonomous systems.

### 2.2.1 ERTRAC Strategic Research Agenda for Road Transport

In Europe the ERTRAC Strategic Research Agenda [24] covers mobility, transport and infrastructure, safety and security, environment, energy and resources, design and production. It highlights a number of key research topics including traffic management, integration of vehicle and infrastructure systems, traffic management using ITS, data collection and processing, business models, optimisation of road space to ensure that vehicles (particularly HGVs) adopt routing systems that minimise adverse impacts, systems for segregating traffic with dedicated infrastructure and prioritised traffic management and methods to assist the booking of optimised slots for freight vehicles. The White Paper produced by ERTRAC [25] highlights a number of ongoing projects around Europe and also highlights the key role that exploitation of new ICT functionality will have on the future of ITS. In order to fulfil the aspirations of the Transport White Paper

there is a need to coordinate the development of systems of systems for surface transport at an EU level with strong political commitment.

## 2.2.2 Traffic Flow and Integration with Infrastructure



Figure 5. Policy Brochure on Traffic Management [9] and Intelligent Transport Systems [12].

The Transport Research Knowledge Centre (TRKC) consortium produced a Policy Brochure on “Traffic Management for Land Transport” [9] covering both road and rail on behalf of the European Commission’s Directorate-General for Energy and Transport (See Fig. 5). Although the use of railway signalling and traffic lights in cities have long been used for traffic management a key tenet of this brochure is the need for sophisticated integrated applications based on Intelligent Transport Systems. This is driven by realisation of the need to manage transport networks more effectively in order to maximise the use of existing infrastructure, provide a reliable service to the end user and increase safety, while reducing negative environmental effects. Urban and inter-urban traffic management research and applications are covered in this publication, including aspects such as network management, public transport priority, safety, punctuality and international traffic. Safety related to traffic management, e.g. speed management is also covered. The aim of traffic planning is to plan, monitor, control and influence traffic to maximise the effectiveness of the use of existing infrastructure, provide reliable and safe operation and address environmental goals. A further aim is to ensure fair allocation of infrastructure space (road space, rail slots, etc.) among competing users.

For road or rail transport the scope includes fleet management and timetabling, matching services and vehicles to meet demand and providing essential services while also fitting in with (or finding ways to improve) constraints caused by network capacity, driver shift patterns and technical aspects. For rail traffic the scope includes the bottom operational level of signalling systems and systems for train location; the intermediate level, consisting of the management of rail operations to enhance both the level of service to users and safety; and the higher strategic level, dealing with network access terms and capacity allocation. European policy has long promoted the use of rail in order to rebalance modal shift and encourage the use of this more environmentally friendly and safer transport mode. European rail policy has been developed in the last twenty years to open the competitive market for rail services, first in freight, then in passenger transport and to provide greater interoperability. This is expected to transfer more goods and passengers to rail, at a lower price and with better quality.

In the automotive domain the report highlights that research and deployment of ITS at the EU level is a key tool for traffic management and control to improve safety and user services and reduce the environmental impact of traffic, particularly at infrastructure bottlenecks. ITS applications for traffic management and control include

rerouting, Variable Speed Limits (VSL) with automated enforcement, lane control, dynamic use of the hard shoulder on motorways or access control measures such as ramp metering, as well as specific measures for freight such as information on Heavy Goods Vehicle (HGV) parking and “stacking” of lorries in the case of disruption. Cooperative systems, whether vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I,) will play an increased role in traffic management and control in the future. To achieve this coordination across countries and regions, as well as with vehicle and equipment manufacturers, is required. Automatic Vehicle Identification and Location (AVI/AVL) and Automatic Number-plate Recognition (ANPR) is a prerequisite in order to ensure full use can be made of traffic management and enforcement strategies. Existing Automatic Incident Detection (AID) measures can be supplemented by linkage with “probe” (or “floating”) vehicle systems.

Traffic control is not a new concept and inductive loops that detect magnetic field changes have been placed in road networks for many years to perform ramp metering in order to manage traffic congestion [13]. The simplest detectors simply count the number of vehicles during a unit of time that pass over the loop, while more sophisticated sensors estimate the speed, length, and weight of vehicles and the distance between them. Loops can be placed in a single lane or across multiple lanes, and they work with very slow or stopped vehicles as well as vehicles moving at high-speed. However, more recently advances in telecommunications and information technology, coupled with state-of-the-art microchip, (RFID Radio Frequency Identification), and inexpensive intelligent beacon sensing technologies, have enhanced the technical capabilities opening up new opportunities for more global control of traffic. Vehicle and infrastructure-based networked systems using infrastructure sensors installed or injected into the road or attached to buildings, posts, and signs, can be placed permanently or during road maintenance to provide better monitoring of vehicles operating in critical zones.

### 2.2.3 INRIX

Founded in 2005 in Kirkland, Washington and with offices in the UK and Germany INRIX [26] combines data from 1 million miles of roads in North America and 1 million kilometres in 28 European countries to provide services in the car, online and on mobile devices for personal navigation, mapping, telematics and other location-based services. The company has 200 customers and industry partners worldwide including the Ford Motor Company, MapQuest, Microsoft, NAVIGON AG, TeleNav, I-95 Corridor Coalition, Tele Atlas, deCarta, TCS, Telmap, ANWB and ADAC.

Using the services drivers get information on the fastest routes and travel journey times that save time, money and reduce fuel consumption. The traffic data services include accurate real-time and predictive information, real-time incident and weather safety alerts, personalized traffic reports and route advice as well as historical traffic information. For fleet operators the company provides traffic congestion information which can be used to reduce fuel costs and optimise schedule planning. The company also provides information to media broadcasters on traffic congestion and estate agents on actual drive time to and from home and work based on traffic conditions.

### 2.2.4 CAR 2 CAR

The CAR 2 CAR Communication Consortium (C2C-CC) [12, 27] is a non-profit, industry driven organisation initiated by European vehicle manufacturers and supported by equipment suppliers, research organisations and other partners.

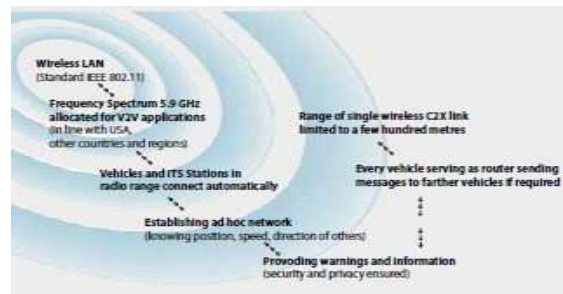
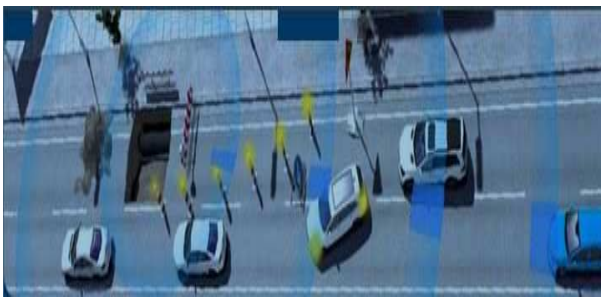


Figure 6. Car2car Communication consortium [27].

The C2C-CC (See Fig.6) [27] is dedicated to the objective of further increasing road traffic safety and efficiency by means of cooperative Intelligent Transport Systems (C-ITS) with Vehicle-to-Vehicle Communication (V2V) supported by Vehicle-to-Infrastructure Communication (V2I). It supports the creation of European standards for communicating vehicles spanning all brands. As a key contributor the C2C-CC works in close cooperation with European and international standardisation organisations. In cooperation with infrastructure stakeholders the C2C-CC promotes the joint deployment of cooperative ITS. The European Commission forecasts a heavy increase of vehicle kilometres. To improve mobility on the roads it has adopted the ITS Action Plan [28] indicating 24 concrete measures in 6 priority areas, with target dates spanning from 2009 to 2014.

An iMobility Forum has been created and a number of R&D programs including large scale field operational tests are being performed. These are expected to contribute to the reduction of road fatalities, improve efficiency and reduce the environmental impact of road traffic in all areas including smart cities.



Figure 7. Partners in CAR 2 CAR.

The C-ITS will provide new active safety measures to enhance the existing passive safety systems preventing or mitigating traffic accidents. As energy consumption and emissions need to be reduced and road traffic needs to exploit road capacities, new driving measures are required to support sustainability, e.g. green driving. The aim is to develop an open European standard for C-ITS with an associated validation process focusing on V2V Systems. This is to be supported with realistic deployment strategies and business models to speed up the market penetration and a roadmap for deployment of C-ITS (for V2V and V2I). A key aim is to also provide a validation route for these technologies. Specifications will be provided to the standardisation organisations, in particular ETSI TC ITS, in order to achieve common European standards for ITS. There is also an aim to push for the harmonisation of C2C Communication Standards world-wide such as 802.11.P and promote the allocation of a royalty free European wide frequency band for V2V Applications and joint deployment of C-ITS by all stakeholders.

The mandate M/453 of the European Commission [29] paved the way for the development of the minimum set of standards by the European standardisation organisations ETSI, TC, ITS, and CEN in 2012, ensuring the interoperability of C-ITS. Deployment will rely on these standards covering the whole communication chain,

including security and privacy issues and starting with day-one applications based on selected common message sets. The project will demonstrate the C2C-System as proof of technical and commercial feasibility.

The standard is close to finalisation and a MOU exists between the major OEMs (See Fig. 7) who have a plan to put various vehicles on the roads in 2015 (although this may be delayed and it is more likely that manufacturers will deploy cars in 2016). Critically day-one applications will reveal if the standards are sufficient and whether further work is required. The initial applications are concentrated on providing all the information in the car rather than having centralised information being sent to the car so cars will also utilise sensing radar, laser scanners and image detection. Importantly cars must be able to understand each other and not be dependent on the OEM.

### 2.2.5 DRIVE C2X

The DRIVE C2X project [30] has 34 partners, 13 support partners and an 18.6 million Euro budget. It aims to provide the foundations for cooperative systems in Europe with the aims of safer, more economical and more ecological driving. The project will carry out field tests of systems leading on from the PRE-DRIVE C2X which implemented technologies in European test sites in Finland, France, Germany, Italy, Netherlands, Spain and Sweden. An aim is to raise public awareness, provide feedback for standard organizations and support for initiating public-private ventures. The work focuses on communication between vehicles (C2C) and the roadside and backend infrastructure system (C2I). Previous projects such as PREVENT [31], CVIS [32], SAFESPOT [33], COOPERS [34], and PRE-DRIVE C2X [35] have proven the feasibility of safety and traffic efficiency applications based on C2X communication. DRIVE C2X goes beyond the proof of concept and addresses large-scale field trials under real-world conditions at multiple national test sites across Europe.

The systems to be tested are built according to the common European architecture for cooperative driving systems defined by COMeSafety [36]. This guarantees compliance with the upcoming European ITS standards. This approach also ensures that the results of DRIVE C2X have long-term validity at a European level, giving system developers as well as decision makers confidence.

To gather correct results from the field operational tests for cooperative systems, a technological basis is a fundamental prerequisite. DRIVE C2X relies on results from the PRE-DRIVE C2X [35] project in terms of specification, hardware and software prototypes, test environment and integrated simulation tool set developed. The basis comprises different technological components, namely the communication system (radio, communication protocols), facilities, human machine interface, applications and management.

DRIVE C2X is also implementing and testing a concept for the integration of a data backend, enabling commercial services based on C2X communication data to be developed for private and commercial customers. Such services are expected to become a major revenue source for cooperative driving systems and are key for successful implementation of this technology on European roads.

### 2.2.6 Mobile Millennium

Mobile Millennium [37] was developed by the California Center for Innovative Transportation (CCIT), the Nokia Research Center (NRC), and the University of California (UC) at Berkeley. The partnership began in 2006 when the National Science Foundation co-funded a joint US/European Union workshop in Helsinki. The aim of the work is to use mobile phone and navigation technologies to monitor real-time traffic flow.

In 2008 the Mobile Century project performed proof of concept work to test traffic data collection from GPS-equipped cell phones in one hundred vehicles driven on a 10-mile stretch of a highway located in the San Francisco Bay Area. The phones, which effectively served as vehicle probes, stored vehicle speed and position information every three seconds. These measurements were sent wirelessly to a server for real-time processing. The Mobile Century experiment enabled the design and development of algorithms and data collection systems to assemble traffic data from GPS-equipped mobile phones.

The aim of the Mobile Millennium project was to demonstrate the potential of GPS in cell phones to alter the way traffic data is collected, by using the existing cell phone infrastructure to collect data and transmit it directly back to drivers as a 24/7 consumer service. This was demonstrated in the Bay Area and New York City in November 2008 and remained operational until June 2010 with 2000 registered users. Mobile Millennium highlighted some future challenges that need to be addressed by transportation agencies and businesses before similar systems become more commonplace. These challenges include new procurement approaches that are focused on purchasing information rather than equipment, defining the respective roles (and business models) of the public and private sectors in provided traffic information to consumers, and trade-offs between individualized information delivered to a smart phone and distracted driving.

### 2.2.7 SMART – US Project

SMART (Sustainable Mobility & Accessibility Research & Transformation) [38], is a project of UMTRI, the University of Michigan Transportation Research Institute and TCAUP, the Taubman College of Architecture and Urban Planning, in Ann Arbor. The US SMART programme is working with Ford to undertake research and demonstration projects related to the sustainable future of transportation in an urbanizing world. This is driven by the need for sustainable transportation to cope with accelerating urbanization, population growth, globalization, and demographic shifts. Key issues are the environment, energy security, social equity, productivity, urban economies and livability. Recognizing the complexity of the challenge and the sophistication of the innovation required, SMART takes a systems approach to urban mobility. It is a university-wide initiative, working on new theoretical perspectives and practical, innovative, systems solutions.

### 2.2.8 US ITS Deployment – Sensys Networks

Sensys Networks is an American SME developing wireless sensor technologies for ITS. They are working on control of intersections and within the PATH project [39] on “connected corridors” which is concerned with coordinated control of freeways and adjacent urban streets. The timeline for implantation of these systems is 2-3 years with drivers for 24/7 operation, low cost, safety and mobility. A key aim is to provide the ability to get a layered view of operations from network level to individual intersections and compare real time and historical performance of road networks. The expectations are that this will reduce traffic congestion and the associated costs and emissions.

### 2.2.9 Autonomous Cars - HAVEit – Highly Automated Vehicles for Intelligent Transport

There is great interest in the automotive industry in introducing autonomous driving features to improve safety. The EU funded HAVEit project [40] has developed concepts and technologies for highly automated driving (See Fig. 8). The key drivers for automated driving are increasing traffic density, the growing flood of information available to drivers and the rising average age of the population. In Europe 1 in 3 people will be over the age of 60 in 10 years time. Automation is needed to relieve drivers of some of the stress of driving guiding them through traffic more efficiently with a consequent environmental benefit.

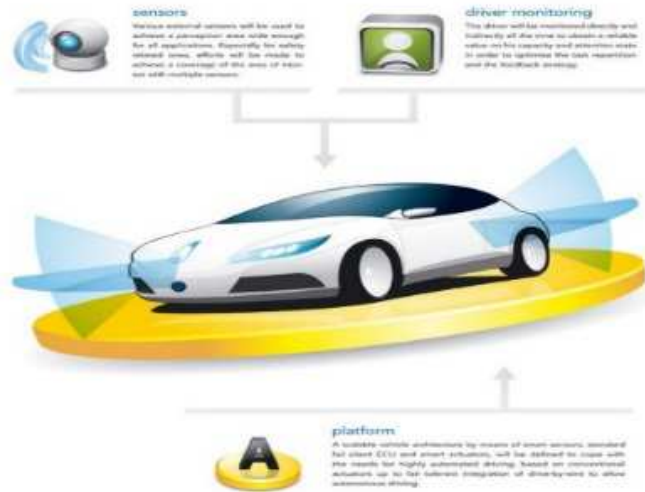


Figure 8. HAVE-it Autonomous Car.

This will help reduce driver workload, prevent accidents, reduce environmental impact and make traffic safer. The HAVEit consortium (17 partners) consisted of vehicle manufacturers, Continental, Volvo Technology AB, Volkswagen AG, automotive suppliers and scientific institutes from Germany, Sweden, France, Austria, Switzerland, Greece and Hungary. In total, investments of 28 million Euro were made into HAVEit, 17 million Euro of which were EU grants and 11 million Euro were contributed by the 17 partners. Seven demonstration vehicles were produced. HAVEit also aimed to bring together research and development resources across Europe and strengthen Europe’s international competitive position in a market full of technical challenges.

Highly automated vehicles can take over three main driving functions: steering (lateral automation), path planning (longitudinal automation) and navigation. These make driving easier for people and create highly automated systems which can be used intuitively. As part of the HAVEit project, three automation modes which can be selected and activated by drivers were developed and implemented in all demonstration vehicles.

- Normal - Lane keep assist and emergency brake assist
- Longitudinal automation - no need to accelerate or brake
- Lateral automation - no need to steer

In the first mode, the driver steers the vehicle alone, assisted by already-available standard driver assistance systems, such as lane keep assist or an emergency brake assist. In partly or semi-automated mode, the vehicle drives with longitudinal automation, so drivers no longer have to accelerate or brake. At the level of high automation, lateral automation comes into play, meaning the driver no longer has to steer. Despite the level of automation selected, the driver is always fully responsible for manoeuvring the vehicle and can take control in place of the system at any time. The driver also has to monitor the vehicle’s driving manoeuvres. In the partially and highly automated modes, the system observes the driver with the help of a camera located inside the vehicle. The moment the driver stops paying attention to the road, the assistant prompts them to take control of the wheel. The German Aerospace Centre (DLR) and the Wuerzburg Institute of Traffic Sciences (WIVW) developed the concepts of adaptive communication between the driver and the automated vehicle.

## 2.2.10 Drive Me

The Swedish Drive Me project [41] is a joint autonomous driving pilot project between the Volvo Car Group, the Swedish Transport Administration, the Swedish Transport Agency, Lindholmen Science Park and the City of Gothenburg with a vision for zero traffic fatalities. 100 self-driving Volvo cars will use 50 Km of selected public roads in everyday driving conditions around the Swedish city of Gothenburg to identify:

- How autonomous vehicles bring societal and economic benefits by improving traffic efficiency, the traffic environment and road safety
- Infrastructure requirements for autonomous driving
- Typical traffic situations suitable for autonomous vehicles
- Customers' confidence in autonomous vehicles
- How surrounding drivers interact smoothly with a self-driving car

The roads to be used are typical commuter arteries and include motorway conditions and frequent queues. The project started in 2014 with work on customer research and technology development, as well as the development of a user interface and cloud functionality. The first cars are expected to be on the roads in Gothenburg by 2017. An aim is that the Drive Me project will help define the role of self-driving vehicles in future city planning reducing infrastructure investments, lowering emissions and improving traffic safety. The driver will hand over responsibility to the vehicle, which can handle all driving functions at the driver's discretion, however, the driver is expected to be available for occasional control with a sufficiently comfortable transition time. For drivers autonomous driving is expected to provide more efficient time-management behind the wheel with the ability to interact safely via phone or tablets. The project will also investigate fully automated parking, without a driver in the car, such that the driver can walk away from the car at the parking entrance while the vehicle finds a vacant spot and parks by itself.

## 2.2.11 Google Car



Figure 9. Google Equipped Lexus Autonomous Car and Google Prototype Driverless Car.

Google has been working on a Self-Driving Car project [42] for several years to develop autonomous car technologies. This has resulted in the Google Chauffeur software. The company has equipped 6 Toyota PRIUS, 3 Lexus RX450h (as shown in Fig. 9) and an Audi TT with \$150,000 of equipment to allow autonomous operation. Google has also been active lobbying American states to allow operation of autonomous cars and has been successful in Nevada, Florida and California. By April 2014, the 10 cars had logged nearly 700,000 autonomous miles (1.1 million km). Google have also announced their own driverless car that has no steering wheel or pedals



(See Fig. 9). Google is not planning on commercial development of the system but they are interested in selling the system and the data behind it to automobile manufacturers.

## 2.2.12 Comments and Discussion

Individual vehicles could already be viewed as systems of systems if the requirements for physical separation of systems were relaxed. Given that at present cars have a driver then they could also be considered to be a CPSoS. Traditionally vehicle development is very component oriented and this has worked because the components had functionality produced by purely mechanical means and the majority of interactions between them was mediated by mechanical transmission of energy. In a modern vehicle the majority of the functionality is produced under software control and the interactions are mediated by information transmission. This has led to components having interactions with other components that they could never have had before. Also, because such interactions are now easy to set up the growth of such interactions has been exponential. This means that the traditional component based development is no longer suitable and OEMs are finding it very difficult to move to a more systems engineering approach. This involves major organisational changes, which can get very political and there are also issues with getting different engineering disciplines to work together, e.g. mechanical engineers need to understand the software/information based view of the system. There is thus already a need for research into organisation structures appropriate for systems engineering of large complex mechatronic systems and issues associated with organisation change. There are also needs for methods/notations/tools for the large representation of mechatronic systems.

The industry has been working for 10-15 years already on car-to-infrastructure and car-to-car communications. The key need here is a world-wide standard that covers Europe, American, Japan and China. Although a common standard is being agreed the software being used to implement the standard is different. Toyota and Denso for instance are developing their own version of the standard and Japan is some way ahead in terms of the technology as it is already used for communication between cars and tolls.

There is good progress on developing a standard for short-range communications using IEEE 802.11 protocols, e.g. WAVE or the Dedicated Short Range Communications standard being promoted by the Intelligent Transportation Society of America and the United States Department of Transportation. Longer range communications in the past have typically used UHF and VHF frequencies but the use of WiMAX and GSM/3G has also been proposed. This would require extensive and very expensive infrastructure deployment. It should be noted that a key requirement in any infrastructure implementation is the ability to be future proof and allow for future likely innovations. This is challenging as electronics typically becomes obsolescent in 18 months and a car in 10 years. An infrastructure investment needs to last 30 years or more and to operate the system requires built-in functionality for remote monitoring to allow for maintenance. Any widespread deployment of wireless sensors or communication nodes within infrastructure would preferably need to be self-powered to avoid the need to change batteries. There are a number of barriers to adoption including the difficulty of integrating with legacy equipment, justifying the need for investment to government and the slow and bureaucratic decision making process of government.

The industry view is that communication between cars and infrastructure is the future but there is a need for experience from day-one applications. A critical issue is the quality of the standard and this needs to work in all the member states. It is expected that deployment of day-one applications in 2015-2016 will reveal new problems which will identify new areas for research. It should be noted that the technology is expected to enhance safety, efficiency and emissions via enabling a better traffic flow. Even if only a few cars are equipped with the technology, e.g. 2-3%, then their modified behaviour will affect all other cars. Even staged roll-out of systems of systems resulting in incremental changes are likely to have a large impact. Cars that operate in stop and go traffic produce 30% more emissions and congestion tends to occur in urban areas.

The technology itself is quite mature and it is thought by the industry that suitable systems engineers exist to support development of ITS systems of systems but a challenge is to convince companies and government bodies to invest in the technology. As traffic congestion and delays are measurable and it is possible to prove that a new approach is better via modelling there is a means to justify investment. Modelling is thus thought to be a key issue, however, the experience is that this is difficult in practice. Modelling needs to show the benefits in terms of monetary savings through improved operations, lower maintenance costs and also improved capacity. A reduction in emissions is achieved through mobility improvements which can be measured by various metrics, e.g. delay, throughput, and emissions. These can be converted into monetary savings using established practice.

Car manufacturers believe that autonomous driving is an important technology to make road traffic more secure and more efficient but tools are needed to support development. The move to greater automation and eventually driverless vehicles is very much the current Zeitgeist and the whole industry is trying to move in this direction. A good overview of the various approaches has been produced by the EU funded TRAMAN21 project [43]. The majority of the work is on quite low level technical solutions, e.g. processor architectures, sensor technologies, data processing algorithms, but little is being done about how a population of such vehicles, mixed with more traditional vehicles, will actually behave, especially under fault conditions. It is unrealistic to assume that the designers will be able to anticipate all possible eventualities and put in place necessary and sufficient mitigations. This is because the scope of the system is effectively unbounded and therefore the number of eventualities is very large but also because 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.

Although increased autonomy is the future there are still technical and legislative hurdles that need to be addressed before a 100% autonomous car is possible. An example of this is that in some European Countries communication between traffic lights and cars is not allowed by law. There are fewer barriers to implementation in the USA.

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.

An example of the privacy problem has already been highlighted by an add-on GSM dongle that fits to the diagnostic port on a car from Delphi. Garages can retrofit these to customer's cars for free to let them know when something is wrong with the car by automatically transmitting the fault codes as they appear. The garage receives alerts from Delphi and can use these to contact a customer to bring a car in and fix it before it breaks down providing a service. An issue with the roll-out of this system in Europe was that the data was to be sent to a Data Centre in America. In order to operate in Europe, due to sensitivities over privacy, another European Data Centre is now being used and currently the system is only being rolled out in two member states because it also has the facility to track cars.

The issue of data privacy 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 also 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 is responsibility apportioned among a myriad of suppliers and sub-suppliers and what do 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.

The key enablers for the successful development of systems of systems in the automotive sector are thought to be advances in sensors, wireless communications and much better theory/algorithms/data. Little work is being done on the systems of systems issues apart from notably the Local4Global project addressing traffic management [44]. 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 systems of systems theoretical framework at present. There is also a need for tools to support quick prototyping of heterogeneous hardware and software for deployment.

## 2.3 State-of-the-art in the Rail Sector

The European rail infrastructure, a highly complex systems of systems, is facing increasing congestion due to unprecedented numbers of passengers requiring innovative ways to increase capacity on existing infrastructure (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. Here the systems of systems management, control and sociological aspects need to be considered in unison.

The interoperability regulations and the 2011 Transport White Paper [45] require that the European railway system behaves as a single systems of systems. The commercial drivers in the industry are for 24/7 operation, high availability, low cost, safety, increased capacity, recovery from disturbance, low carbon emissions and customer satisfaction. Already trains are operating across the European continent and the Commission requires a level playing field without barriers to competition. The main competitors to the rail network are 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. To achieve this there is a drive towards Automatic Train Control and automated maintenance to increase capacity and reduce costs to the point where rail operations do not require subsidy from government. Capacity is currently severely restricted due to controlling train movement through a system of blocks (sections of “reserved” track that no two trains can operate on). Moving blocks improve this but autonomous train-to-train communications and new infrastructure components could increase capacity by more than 100% with an asset value of billions. The 2011 Transport White Paper [45] requires the majority of medium to long distance journeys (freight and passenger) to be by rail. This is driven by congestion costs (1.5% of EU GDP) and the need for greatly reduced transport emissions. Priorities are set at national levels and within the UK for instance the funding for Network Rail is allocated using five year Control Periods that set specific targets in terms of infrastructure condition, renewals and customer satisfaction. Network Rail currently face an estimated £70M fine for failing to meet the 92.5% on time target so there are great incentives to improve. The EU is driving the railway industry towards a single system through interoperability requirements.

The industry also aims for a more resilient infrastructure and some of this resilience can be obtained by a better systems of systems to route traffic in an optimal manner responding to an incident. Systems of systems should have a better overview of the whole system rather than the more localised view of the individual control centres or signal boxes. This would improve capacity and operations reducing fuel costs while increasing revenue by carrying more passengers and freight on the same or reduced infrastructure. Key improvements expected from a systems of systems approach are:

- Improved capacity
  - Improved planning and operation with potentially more flexible timetables could deliver improvements in capacity, by optimising the timetables at peak periods to maximise traffic flow.
- Reduced Emissions
  - Improved timetable planning and operation, can lead to optimised driving to reduce stopping and starting to reduce emissions. A systems of systems approach may also provide the necessary planning

that would allow hybrid rail vehicles to just run the combustion engine away from stations and urban areas, reducing noise and urban pollution.

### 2.3.1 ERRAC Strategic research agenda 2020 for rail

ERRAC [3] was set up in 2001 with the goal of creating a single European body with both the competence and capability to help revitalise the European rail sector and make it more competitive, by fostering increased innovation and guiding research efforts at a European level. Within ERRAC, all major rail stakeholders are gathered, including 45 representatives from each of the major European rail research stakeholders: manufacturers, operators, infrastructure managers, the European Commission, EU Member States, academics and users' groups. ERRAC covers all forms of rail transport from conventional, high speed and freight applications, to urban and regional services. Since its launch in 2001, ERRAC has produced a number of important and influential documents, such as the Joint Strategy for European Rail Research – Vision 2020 [46], the SRRA – Strategic Rail Research Agenda [47] and its 2007 updated version, Suburban and Regional Railways Landscape in Europe [48], Light Rail and Metro Systems in Europe [49], Rail Research in Europe [50] and a comparison of the Member States public research programmes.

A set of roadmaps were developed in the EU funded (FP7) project ERRAC ROADMAP (2009-2012) and in 2012, an initial update of the ERRAC vision for the future of rail to support H2020 was released. This vision “Railroute 2050” [51], highlights the European effort required for research and innovation especially to meet the objectives of the European Commission 2011 Transport White paper “Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system”. RailRoute 2050 offers a range of research opportunities for a competitive, resource-efficient and intelligent rail transport system that meets the future demands of European citizens, stipulates economic growth, creates European jobs, and strengthens the position of the European rail sector in global competition. The European vision for railway research and innovation outlined in RailRoute 2050 illustrates the research pillars that need to be supplemented by the corresponding investment pillar.

Additionally, ERRAC launched FOSTER RAIL (2013-2016) [52] which will support development of a new full and complete vision, including the Rail Business Scenario and the Strategic Rail Research and Innovation Agenda.

### 2.3.2 European Rail Roadmap



Figure 10. European Rail Roadmap.

Between 2009 and 2012, ERRAC carried out a 3 year rail research roadmapping project called ERRAC ROADMAP (See Fig. 13) [53]. This highlights the needs for intelligent mobility, competitiveness and enabling technologies and infrastructure as priority research areas related to traffic management (See Fig. 10).

- In the area of intelligent mobility, the main issues deal with the definition of new management techniques to enhance infrastructure use. These include timetable optimisation, new fleet management tools, and development of information systems, as well as harmonised information exchange between stakeholders in cross-border traffic.
- In the area of competitiveness and enabling technologies, priorities include the compatibility of on-board data collection systems and their integration with communication networks, as well as the analysis of passengers and traffic flows in order to reach a more efficient Europe-wide train path allocation.
- Finally, in the infrastructure area, priorities include the development of train control systems and new operational rules in order to optimise both capacity and service interchange.

The roadmap indicates many technology advances are dependent upon utilisation of ICT. Here there are opportunities for use in infrastructure management and optimization across Europe and in safety management. Identified projects which address potential cyber-physical systems of systems issues are IMPROVERAIL, Excalibur, Lipari, Demiurge, INTERFACE, PROMIT, SAMRAIL, CENTRICO, SERTI, EasyWay, NEW OPERA, PARTNER, BRAVO, InteGRail, INESS and KOMODA.

### 2.3.3 UK Sustainable Rail and FuTRO Initiatives

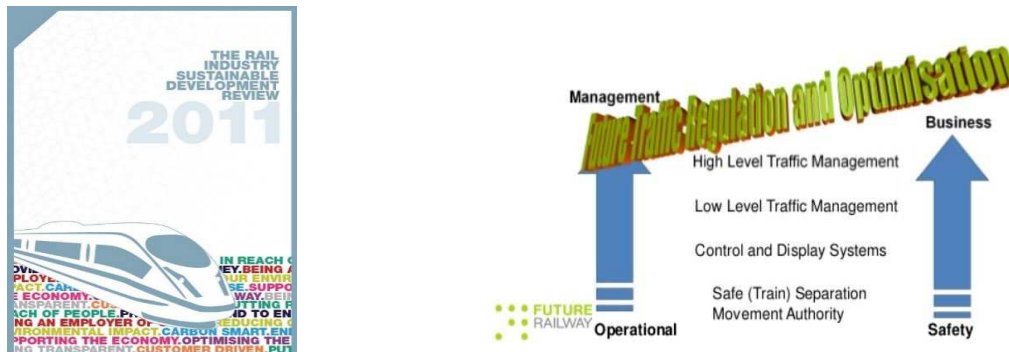


Figure 11. UK Sustainable Rail Programme [54] and FuTRO [56].

The UK’s Sustainable Rail Programme (SRP) (See Fig. 11) [54] supports the industry in meeting the challenges and opportunities of sustainable development. It is a cross-industry programme facilitated by the Rail Safety & Standards Board (RSSB). This body focusses on policy, strategy, and research for the rail industry in the UK. The Programme’s early work focused on agreeing key strategic cross-industry issues and reviewing cross-modal performance. Resulting from this the industry performed a sustainability review called “The case for rail”. In 2009, the programme published the Rail Industry Sustainable Development Principles (SD Principles) that covered social, economic and environmental issues. The intention of this is to provide a platform that can be used for embedding sustainability throughout the UK Rail industry. The SRP has focussed on embedding the SD Principles into industry decision-making processes resulting in a number of activities. The SRP was used to develop the industry carbon trajectory and ambitions for CP5 (the UK rail industry investment is managed over 5 year Control Periods). To support this a railway carbon accounting tool was created. Additionally, a web-based tool was developed to help industry organisations assess their performance and strategy against the SD Principles. The tool has recently been used in planning for capacity enhancement at Waterloo station. The SRP has also provided a response to the EUs Environmental Noise Directive [55] in 600 areas identified in noise mapping and provided

guidance for industry and partners based on the results of ATOC's (Association of Train Operating Companies) station travel plan pilot programme.

Transport integration at the systems of systems level is seen as fundamental to a sustainable transport system. It is acknowledged that while rail can provide the core element of many journeys there will always be a beginning and a section of travel that is not rail. In a National Passenger Survey in Spring 2011 73% of people in the UK thought that connections to other forms of transport were "satisfactory or good", however, of note is that this figure has not changed in the last 5 years. To understand why people do not use the rail system ATOC in the UK engaged with non-rail travellers. This identified that price is the biggest barrier but time and convenience for the whole journey is also a significant issue that needs to be addressed. A study was performed identifying that the best value for money to address this problem would be to improve access to stations and reduce the interchange time between modes (passengers are particularly unhappy about having to wait for connections). ATOCs Station Travel Plan pilot project is covering 31 stations in the UK. This plan identified needs for partnerships with local authorities, wide stakeholder consultation, appropriate resourcing and the need for robust data.

Another key initiative is to optimise the railway to maximise the rail systems capability and efficiency to provide good value for money. The average annual UK public investment in rail has been around £5bn. This figure is reducing as improvements are expected in efficiency and passengers are expected to bear more of the costs. In terms of benefit an audit of the UK rail spending indicated that every pound spent on the railway delivered 2 pounds of benefit. This has been achieved in a variety of ways and a major one has been through improvements in capacity. The UK rail network has been the fastest growing network in Europe over the past 10 years. Passenger numbers have increased by 43% and rail freight has increased by 60% making it one of the busiest mixed rail networks in the world. In 2010 1.3 billion passenger journeys were made over 33 billion miles. A result of this is that some sections of the network have reached their limit in terms of capacity and between 2009-2014 £12bn has been invested in projects to improve capacity such as lengthening stations and allowing more trains to run.

Systems of systems approaches that can further improve capacity are thus of high interest. Network Rail has agreed to 23% efficiency savings for the funding period 2009-2014 following achievement of 27% savings achieved in the previous funding period. A further 30% reduction is believed possible by 2018/2019 and a challenge is to deliver this while maintaining operational performance and safety. The Technology Strategy Leadership Group in the UK is now investigating traffic management and disruption management as a means of doubling capacity. Key areas being looked at are bottlenecks, the relationship between reliability and capacity enhancement and control methods to safely reduce the distance between trains.

Looking more long term the Future Traffic Regulation Optimisation programme (FuTRO) (See Fig. 14) [56] is part of the UKs Rail Technology Strategy 2012. It is addressing how regulation of trains in the UK must change, adapt and improve looking 40 years into the future. The scope of FuTRO is very wide and includes many different aspects and systems in creating and delivering a positive end-to-end experience on the network. Innovation is expected to come from a wide range of sources including the physical and biological sciences, all types of engineering system design and the human/social sciences (considering passengers). Inspiration from outside of the rail industry is seen as a key to success and insights/technology from related and unrelated fields are being sought. The aims are to meet customer needs answering three key questions:

- How will we understand the needs of passengers and freight customers over the next 15-40 years?
- How will customers know what the railway is offering them both in advance and in real time?
- How will the system design contribute to reducing passenger stress and improving satisfaction?

### 2.3.4 Foster Rail

FOSTER-RAIL is a European Level 1 Coordination and Support Action [52] driven by ERRAC aimed at supporting the land transport European Technology Platforms activities. The aim is to strengthen the research and innovation strategies of the transport industries in Europe. This will assist ERRAC and the other transport-related European technology platforms (ETP) in defining research needs for their strategies and programmes for H2020 in order to realise the objectives of the Europe-2020 strategy [46] and the White Paper 2011 vision for a competitive and resource-efficient future transport system [45]. Currently an updated Strategic Rail Research and Innovation Agenda is being produced under Foster Rail. It is being performed in consultation with the European Commission and Member States and Associated States. FOSTER-RAIL will integrate the work of ERRACs Working Groups and progress this building upon the ERRAC ROADMAP project and RailRoute 2050 [51]. An aim is to support and enhance cooperation between stakeholders and decision-makers to provide an enhanced definition of strategic research and innovation needs and establishment of Business Scenarios. A key area is co-modality with other transport modes. The project will support the Strategic Rail Research and Innovation Agenda as well as a Rail Business Scenario for 2050. This Railway Business Scenario shall be the reference for future research agendas and technology roadmaps to be developed until 2050. It should be noted that similar Foster Road and Foster Waterborne activities are also being pursued for the road and maritime sectors as part of a joint initiative.

### 2.3.5 SHIFT<sup>2</sup>RAIL

SHIFT<sup>2</sup>RAIL [57], starting summer/autumn 2014, is a H2020 supported European rail joint technology initiative seeking focused research and innovation (R&I) and market-driven solutions by accelerating the integration of new and advanced technologies into innovative rail product solutions. The integration of systems is a core objective of the programme and it applies to all segments of the rail market: High Speed/Mainline, Regional, Urban/Metro & Suburban, and Freight. SHIFT<sup>2</sup>RAIL will promote the competitiveness of the European Rail Industry and create a Single European Railway Area (SERA). SHIFT<sup>2</sup>RAIL aims to double the capacity of the European rail system, increase its reliability and service quality by 50% and at the same time halve lifecycle costs.

The aim is to achieve this by introduction of better trains (more comfortable, quieter and more reliable), operating on an innovative rail network infrastructure in a reliable way from the first day of service introduction. This will be done at a lower life cycle cost, with more capacity to cope with growing passenger and freight mobility demand. SHIFT<sup>2</sup>RAIL also aims to attract more users to rail. For passengers there will be more travel options, more comfort, and improved punctuality. For the freight forwarder/shippers rail freight will become more cost effective, punctual and traceable as a shipment option. There is an expectation of more job creation, less pollution and more efficient and optimised public investments.

### 2.3.6 ON-TIME

The Optimal Networks for Train Integration Management across Europe (ON-TIME) project [58] aims to introduce a step-change in railway capacity by reducing delays and improving traffic flow. The project integrates railway industry experts, system integrators, small knowledge led companies and academic researchers and draws upon previous research projects and national trials. The project brings together best practice on how national railway companies have improved their own networks. Academic research on algorithm development is being used to address the nature of delay initiation and propagation with a view to implementation in commercial traffic management and traffic planning tools.

### 2.3.7 European Rail Traffic Management System (ERTMS)

The European Railway Traffic Management System (ERTMS) [59] is a major industrial project developed by Alstom Transport, Ansaldo STS, AZD Praha, Bombardier Transportation, CAF, Mermec, Siemens Mobility and Thales in close cooperation with the European Union Railway stakeholders and the GSM-R industry. Currently there are more than 20 train control systems across the European Union. Each train used by a national railway company has to be equipped with at least one system but sometimes more are required to be able to run safely within one country. A problem is that each system is stand alone and non-interoperable. If traffic is cross border this leads to extensive integration and engineering effort with high associated costs. This restricts competition and also hampers competitiveness of the European rail sector versus road transport. As an example the Thalys trains running between Paris-Brussels-Cologne and Amsterdam have to be equipped with 7 different types of train control systems.

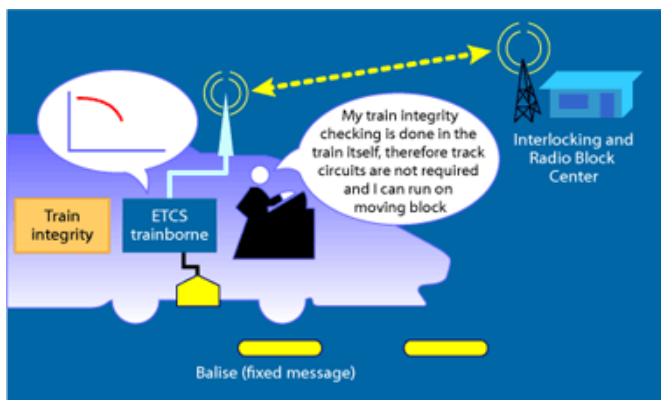


Figure 12. ERTMS Level 3 and Balise.

To address this ERTMS aims to gradually replace the different national train control and command systems across Europe to create a seamless European railway system. Instead of lineside signals, a computer in the driver's cab controls the speed and movement of the train, whilst taking account of other trains on the railway (See Fig. 12). Bringing the control system inside the train will allow more autonomous operation, so that drivers can always run at the optimum safe speed helping more trains run faster and recover from delays quicker. Each train will run at an appropriate safe speed, allowing more trains onto the tracks. This will increase passenger and freight capacity, reliability, reduce maintenance costs, improve punctuality and lead to safer trains and greater competitiveness for the supply market. By moving more people and freight onto trains and reducing delays there is also an expected reduction in pollution.

ERTMS has two basic components, the ETCS, the European Train Control System, which is an Automatic Train Protection system (ATP) to replace the existing national ATP-systems, and GSM-R, a radio system for providing voice and data communication between the track and the train. This uses standard GSM but on a reserved rail frequency. It should be noted that ERTMS is not a new concept and it has been successful outside Europe in countries such as China, India, Taiwan, South Korea and Saudi Arabia. The ERTMS/ETCS is split into a number of application “levels” which range from track to train communications (Level 1) to continuous communications between the train and the radio block centre (Level 2). Level 3, which is in a conceptual phase, will further increase ERTMS potential by introducing a “moving block” technology to increase capacity.

- ERTMS level 1 is used as an add-on to conventional lineside signals and train detectors. Communication between balises (See Fig. 12) and the train ensures that it automatically brakes if exceeding maximum allowed speed.



- ERTMS level 2 does not use lineside signals (reducing maintenance costs by their removal). The movement authority is communicated directly from a Radio Block Centre (RBC) to the onboard unit using GSM-R. Balises are used to transmit “fix messages” such as location, gradient, speed limit, etc.

ERTMS Level 3 is still in its conceptual phase but allows introduction of “moving block” technology. Removal of fixed blocks (sections of tracks where two trains cannot run at the same time) increases capacity greatly. The train itself becomes a “moving block” communicating accurate position data.

### 2.3.8 Comments and Discussion

Existing railway control centres act as a type of systems of systems, where the individual railway sections are subsystems controlled by signalling interlocks utilising 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. ERTMS is aiming to become a much more centralised traffic management system which 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. There are also a number of national initiatives such as FuTRO in the UK. The rail industry is being driven by targets to reduce cost, increase passenger and freight bearing capacity and reduce CO<sub>2</sub> 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. In terms of a competitive environment the European railway infrastructure managers and train operations face little genuine competition with most customers having little choice in whether to change operators, however, there is competition amongst the supply industry.

There is confidence that suitable systems engineers exist in the rail industry to meet future needs and also strong confidence that a systems of systems approach will be better with metrics already being gathered to support this argument. The rail industry have 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” and with comparatively little budget. To convince management that there is a need to invest in systems of systems research requires effort and there is a need for leadership to achieve more than incremental change. There is, however, general industry support for change – if there is no investment in modernisation the railway will become obsolete. With investment capital limited, investment decisions must be weighed against the benefits of other schemes. At a European level there needs to be the strongest possible leadership between national entities. Leadership capable of planning the execution (beyond incremental steps) and convincing government are seen as essential ingredients for rollout.

Within the industry anything new that operates at a low level is difficult to implement on the railways due to the scale of the infrastructure, however, to build a new higher level systems of systems on top of the existing control and command systems is not thought to be as difficult to implement, although safety and security become key issues for railway systems at this level. The migration to a new systems of systems approach is complex as there is a need to maintain the present level of services while the migration takes place. There are generally no public acceptance problems within the rail industry as any change that improves the rail network is welcomed by customers. Customers are, however, becoming more sophisticated and will demand a door-to-door service from public transport in the future which requires a systems of systems integration of different transport modes.

Key enablers are thought to be a well prepared implementation scheme with the benefits clearly mapped out. Already the initiatives identified in this report are providing supporting information for this. 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. Modelling capability is thought to be critical here for optimising the components (operations, maintenance, etc.) within the systems of systems and it is felt that there is a lot of underexploited modelling capability in Universities around Europe. There is also a need for commitment from the top, i.e. from Government as there is a need for large investment. There will inevitably be some disruption to passengers and freight operations during rollout which needs to be minimised.

Three key areas were identified as being important:

1) Data gathering and management

- How is data to be sensed, collected, communicated, processed, stored and deployed?
- How are the vulnerabilities and threats to integrity and security going to be addressed?
- What standards are relevant and how are they to be managed?

2) Optimisation of systems performance

- What are the criteria of system performance that will be important?
- How will tools, algorithms, cost functions, timetables be developed?
- What are the technical and commercial constraints on performance?

3) Autonomy and sociotechnical issues

- Which things should be controlled automatically, which by humans and which in combination?
- How can technology be used to support human decision making?
- What tools and interfaces will be needed between humans and technology?

Within the industry the present levels of knowledge on each of the three topics varies greatly. There is a feeling that much of the knowledge already exists for other industries, e.g. aerospace, and requires adaption for the railway sector.

Systems for autonomous operation of close coupled trains are key for increasing capacity and automated high speed maintenance systems will keep the track open for more time further increasing capacity. There is a need for whole system data management and communications presenting Big Data issues and underlying all areas is a need for modelling at different layers of abstraction.

## 2.4 State-of-the-Art in the Aerospace Sector

### 2.4.1 Passenger Routes and Traffic

In the aerospace sector air passenger volume is predicted to double air traffic density over the next two decades in an already congested airspace. Movement of increasing numbers of passengers requires a complex systems of systems across the world that integrates airport operations, baggage handling and air traffic control to maximise flow. Air traffic control systems by themselves integrate numerous functionalities which 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 communications technologies for predictive health monitoring, integrated with worldwide maintenance and logistics systems to ensure that aircraft are always fit to fly.

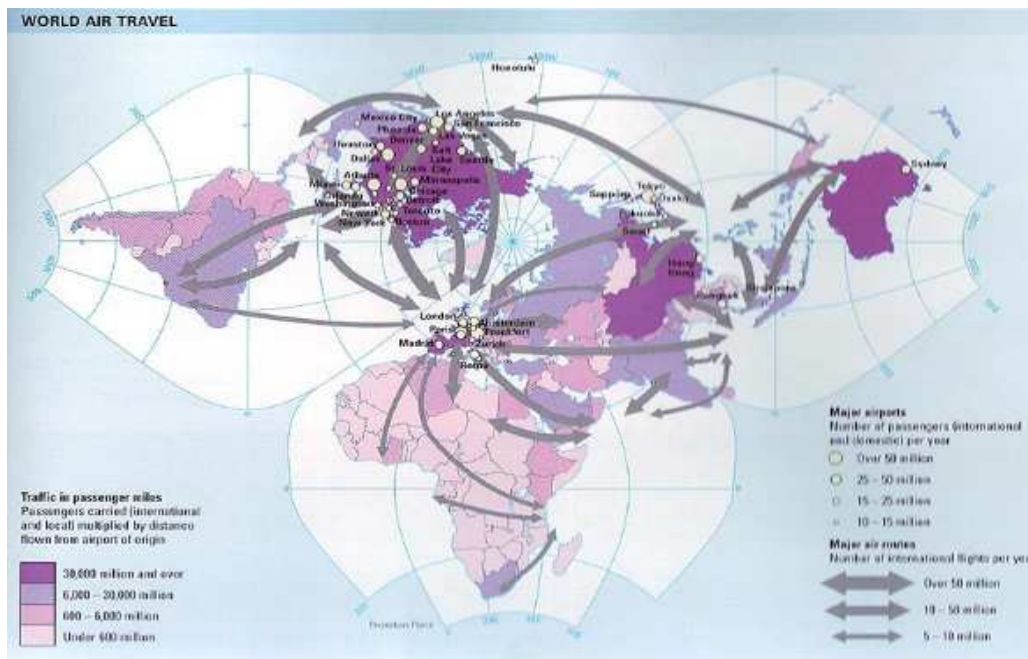


Figure 13. Major World Airports and Traffic Routes [60].

Fig. 13 shows a map of major air traffic routes around the world [60]. On the key routes shown 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 to meet demand. 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.

From a systems of systems perspective Air Traffic Management will be a major topic in the coming years, 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). In the future Unmanned Aerial Vehicles will also be integrated with the normal ATM network presenting further technological, legislative and political challenges. Autonomous aircraft operations are not a new concept in the aerospace domain. Partly this is due to the ability to operate in controlled military airspace and also the 3 dimensional separation of vehicles which is not available in other sectors. Aircraft already feature a number of automated features to reduce pilot workload and rely on very accurate navigation systems supported by a comprehensive network of ground stations and satellite systems. The sector is thus a leader in terms of implementation of autonomous vehicles. The technologies used to integrate UAVs into civil airspace may also be applicable to self-driving cars in the future.

### 2.4.2 SESAR – Air Traffic Management

The Single European Sky programme [60, 61] is reforming the architecture of European Air Traffic Control to meet future capacity and safety needs. Within Europe Eurocontrol predicts 20.4 million yearly flight movements by 2030 which is twice the current figure. In order to meet this need 2.1 billion Euros is being invested in R&D to develop a new air traffic control system for Europe. This will exploit improved air traffic and aircraft positioning and communication technologies, such as GALILEO [62] to provide significant improvements in the efficiency and safety of air travel. The Single European Sky ATM Research programme (SESAR – formerly known as SESAME) is the name given to the collaborative project that will completely modernize the European Air Traffic Control

infrastructure. SESAR (See Fig. 14) aims at developing the new generation air traffic management system capable of ensuring the safety and fluidity of air transport worldwide over the next 30 years.

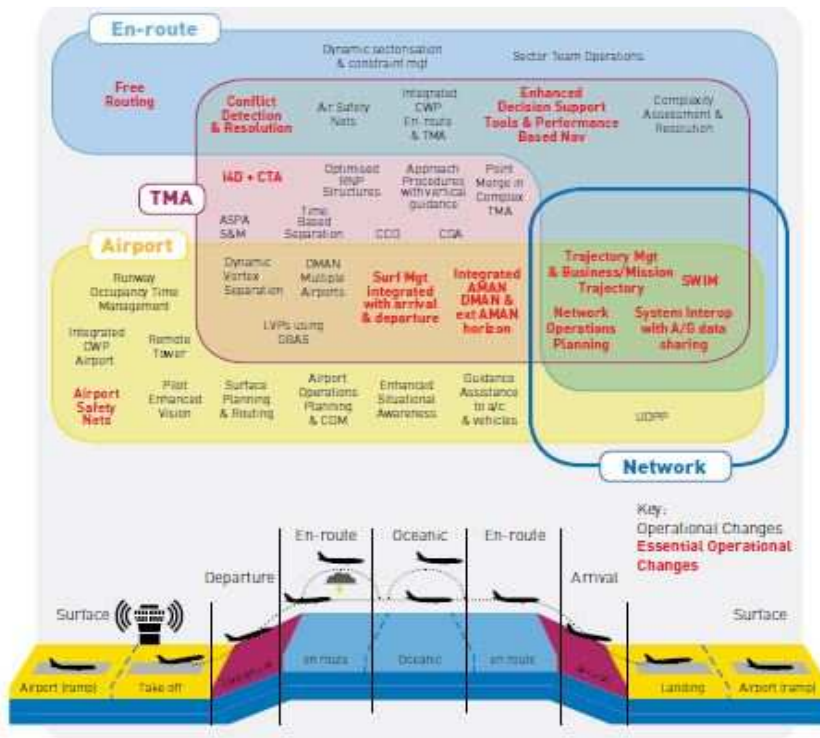


Figure 14. SESAR 4D Routing [61].

The first definition phase of SESAR ended in 2008, delivering an ATM master plan [63, 64, 65] defining the content, the development and deployment plans of the next generation of ATM systems. This activity was led by Eurocontrol, and co-funded by the European Commission under the Trans-European Network Transport programme. Work was executed by a consortium with representatives of all air transport stakeholders and included non-European members reflecting the global nature of ATM. The development phase (2007-2013) provided a new generation of technological systems and components. For this phase the Commission created the SESAR joint undertaking, based on the GALILEO model, supported by public and private funds from the European Community, Eurocontrol, industry and third countries. The current deployment phase (2013-2020) is seeking to build the new infrastructure necessary for the future within Europe and in partner countries. This is being carried out under the responsibility of industry without further public funding. Additionally, there has been some activities performed under the Clean Sky EU programme [66] looking at ATM and related issues to reduce emissions and fuel cost such as work by Thales on innovative Flight Management Systems.

### 2.4.3 NEXTGEN – Air Traffic Control USA

The equivalent of SESAR in the US is NEXTGEN [67]. The National Airspace System (NAS) is the collection of all the components (airspace, facilities, equipment, services, workforce, procedures, etc.) that enable the US air transportation system. Within the United States one organization, the FAA, operates 350,000 airplanes and 18,000 landing facilities. NEXTGEN, is short for the “Next Generation Air Transportation System,” and is a programme to comprehensively transform the NAS into a system to meet future needs that will be safer, more reliable, more efficient and which will reduce the impact of aviation on the environment. The system is due for

implementation across the United States in stages between 2012 and 2025. Again this is a very large programme and contractors include Lockheed Martin (\$500M) and NASA Ames.

There are some fundamental differences between Europe and the US. The European community is by far the most diverse community of air navigation service providers in a high-density airspace. A key issue is in achieving full consensus on modernization – it is a systems of systems problem – whereas in the US everything is under the control of a single body making implementation much simpler. An assessment of the SESAR and NEXTGEN programmes by the US indicated that they believe that SESAR is more advanced with respect to implementation. There is, however, a key difference between the two approaches being undertaken. SESAR’s emphasis is on i4D (using aircraft RTA capabilities – the aircraft themselves calculate the Required Time for Arrival) while the FAA’s emphasis is on ADS-B (Automatic Dependent Surveillance - Broadcast) for Interval Management (where aircraft positions are sent by the aircraft and are monitored and controlled centrally). This potentially may lead to a global harmonisation problem for aircraft operators and manufacturers, i.e. multiple solutions for the same operational problem in the same timeframe.

### 2.4.4 GEOSS – Earth Observation

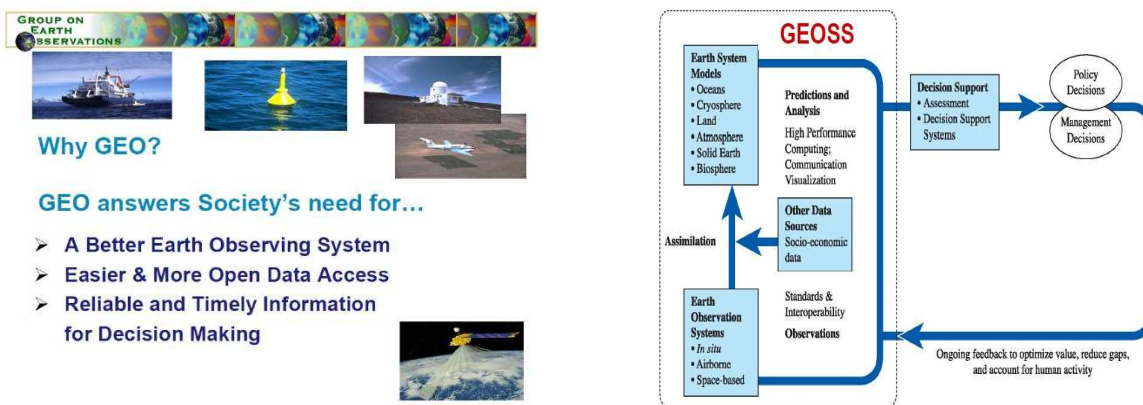


Figure 15. GEO Systems for Systems for Earth Observation and Decision Support Tools [69].

The GEO Systems of Systems (GEOSS) [68, 69] as shown in Fig. 15 is operated by 90 member governments, including the European Commission and 77 Participating Organizations making Earth observations. These include measurements and monitoring of the Earth from all aspects: under water, on the land surface and beneath, monitoring of air and water quality, of atmospheric conditions, and measures of the health of humans, plants and animals. Within the GEO Systems of Systems measurements can be made directly by sensors in contact with the environment or through remote sensing including a range of land, marine and space platforms. These observations support modeling or feed into tools that create information for environmental decision-making.

The societal benefits and uses of such information are in:

- Reduction and Prevention of Disasters
- Human Health
- Energy Management
- Climate Change
- Water Management
- Weather Forecasting
- Ecosystem
- Agriculture
- Biodiversity

The EPA Group on Earth Observations (EPA GEO), serves as a forum to facilitate the Agency's response and contribution to the development of GEOSS, including EPA’s Advanced Monitoring Initiative program and projects.

There are numerous datasets, models, decision support tools, and programs that EPA manages, oversees, supports, or uses (See Fig. 17). The GEOSS architecture integrates environmental observation, monitoring data and measurements with modeling to support and inform environmental decision-making. The ultimate goal of GEOSS is to provide decision makers with scientific information that can advance societal benefit areas including human health, ecosystems, climate change, air and water quality. On 17 January 2014, the Group on Earth Observations (GEO) agreed to continue building on the organization’s first 10 years of pioneering environmental advances. Fuelled by open data, GEO’s efforts are now evident in most regions of the world. Other federal agencies such as the National Aeronautics and Space Administration and the National Oceanic and Atmospheric Administration work with a myriad of databases, models, and programs that also contribute to the GEOSS.

### 2.4.5 Unmanned Aerial Vehicles (UAVs)

There are numerous UAV activities being undertaken within Europe with several major large programmes and many smaller programmes investigating and developing UAV technology for military and civilian use. It is not possible to cover all of these in a report but in this section a few key large programmes are highlighted. In larger UAV programmes multiple vehicles are operated as part of systems of systems implementations to gather information or perform tactical missions.



Figure 16. Watchkeeper UAV [70].

The Thales Watchkeeper WK450 [70](see Fig. 16) is a remotely piloted air system (RPAS) for all weather, Intelligence, Surveillance, Target Acquisition and Reconnaissance (ISTAR) which has been developed for use by the British Army, in a €1bn contract awarded to UAV Tactical Systems (U-TacS) in 2005, a joint venture between Thales UK and Israeli Elbit Systems. A UAV “system” such as Watchkeeper is not a systems of systems in itself, it is a single system since it is managed and operated as a single distributed system, however, Watchkeeper detachments will be deployed and integrated into task forces and force packages so will form part of an ad-hoc contingent of systems of systems. Watchkeeper does have an important characteristic that is shared by some “systems” and all systems of systems in that the “system” dynamically reconfigures as entities leave and join the system, and external systems connect to and disconnect from it.

Named after the Celtic god of thunder, the £185 million Taranis concept aircraft [71] (See Fig. 17) is jointly funded by the UK MOD and UK industry. The Taranis demonstrator aircraft was formally unveiled in July 2010. It is about the size of a BAE Systems Hawk aircraft and has been built by BAE Systems, Rolls-Royce, the Systems division of GE Aviation (formerly Smiths Aerospace) and QinetiQ working alongside UK MOD military staff, scientists and other smaller companies. The Taranis demonstrator is the result of one-and-a-half-million man hours of work by scientists, aerodynamicists and systems engineers from 250 UK companies. The aircraft was designed to create an unmanned air system which is capable of undertaking sustained surveillance, marking targets, gathering intelligence, deterring adversaries and carrying out strikes in hostile territory. The aircraft has low observability, high levels of systems integration, supporting control infrastructure and full autonomy elements. The aim of

TARANIS was to help the UK MOD and Royal Air Force make decisions on the future mix of manned and unmanned fast jet aircraft and how they will operate together in a systems of systems in a safe and effective manner.

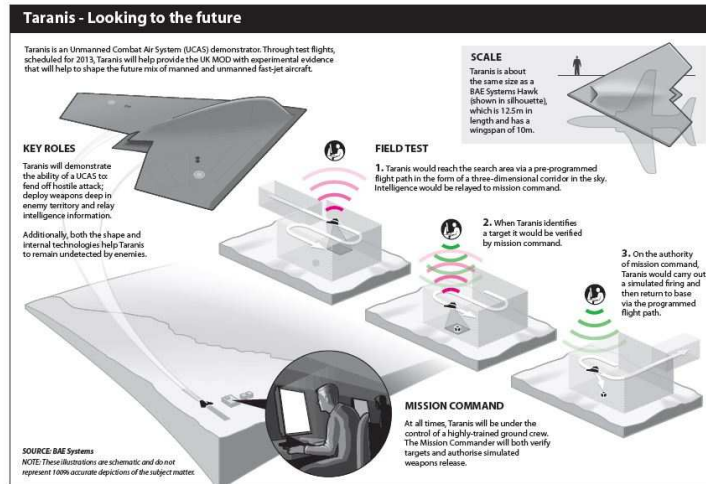


Figure 17. TARANIS UK Military Programme [71].



Figure 18. Lockheed Martin Unmanned Aerial Vehicles [72].

Lockheed Martin are key proponents of systems of systems and produce a range of military autonomous vehicles for aerospace, land and underwater marine [72]. They also regularly send out press releases highlighting the importance of systems of systems to best meet future military power projection requirements. Two examples of their autonomous air vehicles are shown in Fig. 18. These are the Aerial Reconfigurable Embedded System (ARES) design concept which was developed as part of the Transformer (TX) program in 2009 [73]. Transformer aimed to develop and demonstrate a prototype system that could provide flexible, terrain-independent transportation for logistics, personnel transport and tactical support missions for small ground units. The other is the K-Max unmanned cargo helicopter which is designed to keep forward operating bases supplied, reducing the number of truck convoys, and the troops that protect them, on the dangerous roads of Afghanistan. Here difficult terrain and threats, such as ambushes and Improvised Explosive Devices (IEDs) can make ground-based transportation to and from the frontline a dangerous challenge. While manned helicopters can easily bypass those problems, they often present logistical challenges of their own and can subject flight crews to different types of threats. Additionally Lockheed Martin also make smaller Unmanned Aerial Systems such as Desert Hawk III that enables soldiers to see what is over the next hill and “persistent surveillance” platforms like PTDS, High Altitude Airships,

Hybrid Air Vehicle and ISIS [73] to keep “eyes in the sky” over large areas for weeks, months and even years at a time.

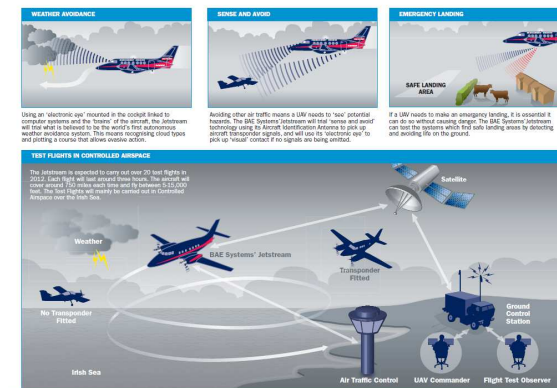


Figure 19. ASTRAEA UK Civil UAV Programme [74].

The ASTRAEA (Autonomous Systems Technology Related Airborne Evaluation & Assessment) programme [74] (See Fig. 19) is a UK industry-led consortium focusing on the technologies, systems, facilities, procedures and regulations that will allow autonomous vehicles to operate safely and routinely in civil airspace over the UK. The aim of the ASTRAEA programme is to enable the routine use of UAS (Unmanned Aircraft Systems) in all classes of airspace without the need for restrictive or specialised conditions of operation. This will be achieved through the coordinated development and demonstration of key technologies and operating procedures required to open up the airspace to UAS. The programme is a £62 million effort led by seven companies: Autonomous Decision Making Software (AOS), BAE Systems, Cassidian, Cobham, Qinetiq, Rolls-Royce and Thales. The programme consists of two separate projects:

**Separation Assurance & Control** – covering the particular technologies required to control the flying vehicle in the airspace considering the ground control station, the spectrum, security and integrity of the communication system and the vehicle's sense and avoid sensor system.

**Autonomy & Decision Making** – providing the intelligence within the vehicle through a variable autonomy system that shares decision making for the mission and contingency management with the human operator.

## 2.4.6 Comments and Discussion

Systems of systems are not a new concept in the aerospace industry and there was considerable discussion and comment from this sector. There is a lot of military experience in the operation of aircraft and other assets within systems of systems and it is well known that military capability is enhanced through the synchronisation of force elements across time and space. Although systems of systems is a well-known term within military aerospace there is still a greater understanding of the concept of “combined operations”. In a civilian context the same approaches can be used for more effective and focused disaster response by making best use of information and assets and indeed these are areas that are already being explored in EU funded systems of systems projects. With respect to civilian use for general aircraft operations the expectation is that systems of systems approaches to Air Traffic Management will reduce costs and delays with better integration of systems offering the opportunity to optimise gate-to-gate transits without on-the-ground delays or stacking before approach (with consequent reductions in emissions). Already air space is becoming congested and better coordination of aircraft and existing assets will allow for increases in capacity and real-time deconfliction of flight paths. This results in better



performance and also monetary savings due to reduced need for capital equipment and more efficient utilisation of assets and resources.

The requirements for systems of systems depend on the application:

- For military and home-land security domains, the requirements are mainly performance, security, safety and human factors
- For crisis management the requirements are dynamic goal-driven
- For the civil domain, the requirements are economical, environmental, legal and social

It was noted by the industry that Systems Engineers are often stuck in a “requirements first” clean sheet design paradigm and are used to having a level of control over the system elements. This is not available to them in systems of systems engineering. Specification needs to be thorough in the context of real systems of systems use cases, which should be as simply and clearly articulated as possible. 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 modelling and simulation. Although modelling, optimization and simulation tools are useful in reducing the amount of investment needed for development there is also a need to link these with Validation and Verification applicability so that the modelling and simulations are also used to increase confidence in the systems of systems. The biggest problem in modelling 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. Testing needs to be thorough in the context of real systems of systems use cases and also “mis-use cases”. The relevant state space needs to be limited to contain the cost and maximise the relevance of the limited Validation and Verification resources and time available. Here the aviation industry has great experience. Any developed Validation and Verification procedures should allow systems of systems to be adopted in the public domain so there is a need to closely link research in this area with regulatory aspects.

A key aim in systems of systems engineering is to reuse existing systems, integrate them in an operational environment with new ones and obtain the benefits of the resulting synergy. Consequently, monetary savings and improved capability are drivers for systems of systems. However, often 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 capability. This results in high levels of uncertainty and over-selling of individual projects. This presents problems as projects are assessed on an individual basis in most organisations and the accountants tend not to have the tools for assessing systems of systems added value or if they do, they are based on a very different worldview from the engineering one. It is almost impossible to make a business case for systems of systems investment to create better marginal capability, because financial systems do not know how to put a value on “better capability”. More usually the running costs are considered as these are more visible. As a consequence systems of systems activities tend to be funded when there is a consumer “pull” and the potential to create a big enough extra market that everyone believes they will benefit from (even given the level of uncertainty). Alternatively legislative and regulatory changes may drive the need for a systems of systems approach, e.g. reduction of greenhouse gases which, for instance, is also a target for SESAR. It was noted that often individual projects are underfunded and overspent. As a consequence the funding for interfacing and systems of systems integration are the first things to be traded out – they are seen as luxuries that might not be needed rather than as essential elements of the overall enterprise-level business case.

Decision making is also challenging due to the need to integrate decision makers of different types (e.g. autonomous vs human) and, in Europe in particular, the need to deal with different legislation. It is important to master the life-cycles of the constituents systems and resulting behaviour of the systems of systems. It should be noted that the aim is not to have strong integration; but to have dynamic integration along the life-cycle of the systems of systems in order to take into account addition and suppression of constituent systems, their evolution

and the emerging effects. The challenge in rolling out a systems of systems are the asynchronous lifecycles 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 incentivised to join the systems of systems because they get benefit for each integration step. To support this the interfaces must be simple and easy to test. Another important research area is the interaction between systems of systems and the systems they are meant to replace as during staged roll out they need to co-exist with existing systems. Once rolled out operating and maintaining a systems of systems requires a good knowledge of the “as-deployed-and-configured” system physical, functional and behavioural configuration.

Considering the development of systems of systems, companies have to demonstrate their ability to manage huge complexity. Leading companies in the area, e.g. THALES, Cassidian, etc. have demonstrated their ability in 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 are the knowledge and the usage of Architecture Frameworks, Systems Engineering norms and standards.

Looking to the future 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). Cassidian, for instance, validate all communication protocols used in a system including those used in legacy parts of the system as there is a need to guarantee a Quality of Service to maintain operation. Again, communication between the systems is paramount, as well as an increased level of autonomy to deal with the times when communication may not be possible. For systems of systems that do not operate in a strictly controlled environment, dynamic reconfiguration is key.

Finally, there is a need to not only consider the technical issues but also training, equipment, people, information, doctrine and process, organisation, infrastructure and logistics. These all need to be considered and aligned to be successful in systems of systems development.

## 2.5 State-of-the-Art in the Maritime Sector

### 2.5.1 Drivers within 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. Here systems of systems thinking is leading to integrated world-wide ship management systems being linked with ship fouling efficiency metrics and navigation systems to optimise performance to reduce fuel consumption and emissions. The introduction of emissions monitoring [75] 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 network to move the goods onwards as quickly and efficiently as possible.

European shipbuilders are world market leaders by turnover [6]. 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, e.g. European equipment suppliers have provided on-board total waste management systems ahead of future environmental regulations.

A key driver in the maritime industry is improving safety of waterborne operations. This is because recent maritime disasters and accidents in inland navigation have shown that accidents come with high costs in terms of loss of life, environmental damage and with high economic impact. Additionally, high profile accidents have tarnished the overall image and public perception of the waterborne sector. With the increase in cargo traffic in busy North Sea lanes there is a need to maintain safe operations of cargo vessels. At the same time passenger cruise ships have also got bigger and are now operating in non-traditional, remote and difficult regions such as the arctic with new and increasing risks. Passengers have high expectations for comfort and a wide range of on-board amenities. The current research drivers are to develop and demonstrate innovative solutions for ship design and waterborne operations to avoid and mitigate passenger risks and ensure high levels of safety.

The industry believes that new technologies for maritime traffic management will be key for safer and more secure operations. In the marine sector there is great interest in optimised shipping operations and voyage optimisation, condition based maintenance, reducing costs and reducing emissions. Local legislation has resulted in emissions monitoring being introduced in ports and local governments have introduced their own requirements. The drivers are for reduced maintenance, enhanced asset life, reduction in crewing levels through increased automation and fleet optimisation via shore based decisions. Key enablers in the industry are the introduction of VSAT systems [76] that allow much greater data rates for data transfer.

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 Information and Communication Technologies (ICT) systems, which monitor vessels, freight and port services.

## 2.5.2 Waterborne



Figure 20. WATERBORNE European Technology Platform Research Summary [78].

In Europe the marine industry has come together with the aim of providing sustainable waterborne transport for the future. To support this the WATERBORNE European Technology Platform [77] has been created with the aims highlighted in Fig. 20 [78]. The WATERBORNE initiative was driven by the Maritime Industries Forum (MIF) and its R&D Committee in 2005. Waterborne identifies R&D requirements for European competitiveness in the industry

and the innovation and research needs to meet new regulations for safety and environmental goals. The programme is very wide with stakeholder coverage from deep and short sea shipping, inland waterways, ship yards, equipment manufacturers, the marine leisure industry, research and university institutions and classification societies. In addition to a stakeholder Support Group, there is a Mirror Group of government appointed delegates. The WATERBORNE TP published a Vision 2020 paper in 2012 [79], a Strategic Research Agenda in 2011 [80] and an Implementation Plan in 2011 [81]. These documents are being used by the European Commission to direct calls under the R&D workprogrammes and also national R&D programmes. They are also being used by industry to guide research and development.

### 2.5.3 Marine Vision 2020 and Strategic Research Agenda

Although waterborne transport is the most sustainable, fuel-efficient and environmentally friendly transport mode, special consideration is required of the consequences of accidents, particularly in sensitive coastal areas. As a mode of transport ships have the capacity to transport very large quantities of cargo or large numbers of passengers, consequently there must be a strong focus on safety and also environmental protection. The development and expansion of port capacity is required but care must be taken to preserve natural habitats in surrounding areas. Additionally, security is increasingly an issue and operations must be protected against threats. The EU shipping industry working with public authorities has progressively enhanced safety at sea and introduced greater measures to protect the environment and is actively promoting this on an international basis. The Vision 2020 paper [79] produced by the industry highlights the needs for effective designs, systems, procedures and techniques to increase the level and reliability of the ship system’s performance, with the goal of a “zero accident” record. To do this there is a need for research into:

- Effective means to avoid accidents
- Robust ships and reliable equipment
- Improved survival in extreme conditions (ice, freak, waves, etc.)
- Competent crew, ship management and shore operations

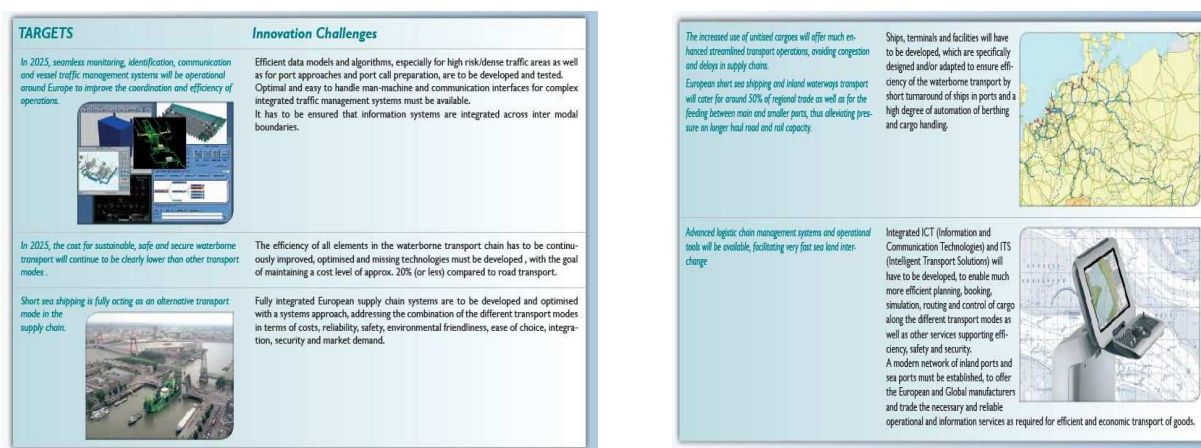


Figure 21. Innovation Challenges: Traffic Management, Integrated Supply Chains, Port Efficiency [79].

Supporting this there is a drive to improve man-machine interfaces and decision support systems to minimize impact of human error. Ships built in Europe will be equipped with on board systems for performance monitoring (see Fig. 21) with the aim of reducing life cycle maintenance and also providing safer operation. This will include monitoring and failure prevention strategies and systems for corrosion and wear monitoring. This requires the development of predictive maintenance and inspection capabilities to support the whole life cycle. For safer

operations cheap, fool-proof and safe communication and identification equipment needs to be developed to support smaller coastal craft (e.g. fishing and recreational craft, craft with amateur crew) that can be integrated within traffic management systems. This is required if a political decision driven by safety is made to include all small coastal craft in traffic management systems. Additionally, safe and efficient data models and algorithms will be required to cope with the expected huge numbers of traffic participants. If no political decision is made safety is still a concern and so alternative safe and user friendly strategies to traffic management also need to be developed.

Emissions are another key issue and a 'zero emission' approach, to SO<sub>x</sub>, NO<sub>x</sub>, CO<sub>2</sub>, PM, VOCs presents a technological and economic challenge particularly as approaches to reducing one pollutant tend to increase the emissions of other pollutants with different options being needed for a variety of ships.

Efficient data models and algorithms are needed to manage operations in high risk / dense traffic sea ways. Additionally they are required for port approaches and port call preparation. From a human factors perspective these need to be supported by optimal and easy to handle man-machine and communication interfaces for implementation of complex integrated traffic management systems. Shipping information systems need to be integrated across inter modal boundaries. The expectation is that in 2020 the costs of waterborne transport will still be lower than other modes, however there is a need to continuously improve the efficiency of all elements in the waterborne transport chain. The aim is to maintain a cost level of approximately 20% (or less) compared to road transport through introductions of new ICT based technology and improved integration and optimisation of systems. Fully integrated European supply chain systems are to be developed and optimized with a systems of systems approach, addressing the combination of the different transport modes in terms of costs, reliability, safety, environmental friendliness, ease of choice, integration, security and market demand. The Waterborne Strategic Research Agenda [81] focuses on three themes:

- Safe, sustainable and efficient waterborne operations
- Maintaining a competitive European maritime industry
- Managing and facilitating growth and changing trade patterns

These are subdivided into topic area such as short-sea shipping, inland waterways, ship design, operation, and maintenance, maritime safety and ports and port operations. Within each of these areas a number of projects have been funded. In the area of short sea shipping several projects address aspects of systems of systems. These include activities on regional and coastal traffic management, decision support systems and logistical integration. At the inland waterways level research is being performed into tele-maintenance, intelligent ship operations and data management. In the topic of user comfort and quality there are a number of projects addressing efficient and environmentally friendly ship operations, navigation and information management and management of hazardous goods. Within the area of ports and port operations there are a considerable number of projects investigating topics such as environmentally friendly shipping operations, efficient management of passenger terminals and support tools to help ports improve shipping operations.

#### 2.5.4 Horizon 2020 Call

Under mobility for growth 2014-2015 there is a major programme [82] supporting innovation actions to develop safer and more efficient waterborne operations through new technologies and smarter traffic management. The key areas related to ICT and systems of systems are:

- New and improved systems for the surveillance, monitoring and integrated management of waterborne transport and other activities (commercial and non-commercial).

- New and cost effective European Global Navigation Satellite System (European GNSS)-based procedures for port approach, pilotage and guidance, ICT-enabled shipping lanes and maritime services that will reduce the risk of accidents and incidents in port approaches and dense traffic lanes, and minimise both delays and turn-around times.
- For traffic management, solutions that support the extension, integration and optimisation of waterborne transport information and communication systems with the aim of contributing to build a comprehensive "e-maritime" environment (including e-Navigation components that are compatible with existing or emerging international standards). The objective here is to build a "European Maritime Transport Space without Barriers" allowing waterborne transport (including inland navigation) to be used to the full potential within an integrated intermodal logistic chain.

Of particular note is that the call is asking for solutions that will also provide the foundation for the deployment of autonomous and actively guided ships as well as the possibility to verify all related safety certificates before a vessel enters the port. This is to support the future long term goal to reduce crew numbers still further and move towards autonomous and actively guided ships. In parallel with the research activities there is a need to also provide inputs into EU and international regulatory regimes. An aim is to promote standardisation and international research co-operation particularly in the areas of safety devices and e-Navigation solutions.

The expected impacts are to:

- Achieve significant improvements in terms of navigational safety and efficiency (in particular emission reductions) along the entire waterborne transport logistic chain, and decrease administrative burdens
- Facilitate the transfer of new safety concepts from passenger shipping to other areas of maritime operations
- Show a statistically relevant decrease in the number of fatalities caused by maritime accidents, the number of ship losses and specific incidents such as fires or black-outs accompanied, where relevant, by operational empirical evidence
- Support the upgrading of international maritime safety regimes through relevant inputs

### 2.5.5 e-Maritime

The EU e-Maritime initiative [83] aims to foster the use of advanced information technologies for working and doing business in the maritime transport sector. Maritime transport administrative procedures are complex, time-consuming and, even today, are quite often done on paper so there is a need to embrace modern ICT technologies and ways of doing business. Major European ports have deployed advanced information systems. These deliver considerable quality and efficiency gains, however, currently there is no interoperability between port information systems. From a systems of systems perspective this limits the potential for new services and economies of scale. Small ports may not have any electronic data transmission capabilities at all. The usual practice is that shipping companies at each port manually enter the same data repeatedly, resulting in duplication and errors.

For the next generation of sailors (the "Internet" generation) access to cyberspace is a must. e-Maritime aims to stimulate coherent, transparent, efficient and simplified solutions in support of cooperation, interoperability and consistency between Member States and transport operators.

Going beyond e-Maritime there is also an activity to provide a mechanism for a Common Information Sharing Environment (CISE). This is currently being developed jointly by the European Commission and EU/EEA member states [84]. It will integrate existing surveillance systems and networks and give all concerned authorities access

to the information they need for their missions at sea. CISE will make different systems interoperable so that data and other information can be exchanged easily.

### 2.5.6 Highly Automated Marine

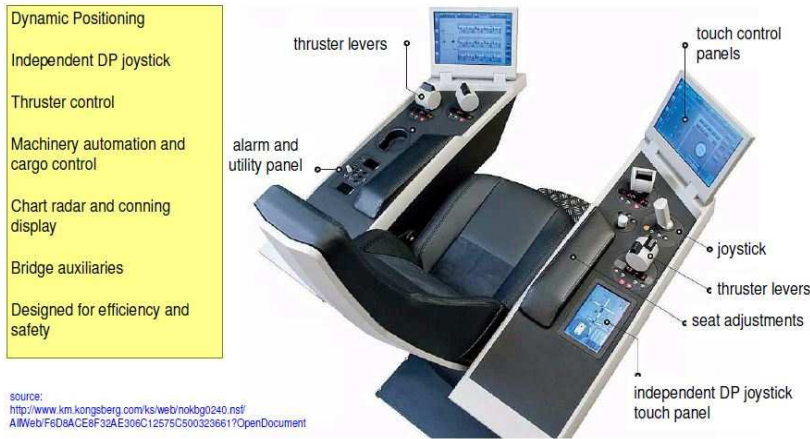


Figure 22. Captain’s Chair (Wartsila).

Modern ships are operated with much lower numbers of crew than in the past. This has been achieved by introducing much greater levels of automation and also through more advanced on-ship monitoring systems. Within a systems of systems interactions with users and the Human Machine Interface are highly important. New systems are providing key information directly to the captain or first officer allowing much greater situational awareness and the ability to control a myriad of systems (See Fig. 22). This not only includes the ships systems, e.g. chillers, etc., but also functionality such as deck winches, anchors and station keeping linked with GPS technologies controlling thrusters around the ship. New advanced systems are being designed to optimise operator comfort and improve ergonomics. Much work has been done for instance by Rolls-Royce on monitoring eye movement, if there is excessive scanning this may indicate that the operator is confused so positioning and displays are placed such that very precise eye movements are seen [85]. Reducing unnecessary scanning so that the user does not have to search for information leaves more mental capacity (less cognitive load) to handle safety critical situations, which can actually mean the difference between incident and accident in many situations. Movement of a display by a few centimetres can be the difference between operating in a relaxed position where the operator leans on the chair's backrest versus that where the operator has to lean forward numerous times to touch a display that is just out of reach. This causes annoyance and strain and increases cognitive load.



Figure 23. Rolls-Royce Unified Bridge [85].

With reduced crews covering more ergonomics become a much greater requirement and the Rolls-Royce unified bridge (See Fig. 23) has been designed to ensure low reflection of sunlight during day operations, and common dimming to ensure good night time vision, and clear views of the deck. The front end of the consoles has been angled so that the operator can have an even better ergonomic position during operation and the winch and anchor handling operations are specially designed to minimise strain on the operator. Levers and emergency switches have been placed in easily recognizable positions. Bridge chairs have been made flexible enough to support both seated and standing operation and are designed to better enable the operator to vary their posture.

### 2.5.7 Unmanned Ships



Figure 24. Rolls-Royce Unmanned Ships Concept [86].

Rolls-Royce’s Blue Ocean development team has set up a virtual-reality prototype that simulates 360-degree views from a vessel’s bridge [86]. The idea is that eventually captains on dry land will be able to use similar control centres to command hundreds of crewless ships. Drone ships would be safer, cheaper and less polluting for the shipping industry that carries 90 percent of world trade (See Fig. 24). The European Union is funding a 3.5 MEuro study called the “Maritime Unmanned Navigation through Intelligence in Network” project which will produce a prototype for simulated sea trials to assess costs and benefits. The Rolls-Royce design for an autonomous ship (See Fig. 24) has no bridge with just containers from front to back. By replacing the bridge and the systems that support the crew, e.g. electricity, air conditioning, water and sewage, the ships can be 5 percent lighter before loading cargo and would burn 12% to 15% less fuel. Additionally, from a financial perspective figures show that a crew costs \$3,299 a day and account for about 44 percent of total operating expenses for a large container ship.

There are considerable hurdles to adoption of unmanned ships coming from regulators who are concerned about safety and unions who are concerned about job losses. In fact current regulations dictate minimum crew levels by international conventions. The country where a ship is registered is responsible for regulating vessels within its own waters and for enforcing the international rules. The international IMO regulations apply to seagoing vessels trading internationally and exceeding 500 gross tons, except warships and fishing boats. If drone ships do not comply with the IMO rules, they would be considered unseaworthy and ineligible for insurance. There is, however, interest in deployment of unmanned ships in the Baltic Sea. The expectation is that computers will gradually increase their role in navigation and operations reducing crew levels further. Container ships and dry-bulk carriers are the most likely first candidates for total autonomy as tankers carrying hazardous materials such as oil and liquefied natural gas will probably remain manned longer because of the perception that having a crew on board is safer.



To successfully replace crews unmanned ships will need constant and comprehensive computer monitoring to anticipate failures in advance and “redundant” systems to maintain availability. Computer systems can also be used to analyse ship information and optimise performance. Cameras and sensors can already detect obstacles in the water far better than the human eye. Of particular note is that human error causes most maritime accidents which are often related to fatigue. Unmanned ships would also reduce risks such as piracy, since there would be no hostages to capture, however, ships would become vulnerable to a different kind of piracy from computer hackers.

### 2.5.8 Ocean Monitoring via Surface and Underwater UAVs

Already it is possible to download free Apps that allow the real time position and pictures of the ships to be shown on Google Earth (see [http://www0.marinetraffic.com/ais/ge\\_marinetraffic.kml](http://www0.marinetraffic.com/ais/ge_marinetraffic.kml)). However, this only gives information of where vessels are, not what is actually happening at sea. The world’s oceans cover 71% of the Earth’s surface, yet, they are the least understood and most vulnerable resource on the planet. There is interest in monitoring accidents at sea, pollution spills, ocean acidification, wildlife, and also the relationship between the oceans and climate change. Traditionally, large ships have been used to take measurements, however, ships are very expensive and burn huge amounts of polluting diesel fuel during their operations. There are now several companies such as Saildrone [87] and Liquid Robotics in California working jointly with Fastwave Communications in Australia [88] producing unmanned self-powered sea gliders, and drifting bouy’s for monitoring at sea. The Wave Glider [88] for instance is a low-profile, unmanned surface vehicle that is capable of long-range, extended deployments (up to one year) with minimal human intervention. It is propelled by wave generated energy, with solar panel arrays providing power for on-board communications, sensor payloads and computing. Typical applications include marine environmental monitoring, maritime surveillance, metocean data acquisition, fisheries and aquaculture management, marine mammal detection, dredge and outfall plume monitoring, CO<sub>2</sub> studies, hydrocarbon detection and pipeline leak detection.

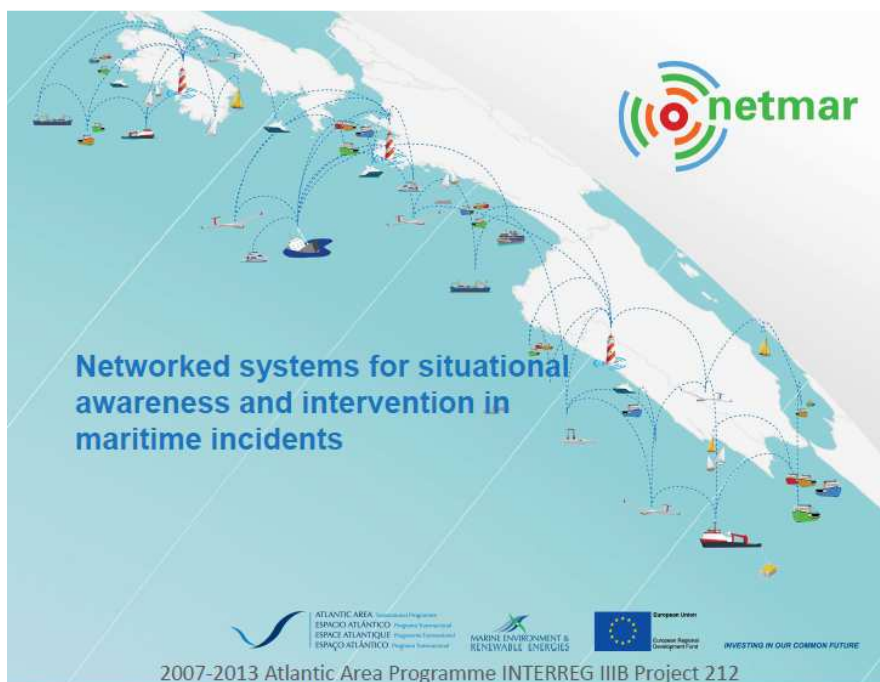


Figure 25. Netmar – Situational Awareness and Monitoring in Maritime Incidents [89].

Most of the current work is investigating the development of the individual platforms themselves but more recently deployments of multiple vehicles in systems of systems has been performed such as the NetMar

deployment of surface and aerial vehicles to monitor a stretch of coast [89] (See Fig. 25). Monitoring of the oceans is seen as a major opportunity and Google are taking a lead in this organising the Ocean Agenda Conference [90] with the aim of gathering people together to exponentially accelerate and enhance the protection of marine life using new technologies. Already examples of sea life tracking have been demonstrated such as in May 2014 a team from Porto, working with researchers from the United States, Spain and Norway tracked tagged Ocean Sunfish (the largest bony fish in our oceans) using a combination of autonomous aerial, surface and underwater vehicles off the coast of the Algarve near Olhão [91].

At the European level the FP7 PERSEUS project [92] is developing a new maritime systems of systems surveillance system. This aims to increase the effectiveness of the current systems by creating a common maritime information sharing environment for the benefit of National Coordination Centres, Frontex and the European Maritime Safety Agency (EMSA). The solution will provide a description of the situation from coastal areas to the open seas in real time improving and automating detection and identification of suspicious or non-collaborative vessels, facilitating decision-making and reducing the response time of authorities. It will also help in interception and rescue missions at sea. The system will detect small boats and low flying targets through the integration of sensors and capacities. Interoperability among different institutions and states is an aim with integration of the new system with existing systems. Information will be fused to provide a common operational picture at regional and European levels. The data will be integrated and processed for better quality, thus obtaining filtered, reliable and more useful information. In particular, PERSEUS will support the implementation of EUROSUR. The project also plans collaboration with non-European countries and international agencies such as NATO and the International Maritime Organisation (IMO).

### 2.5.9 Comments and Discussion

The maritime industry is being driven by the problems of increasing traffic in already congested waterways. Still by far the cheapest way to move goods around there is a continuous drive for improvement and reduction in shipping costs. This is being addressed through the introduction of ICT technologies and algorithms to optimise shipping movements and port operations. There is also a big drive to improve safety across all types of shipping due to high profile accidents. The increasing size of passenger ships and their operation in more remote and inhospitable locations is also leading to more concerns about safety. In recent years emissions have also become a major issue and local ports have introduced restrictions on operations. At an international level restrictions and legislation, e.g. IMO Tier III [75], is also driving for increased monitoring of emissions. The commercial requirements are for high performance, fuel cost reduction, reliability, safety, lower capital expenditure and lower operating expenses (maintenance). The business aims for suppliers are for simplification of the total system for the end customer.

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 advent of supporting Satellite systems such as those from Inmarsat are introducing the capability to provide connectivity to ships which enables transfer of considerable amounts of data. Presently there is not a clear view of what data should be transferred and how this should be used. The fact that ships are regularly sold on to other ship owners makes investment in on-board technology such as monitoring more difficult as installed expensive equipment may be lost within a few years. The suppliers of equipment, e.g. Rolls-Royce, are now building in monitoring for their own equipment which is provided free as part of the package. The data from these systems goes back to the suppliers rather than the ship owners and helps with product improvements. The ship owners are offered the option of purchasing monitoring and management services by the suppliers, e.g. in power-by-the-hour contracts. In general at present there is a low

uptake of monitoring technology in shipping with a tendency towards scheduled maintenance rather than on-condition maintenance.

The 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. A systems of systems approach would allow much better coordination of port services around Europe and advances in this area are being driven by actions such as Waterborne and e-Maritime. The introduction of data exchange standards would be a major move forward allowing current 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.

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 an increase in autonomous ship operations as crew levels are gradually reduced leading in the longer term to unmanned ships once regulatory authorities are happy that this is safe.

As systems become more interconnected it will be possible to combine mixes 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 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.

## 2.6 State-of-the-Art in the Logistics Sector



Figure 26. Logistics Issues – Traffic Jams [photo dpa-Zentralbild], Congestion from Deliveries [photo Abenblatt.de].

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 [93]. Order-to-delivery excellence is now a key requirement for demand management driving 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 System 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 are that transport volumes keep growing globally (See Fig. 26) leading to congestion on roads, however, the sizes of individual shipments are not increasing and indeed there is a move towards shipments of smaller loads [94]. The move towards global sourcing has changed the dynamics of logistics. For example, 10 years ago 90% of the parts for a car would come from factories within a 200Km radius, now the parts are sourced from a world-wide supplier base. 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 emissions 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 (See Fig. 26) and ways of bundling deliveries at local hubs to reduce the numbers of vehicles making deliveries is also challenge. Urbanisation is a key challenge and air quality directives such as Euro 6 [95] are driving new truck and powerplant design. Likewise stricter standards are being introduced in the USA and China for fuel economy and emissions.

This is challenging for truck manufacturers who want to sell trucks on a world-wide basis where the term “long haul” means different things and fuel quality varies greatly. The requirements in different countries are also a factor. In China the key customer requirement is for safety as most truck drivers are owner operators. In India most trucks are owned by operators and here fuel economy is the key requirement. The dimensions of trucks are also strictly regulated which limits what is possible aerodynamically. Although aerodynamic additions can reduce fuel consumption by about 5% this is only at higher speeds (80Km/hr) and these can easily be negated by poor driving. At lower speeds the rolling resistance of tyres is the most important factor in efficiency. Design shows that larger trucks and double trucks would be far more efficient (around 35%) but this is not possible politically due to public opposition to larger vehicles. Additionally, member states have regulations in place that dictate that trucks cannot operate at night during curfews in urban areas. As a consequence trucks are often also operated in the rush hour traffic which increases fuel consumption by 50% as trucks are highly inefficient when stopping and starting. There are thus a number of political and public acceptance problems which need addressing in order to achieve significant improvements in operational efficiency and emissions reductions.

The trucking community is familiar with the use of ICT and already automatic tolling systems are used across Europe, however, there is a lack of harmonisation of systems and to operate across all of Europe a lorry driver needs a myriad of different devices on the dashboard. For main routes across Europe drivers typically need 7 different tolling devices.

The use of telematics and connectivity is seen as the future to make major improvements in management of freight efficiency, emissions, safety and personal effectiveness. Take up of telematics is, however, still low in the industry as the average fleet size in Europe is 10 trucks. Medium to large companies account for around 25% of the trucking companies in Europe and small companies for the remaining 75%. There is also driver resistance to being tracked. Typical experience shows that just by introducing a tracking device on a vehicle there is a 5-10% saving in fuel – indicating that drivers do not always use their vehicles for work.

There are a number of potential benefits from introducing tracking. These include monitoring of driving behaviour which can be fed back to the driver (highly fuel efficient trucks do not make a difference if the driving is bad), provision of routing to the cheapest petrol stations, and reductions in insurance claims (from providing proof of speed, etc. in court cases). Additionally, monitoring of key truck parameters can be used to optimise efficiency, e.g. truck tyre pressures have a big impact on efficiency, and there is a great interest in moving from

remote diagnostics to prognostics as batteries and tyres account for 50% of breakdowns. Already companies such as Scania give away a free telematics system with all of their trucks and currently 800,000 vehicles are fitted with it. Services are provided based on this and customers have the option of buying them.

The key benefit of telematics is in gathering and exploiting data in fleet management. Customers want to know every minute where a delivery is and there is a move from reactive to proactive operations through data mining of big data. A major issue that contributes to unnecessary fuel consumption and emissions is the shipping of goods in half empty trucks and the return of empty trucks (where there is an immediate 40% penalty in fuel consumption). Means of co-ordinating and optimising deliveries across fleets of vehicles can thus bring huge savings.

### 2.6.1 DHL GOGREEN Initiative

The DHL GOGREEN initiative [96] is introducing optimized transport routes, alternative drive vehicles and energy-efficient warehouses to reduce CO<sub>2</sub> emissions and other environmental impacts in the transportation and storage of goods. By 2020 the company aims to increase the carbon efficiency of its operations by 30% compared with 2007 levels. Already the company has achieved a 10% reduction. Sustainability is seen as a competitive factor driven by consumer demands and also by investors who consult sustainability rankings when looking for viable investment options. To address this the GOGREEN initiative is considering a complete view of emissions with the aim to “burn less and burn clean” across all vehicles, buildings and aircraft. Already there are 11,500 green vehicles on test utilising a mix of electric and alternative fuels. A systems approach is being adopted and solar panels are used to charge electric vehicles at warehouses and a new rail link to China is being used as an alternative to flying goods. This allows goods to be shipped from China priority within 7 days by air or 28 days by rail depending on customer requirements.

The company provides Carbon Reports and a Green Optimization service to identify ways to minimise greenhouse gas emissions and improve overall environmental performance. Carbon accounting has been integrated into financial accounting systems so that the emissions are automatically calculated from fuel and electricity consumption data. To compensate for unavoidable emissions a climate neutral approach is offered using energy provided by solar panels and wind turbine energy.

### 2.6.2 United Parcel Service

UPS perform 17 million shipments per day and are moving from being a trucking company to being a “technology company with trucks” with extensive use of package routing technology and telematics. All road, rail, air and shipping hubs are connected by a private IT system to provide a single network for all categories of service. They have obtained huge savings from network efficiency through development of the ORION (On Road Integrated Optimisation and Navigation) system [97] for predictive and prescriptive operations. This provides an in-cab computer that performs highly complex optimisation of deliveries to minimise miles driven and minutes vehicles spend idling while at the same time maximizing the number of pickups and deliveries made per litre of fuel used. It also gathers information on driving behaviours (which can be used to identify and improve driving performance to reduce fuel consumption) and collects information on mechanical variables from the engine and drive train that can be used for on-condition maintenance saving money and reducing waste (parts, oil, etc.).

Vehicles are used as rolling laboratories and data has been collected for 185 million miles since 2000. Small adjustments to operations can be made with large payoffs over 100,000 drivers around the world. For example, the most efficient vehicles can be matched to routes, the number of stops and starts performed can be

minimised and safety can be improved by minimising backing up required in residential areas (which are full of other vehicles, fixed objects, people and pets).

In 2010 telematics-equipped vehicles eliminated more than 15.4 million minutes of idling time saving 103,000 gallons of fuel (and avoiding of 1,045 metric tonnes of CO<sub>2</sub>). Additionally, the number of stops per mile were reduced delivering more packages with fewer engine restarts that consume fuel. The use of telematics saved 1.7 million miles of driving in 2010, equating to more than 183,000 gallons of fuel or 1,857 metric tonnes of CO<sub>2</sub>. The company is also increasingly using electrification for local deliveries and biomethane as an alternative fuel for larger trucks to further reduce emissions.

### 2.6.3 Carbon Footprint

The growing freight transport sector is a major contributor to greenhouse gas emissions. Several initiatives exist for the calculation of the carbon footprint of freight transport chains. However, there are problems in terms of comparability, transparency and accuracy since these initiatives are based on different starting points, approaches or intentions in development. The EU co-funded project COFRET (Carbon Footprint of Freight Transport) [98] is developing a unified approach to calculate logistics related carbon footprint emissions along complex supply chains. Likewise there are efforts in the logistics industry to harmonise the measurement of emissions from trucks for specific driving cycles and introduction of badging of truck CO<sub>2</sub> efficiency by Green Freight Europe [99].

### 2.6.4 Physical Internet for Logistics

A key issue is that logistics is changing to become far more dynamic. Customers demand flexible processes and this is being enabled by the increased use of technology. Networks are worldwide offering a range of individual services with a large number of different items. This presents great challenges in planning and controlling of logistical systems as information through the network is distributed and fragmented. To meet these needs the Physical Internet (PI) approach has been proposed [100] to provide an open global logistics system founded on physical, digital and operational interconnectivity through encapsulation, interfaces and protocols. An aim is to link classical distribution networks to better utilize transport and distribution resources. This would allow movement from point-to-point or hub-and-spoke transport networks to distributed multimodal transport networks with flexible, shared use of resources. This will enable better utilization of nodes within logistics networks.

Looking to the future cooperation between different retail and transportation companies would allow efficient group urban deliveries through local hubs. Here already there is work on a cloud-based tool [100] to support multi-modal transport chains and a global consolidation of freight. This includes a web application that can detect possible savings and the screening of transport flows for potential for combined transport including grouping potentials across companies.

### 2.6.5 Autonomous Vehicles

At the warehouse level there is a lot of interest in the use of smart items and sensors based on Internet of Things technologies. Here it is believed that the future is a distribution of central control to a multiplicity of small self-organized units. Already autonomous vehicles are used in warehouses for picking goods for dispatch (See Fig. 27) and there is interest in automatic adaption to environmental changes without the need for reprogramming through communication between infrastructure and the vehicles.



Figure 27. Automated Picking Machine [100].

Supporting this there is work on infrastructure to vehicle communications through concepts such as the Intelligent Bin in the InBin project [101]. Here the Intelligent Bin can communicate with people and autonomous machines allowing better control of logistics processes and management of the picking process. The bin can also manage its own environmental conditions monitoring temperature, vibration and position.

As warehouses become more complex there is interest in safely operating swarms of autonomous transport vehicles to perform tasks. The aim is to replace inflexible conveying systems by autonomous transport vehicles. Here the swarm is responsible for the task of transportation with scheduling being done within the group. This potentially will increase flexibility and changeability allowing simple scale-up and scale-down of systems.

In the trucking sector more driver assist systems are being added such as detectors for blind spots and cyclist detectors but these are causing concerns about information overload for drivers operating in urban areas. Autonomous driving for trucks is possible but too expensive at present. There are also a number of implementation issues including the need for trucks to be connected to cars. Platooning of trucks has been considered but a driver needs to consider which road chain to join, is the driver in front an efficient driver and will joining the road chain compromise the required delivery time. There is also pressure on truck designers to produce more aerodynamic trucks when a “brick shaped” truck would be more efficient in a platoon.



Figure 28. Amazon Prime Air [102].

Going one step further Amazon are developing their Prime Air concept [102] with drones that deliver packages to customers (See Fig. 28). The main goal of the new delivery system is to get packages into customers' hands within 30 minutes or less using unmanned aerial vehicles. Actual deployment of such systems is still many years away as a major barrier is gaining approval from the FAA for operations. This would be even more complicated for operations in Europe due to the more fragmented nature of airspace control. Amazon do not see this as an issue but rather an opportunity to work on the underlying technology and improve payload and endurance which are presently very limited.

## 2.6.6 Comments and Discussion

Systems of systems is not a new concept in the logistics domain with world-wide 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, emissions reduction and increased congestion on roads and in cities. At the same time customer service expectations are increasing with the need for order to delivery excellence. 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 develop new service concepts. Data and knowledge are becoming key competitive criteria with tracking of items through the logistics chain being the norm and companies competing to provide efficient and cheaper services. The underlying ICT technologies for tracking and exchange of information are thus already largely in place.

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 infrastructure. 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 systems of systems level there is a need to understand how much centralised planning is needed versus the use of decentralised 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 but it may well be a factor in the future as customers become more eco conscious. Green operations are a key concern for larger operators who have shareholders and sophisticated systems are being introduced that allow optimization across large numbers of vehicles. Big savings in fuel consumption and emissions can be made by increased use of telematics and more efficient operations, in particular, to reduce the number of trucks running half empty or empty on return journeys.

The use of autonomous vehicles is not new in logistics with 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. Moving out of the warehouse the industry is beginning to think about increased autonomy in vehicles for safety and the use of platooning for reduction in fuel consumption and emissions. Looking much further into the future automated delivery systems such as Amazon Prime Air are being developed but these are still many years away from deployment.

## 2.7 Commonalities and Overarching Research and Innovation Issues

### 2.7.1 Identified Commonalities

This section has considered the automotive, rail, aerospace, maritime and general logistics sectors. It is clear that there are common issues being addressed in these sectors. Many of the challenges within Europe in the area of transport 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, co-operation leading to a natural need for systems of systems approaches in order to meet the pan European transport flow of goods and people. In order to address many of the political, standardization



and legislative requirements in order to harmonize systems across Europe the European Commission has a significant role to play.

Considering technology, a key commonality across transport sectors is an interest in the increased use of ICT for optimization of operations. Here there are drivers to reduce time, cost and emissions. As much of the infrastructure already exists and there is a need for increased capacity the main challenge is to use the existing infrastructure more efficiently.

The introduction of ICT and remote connectivity to assets also introduces the ability to perform increased condition monitoring of assets through deployment of sensors everywhere. This is expected to bring huge savings in maintenance of infrastructure for instance in the rail industry and also more reliable operation of cars, trucks, aircraft, ship and trains. A challenge here is the generation of big data and the need for tools to data mine large data sets to extract useful information. Here there is an opportunity to introduce new service industries and already in the aerospace and marine domains maintenance service contracts are being offered commercially by manufacturers.

Communication is seen as a key enabler in all sectors between vehicles/assets and intelligent infrastructure. Here there will be increased communication between cars, aircraft, ships, and trains to allow safer operation and also operation of more vehicles. Linked with this is the need for security of communications and also a need for guaranteed levels of Quality of Service. Safety is paramount in all transport operations and is a key driver in all sectors.

Finally, increasing levels of automation/autonomy are being pursued in all sectors. The aerospace sector is currently leading in this field with autonomous vehicles already deployed for many years driven by military applications and enabled by the controlled nature of airspace. Cars are expected to introduce autonomous features by 2015 and many systems of systems challenges are predicted. The rail and maritime industries are also pursuing more autonomy to increase safety. For the rail industry plans are already well underway with roll out by 2024. In the maritime industry ships are becoming increasingly more autonomous but there is still quite a lot of work to do before ships can become completely autonomous. A major new area that is developing is monitoring of the Earth and the oceans and here there is a great interest in sustained systems of systems deployments of autonomous vehicles.

## 2.7.2 Transport CPSoS and Mapping to CPSoS Attributes

Many of the ideas for systems of systems come from development of concepts in the military domain. In a military organisation, every force package or task force is an ad-hoc “contingent” (i.e. configured in response to a contingency) systems of systems. It is temporarily configured from available assets and resources for the task in hand, then stripped down to the component elements at the end of the operation. Similarly systems of systems that react to unforeseen events, e.g. air sea rescue operation, disaster relief operation or “blue light” major incident response, can also be considered to be “Contingent Systems of Systems”. Here the problem is one of coordinating the available assets against a tight timescale. Already work is being funded by the European Union on these types of problems in the systems of systems cluster.

In contrast the systems of systems considered in this document for transport, e.g. the European rail network and air traffic management, etc., can be considered to be “business-as-usual” systems of systems as operationally and managerially the independent systems co-exist and co-operate in a dynamically stable and persistent systems of systems. Individual elements enter and leave the systems of systems but the systems of systems as a whole is persistent. A consideration here is that the concepts already developed in the military domain may not directly

apply to these types of systems or may require considerable modification. There are thus still a lot of open research questions. The key CPSoS attributes identified in this report for transport and logistics are:

- **Significant number of interacting components** Examples of significant numbers of interacting components can be found in the automotive, rail, aerospace and marine sectors. Here the components are vehicles interacting with each other and with infrastructure.
- **Control and management** In all sectors control and management are key issues. Key drivers are for operational efficiency and this can only be achieved by better control and management.
- **Partial autonomy of subsystems** At a local level the cars, trucks, aircraft, trains, ships all exhibit autonomy and indeed there is a need for loose control of systems in order to support flexibility for reconfiguration.
- **Dynamic reconfiguration** All the transport modes are subject to a variety of external disturbances that are both predictable and also unpredictable. These include disturbances introduced by weather, congestion, accidents and vehicle and system failures. A key aim is to maintain a level of local control that can be used to dynamically reconfigure at a local level and allow an overarching optimisation of the entire system in a dynamic fashion.
- **Possibility of emerging behaviours** In any system where there are very many elements under local control there is an opportunity for emergence to appear.
- **Continuous evolution** The road, rail, air traffic and maritime networks have evolved over 100's to 1000's of years within Europe. These are constantly changing but the challenge is to increase the capacity of existing networks. The introduction of new technologies will allow this increase in capacity but introduce new problems of how to deal with obsolescence. A car for instance has a supported life of 10 years. The infrastructure requirements tend to be to last for 30 years or more. Introduction of today's communications technologies will become obsolete within a matter of a few years so sustainable evolution is required.

### 2.7.3 Issues Identified

In all sectors of transport there are greater demands being placed by an ever increasing flow of people and freight traffic. This is putting great strain on existing infrastructure which has evolved over many decades. To increase capacity and avoid congestion there is a need to use existing infrastructure more efficiently. To support this here is a need for forecasting and coordinated control among subsystems and optimal routing for dynamic traffic networks. Increasingly multi-modal traffic is being considered. In the rail domain, for instance, the end-to-end journey time and ease of travelling for the passenger is a key factor. The rail segment is only part of the complete journey and there is a need to be able to model multi-modal traffic and also the passengers as they move between transport modes. In the aerospace domain the transport of passengers to and from the airport terminal, the process of passing through security and the boarding and deplaning all needs to be streamlined in order to increase passenger movements to meet future demand.

With the increasing numbers of vehicles being operated the probability of accidents and fatalities becomes a significant issue. Both the US and the EU have set aggressive targets for reducing loss of life and limb from accidents related to mobility. These concerns are driving work on automated and semi-automated systems across multiple transportation domains to improve safety. The European Union is committed to halving fatalities on the roads and this is driving the introduction of increased communication between vehicles, between vehicles and

infrastructure and the introduction of autonomous functionality. Similarly in the aerospace, rail and maritime sectors there are initiatives to increase levels of autonomy to reduce risk of accidents and fatalities.

Consumer demand and government regulation are driving the transportation sectors to use less energy overall, emit fewer harmful emissions and utilise an increased mix of sustainable energy sources. Countries around the world have agreed to CO<sub>2</sub> emissions targets that have been spelled out in the Copenhagen accord of 2009 [103], with the EU offering to increase its emissions reduction to 30% (from 1990 levels) by 2020. With the transportation sector emitting over 25% of CO<sub>2</sub> globally, this represents a significant challenge. To achieve greater efficiencies and reductions in emissions operators are now turning to systems of systems thinking to optimise the use of assets to minimise fuel costs and emissions. This needs to be achieved while at the same time delivering increasing levels of service.

In all domains the increased use of ICT is seen as the answer to many problems to allow better scheduling of traffic flow to reduce congestion, enabling increased communication with infrastructure and between vehicles to reduce congestion and avoid accidents, and as a central element in introduction of more autonomy within systems to improve efficiency and increase safety. The pervasive use of ICT will lead to highly complex interconnected systems of systems in the future.

### ***Support for Development***

Underpinning development of these future systems there is a need for a fundamental methodology to be developed for systems of systems Engineering. Much of the infrastructure is already existing so approaches to development are needed that can deal with legacy integration. As engineers are used to a clean sheet of paper design approach and classical V models of development a significant challenge is in developing new approaches to dealing with requirements engineering and model-based systems engineering that support systems that continually evolve and can never be considered to be finished. There is a need for comprehensive interdisciplinary heterogeneous, multi-scale modelling at different levels of resolution. This is needed for methodology development, multi-objective optimisation of performance, and for proving the economic benefits of increased integration/system-wide control as a means of unlocking investment. A key challenge here is gaining access to data and models which may be commercially sensitive/valuable. Modelling is also seen as key to giving confidence in safety and in identification of any emergent behaviours. For safety-critical and safety-related applications certification is required and this is complicated by the fact that the automotive, aerospace, rail and maritime industries have their own industry standards. Certification for a systems of systems is particularly challenging as they are not predictable and predictability is a fundamental requirement for many certification standards. There is thus a need to think differently about validation and verification and come up with new standards/techniques for the different transport sectors.

### ***Autonomy and Increased Interconnectivity***

Approaches to system wide control and coordination are required. Increasingly autonomous decision making will be introduced and this introduces sociotechnical issues about what systems should be made autonomous and what should be left to the human operator, and the need for homogeneous HMIs that allow users to interact easily and effectively with the system. 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, marine environments and on the roads. Here there is a need for interoperability, guaranteed quality of service and security of communications. Societal acceptance will be a key challenge. Trust is key and 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 safe even in the presence of a security breach (for instance one cannot shut down an aircraft engine if a security

breach is detected). Privacy is also a key issue and increasing interconnectivity results in a potential loss of privacy. This is complicated by different national attitudes towards privacy in Europe. Finally, 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.

### ***Situational Awareness Monitoring and Resilience***

The maintenance of systems is an issue and a complex systems of systems will require a high degree of monitoring. To support this there is a need for low cost smart sensors, self-powered sensors and exploitation of the Internet of Things (IoT) to provide information and create new services. It is clear that 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. This highlights the pragmatic need for a loose integration of systems rather than a tight integration. At an individual vehicle level there is a need to build in fault tolerance to situations that may arise such as a vehicle stopping unexpectedly or not following the “rules” of the rest of the system. The ability to deal with these situations strongly depends on real-time availability of high-quality data and on efficient data processing. Thus a key challenge for the future is data management. This needs to address the data deluge problem via large-scale online data integration and analysis of heterogeneous data sets to extract information. Visualization tools are also needed to present a view of the “real-world in real-time”. Supporting this there is a need for data exchange standards that allow the seamless integration of systems and provide interoperability. Challenges here are heterogeneity in the data but again also in maintaining security and privacy.

## **2.7.4 Research Priorities**

### ***Open Problems – Short and Long Term Priorities***

The problems within the transport domain were prioritised into short term (< 5 years) and long term (>5 years) issues.

#### **5 Years**

- Data – instrumenting with sensors (energy harvesting is considered to be a key enabler), collecting and managing maintenance and diagnostic data, dealing with heterogeneous data considering provenance and quality of data, designing for resilience considering the reliability of data, providing security and harmonizing standards (which are different in EU countries)
- Modelling – providing different levels and types of model, e.g. for design and development, managing complexity (also incorporating legacy systems), creating economic models to show business benefits for systems of systems to unlock funding in industry
- Due to large scale and complexity failures are the norm in CPSoS – there is a need for resilience and fault tolerance at the systems level and fail soft mechanisms
- Legal issues across countries – there is a need for uniformity in laws to allow data to be obtained from infrastructure, e.g. this is not presently possible for traffic lights due to legal restrictions and there are issues with information relating to the speed of car which could be potentially be also used for identifying speeding

#### **10 Years**

- Integrity, security and trust – to deal with malicious entities, crime and natural disasters, models are needed to test cyber security and cryptography is required

- System complexity is a major issue and there are needs for self-adaptation and self- maintenance
- Simulation to prove acceptability of coordination and control of systems of systems
- Optimization – optimal routing and planning on-the-fly to respond to changes and multi-objective (with potentially conflicting objectives) decision making approaches

**Other areas identified which are underpinning but cannot be classified into a timescale were:**

- New business models and services for operators – the car manufacturer or mobile phone service provider will not provide the final service so there is a need for systems of systems operators to develop new business models and services, for instance cloud computing connected to assets could be used to create a new service allowing global optimization of city traffic to reduce emissions.
- Controlling interaction with users – there is a need to explore approaches to controlling demand, e.g. incentives/rewards to take different routes in traffic planning or persuade customers that immediate delivery of parcels is not necessary (to allow more flexible logistics approaches such as bundling). Additionally, approaches to co-ordinating control and scheduling that take into account vulnerabilities in the system, dynamicity and multiple decision levels need to be considered.
- Communication standards – although many of the necessary communication standards will largely be in place within a 5 year timescale there is still a continuous need to work on new architectures and standards and consider their exploitation, e.g. high datarate (Gbytes/s) wireless communications, 5G mobile phone communications, etc. as they will have a significant impact on future systems of systems.

### 2.7.5 Proposal for a Strategic Research Agenda in CPSoS for Transport and Logistics

The proposed research topics arising from the analysis of the Transport and Logistics sector can be subdivided into three key categories covering:

- the development of systems of systems,
- the issues of autonomy and the increased connectivity between systems of systems,
- the operational issues of monitoring and maintaining levels of service in a systems of systems.

The 3 areas are outlined below along with the key underlying research subtopics that have been identified as important:

#### **Support for Development**

- Requirements engineering, model-based systems engineering and validation and verification that support “systems that are never finished” and legacy integration
- Modelling (interdisciplinary) and large-scale simulation of heterogeneous systems of systems
  - Multi-objective optimisation of systems of systems
  - Proving (economic) benefits of increased integration/system-wide control
  - Giving confidence in safety
  - Identifying any emergent behaviors

#### **Autonomy and Increased Interconnectivity**

- Autonomous decision making, system-wide control and coordination
- Socio technical issues of humans interacting with “autonomous” systems of systems (noting that not everything will be autonomous)

- Interoperability between systems and development of data exchange standards
- Trust – which becomes more of an issue as systems become more autonomous and highly interconnected (considering security, privacy, and designing to fail safe or operate in presence of security breaches)

#### **Resilience and Monitoring (Situational Awareness)**

- Condition monitoring, fault detection and reconfiguration strategies to provide resilience
- Low cost (self-powered) sensor technologies to provide data
- Management of data deluge via large-scale online data analysis to extract information and visualization tools to provide a view of the “real-world in real-time”

It is recommended that these research topics are addressed in a Strategic Research Agenda in order to enable the future development, deployment and maintenance of systems of systems within the Transport and Logistics domain.

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## 3 Physically Connected Cyber-physical Systems of Systems

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This section summarizes and analyses the state of the art of technology and practice for engineering and management of cyber-physical systems of systems that exhibit a physical coupling among the constituent entities. The application domains that are studied, as prototypical examples, include electric power grids, smart buildings and process industries as the systems present in these domains represent leading consumers of the resources and leading sources of employment in Europe.

### 3.1 State of the Art in Electric Power Grids

Electric power grids are designed and engineered to ensure the seamless transport of electrical energy from the place of its production (supply side) to the place of the consumption (demand side). These systems form networks that are naturally distributed over large areas, such as a country or a continent, and they encompass multiple nodes of electricity generation and consumption and the infrastructural interconnections, such as lines and transformers, between the nodes. In order to ensure a reliable and quality power supply to all consumers that are distributed over the grid, the operational goals of the grid relate first of all to maintaining grid stability while adhering to the grid codes, i.e. the network specifications for the operation of the grid, such as voltage level references at different transmission (high-voltage, HV) and distribution (low-voltage, LV) lines, power transfer levels for transmission and distribution, and frequency references in the system, the provision of a connection to the grid, the performance of electricity transmission across the grid, and cross-border transmissions. In the last two decades, the electricity transmission and distribution systems have gone through severe changes that have brought them to their limits.

In the first place deregulation has transformed integrated, top-down operated, state-owned systems into new distributed and concurrent unbundled companies. This new face of power systems is now being even more altered by the creation of real-time electricity markets (spot markets) that, on one hand, create new opportunities for better load balance in the network, on the other hand, introduce new needs for communication, real-time control and interaction with computer sciences and economics.

Secondly, the grid has gone through the transformation that resulted in the interconnection of the formerly independent grids. The resulting network has become extremely large. For example the European grid, that in a sense is the largest man-made system ever built, spans 29 countries in three continents and supplies electricity to nearly 500 million people. This large system of systems introduces difficulties that are hard to overcome by today's technology. Several ill-understood phenomena, in particular oscillatory cross-continent behaviours, appeared and are continuously reinforced with the growth of the system. Lack of on-line information and difficulty to analytically model the system also opens broad fields for technological development and innovations.

Finally, the third change has emerged from the large introduction of renewable energy sources (renewables) into the energy mix. This energy mix has been stable for a long time, but is now changing dramatically fast. In fact, even if in Europe 44% of electricity production is still based on fossil sources and 26% is from nuclear energy, 13% comes already from renewables (excluding hydraulic energy that stands for 18% of overall produced electricity) [1]. By the year 2020, the objective is to reach at least 20% of electricity generated from renewable sources in the average European production. This means more than double of the 2010 capacity (9.8%) in less than 10 years. Even though such numbers might appear modest, they represent an enormous challenge for the grid. Because of the nature of the system, even the smallest imbalance in the produced and consumed power has

immediate effects in system stability (frequency and voltage) that may or may not be absorbed by the system due to its vastness. The inherent variability of the renewables such as wind and solar power must consequently be instantaneously compensated on a system-wide level, while the consumed power also constitutes a time-varying load. In the same time, this physical layer co-exists with an economic layer, interconnected through a telecommunication layer to a control and management level. This cyber-physical nature of power systems makes such on-line compensation of variations in availability of renewables-based electricity still an open problem.

Most of these new challenges concerned mostly the transmission part of the power grid. Currently some of these problems have entered into the distribution system, which was never designed to deal with them. One of such new problems arises in the presence of distributed renewables production in the low voltage distribution grid. Such distributed generation creates important local imbalances between generation and consumption. In addition, this imbalance is often asynchronous, i.e. the peak of power generation is not correlated with (or compensated by) the peak of its consumption. This problem can be dealt with by different new technical measures complementing standard supply-demand balance techniques, consisting of production planning and reserves in order to make the system more technically and economically agile in the newly emerging conditions. These new techniques are demand-side management and distributed energy storage, which both mainly reside on the distribution system level. This has led to the concept of microgrids with island capabilities which are local interconnections of source, storage, and consumption entities connected to the distribution grid. Microgrids are operated and managed independently from the distribution system operators and can optimize their internal power flow and the power exchange profile with the grid based on varying electricity prices, local energy needs, the states of the storage devices and availability of energy sources such as the renewables. They can also be used to stabilize grid voltage conditions (and frequency if in island mode), to shorten the energy path to the consumers, and to minimize the CO<sub>2</sub> footprint of the distributed energy.

If the microgrid and the distribution grid are, however, not properly interoperated or are not interoperated at all, the distribution and/or transmission system can experience grid codes violation at certain consumption points as well as excessive grid losses or even congestion through certain distribution paths. With the lack of robust and reliable interoperation concepts, the distribution system operators in current practice act conservatively and prohibit connections of units with production capacity to certain grid points in situations when worst-case static simulations show that grid codes violation might occur. This is especially rigid since all already approved, but possibly not yet built, distributed production capacities are also considered in these worst-case simulations. Moreover, the electricity grid infrastructure dates from the times of unidirectional power flows and is thus very inflexible in terms of controllability. For example, transformer taps that can adapt the voltage level on the output of the transformer stations are only manually controllable in no-load state while they possess significant potential in terms of support for grid codes adherence.

All the presented characteristics show the electricity grid as a prototype of a physically connected system with spatial distribution and management, multi-scale dynamics, partial autonomy of the subsystems, temporal evolution of the system, and possibility of emerging behaviours, hence a system of systems.

Smart grids promise a revolutionary advance over today's power grids by enabling two-way flow of both electricity and information, seamless integration of renewable resources at distribution and customer points, widespread use of storage technologies and battery-electric and plug-in-hybrid-electric vehicles, demand response for efficiency and peak reduction, and other technological solutions (see Figure 29). The extended electrical power system connects beyond the physical grid itself to consumers at all levels, third-party energy service providers, demand aggregators, electricity markets, and other players. Information integration in terms of measurement, command, and control signals will supplement power flows. Individual systems, complex entities themselves, will retain their ability for autonomous operation, but are coupled via the grid and have to be coordinated.

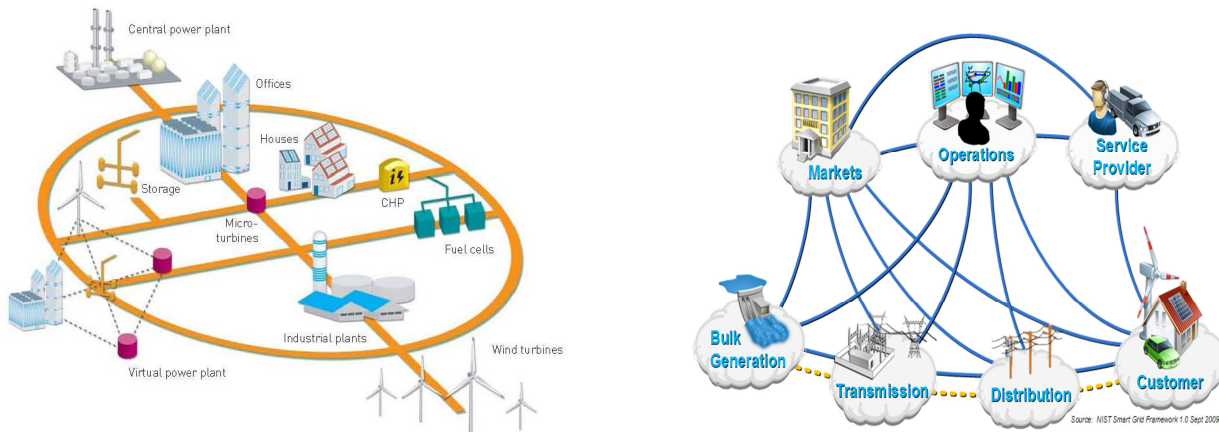


Figure 29. Smart grid conceptual diagrams from the Smart Grids European Technology Program (left) and the NIST Smart Grid Interoperability Panel (right) showing different views on a smart grid.

### 3.1.1 Management of Electric Power Grids

The operational goals of power grids are to ensure adherence to grid rules while maximizing the economic benefits of the distribution and transmission grid operation, which include:

- Maximizing the environmental value of energy transfer by taking into account the CO<sub>2</sub> equivalent of the transferred energy as the European grid is committed to delivering carbon-neutral electricity by 2050,
- Minimizing energy losses in the grid by proper configuration of power flows over grid segments.

Operational constraints are posed on the grid frequency and voltage amplitude at all connection points, as requested by the grid codes. Furthermore, power flows through individual grid segments and transformer stations are constrained to prevent excessive power dissipation and equipment damage. System-wide possible control actuations are diverse, and dependent on the considered voltage level. For the low voltage distribution system, for example, they are mainly composed of transformer tap changes in transformer stations and capacitor banks switches, both actuated in discrete steps, generator loads and circuit breakers for grid topology reconfiguration. Recently introduced Distribution Flexible Alternative Current Transmission System (D-FACTS), storage units and the power converters associated to renewables like solar panels, represent new possible control actuators, that can be used to mitigate the new challenges created by distributed generation, large scale renewables integration and a future large share of electric vehicles.

The decisions that are made in the operation of the electrical grid can be classified according to their temporal influence of the system into a hierarchical structure. At the upper level, the efficiency, security and sustainability of electrical power generation and transmission are of a concern. This level makes the decisions on the planning for long- and medium-term operation while taking into account expected loads and demands and present infrastructure and its planned revisions. Aggregate, normally static, models are used for the prediction of the production and consumption at the network nodes such as big power plants, wind farms, micro grids, smart grids, etc. On the other hand, at the lower (e.g. microgrid) level the focus is on the achievement of the reliability of the network via means of congestion management techniques which include demand side management, exploitation of storage capabilities, and flexible electricity generation using conventional sources. In practice congestion management is usually performed via ramping up or down the load (demand) of the biggest electricity producers (consumers) which includes the use of virtual power plants, i.e. large production facilities that require a considerable amount of power and that can be given the incentives to ramp down their production in order to stabilize the grid.

Table 2. Multiscale Time Hierarchy of Power Systems (taken from [2]).

Action/Operation	Time Frame
Wave effects (fast dynamics, lightning-caused overvoltages)	Microseconds to milliseconds
Switching overvoltages	Milliseconds
Fault protection	100 ms or a few cycles
Electromagnetic effects in machine windings	Milliseconds to seconds
Stability	60 cycles or 1 second
Stability augmentation	Seconds
Electromechanical effects of oscillations in motors and generators	Milliseconds to minutes
Tie line load frequency control	1–10 s; ongoing
Economic load dispatch	10 s to 1 hour; ongoing
Thermodynamic changes from boiler control action (slow dynamics)	Seconds to hours
System structure monitoring (what is energized and what is not)	Steady state; ongoing
System state measurement and estimation	Steady state; ongoing
System security monitoring	Steady state; ongoing
Load management, load forecasting, generation forecasting and scheduling	1h to 1 day or longer; ongoing
Maintenance scheduling	Months to 1 year; ongoing
Expansion planning	Years; ongoing
Power plant site selection, design, construction, environmental impact	2–10 years or longer

The time-scales on the different levels of the presented hierarchy are largely different; they vary from microseconds to long-term contract management (see Table 2). Even if differing from country to country, most grids operate in a hierarchical scheme starting with the fastest level of local controllers, followed by primary, secondary and tertiary control levels. The human-operator actions are usually employed at the time-scale of hours and longer. For the achievement of the lower-level goals, preference is given to decisions provided by automated solutions as the system-wide actuation in the distribution grid must possess effective fault management capabilities, i.e. to provide a safe and fast recovery from possible large disruptive events (e.g. failure of large producers or consumers, line breakages, unavailability of transformer stations, etc.) to prevent possible outages. The price to pay for automatically guaranteeing safe and fast recoveries is the implied conservativeness of the actuation. This conservativeness can be understood by the huge cost of major failures. For example, estimated costs for the 2003 US blackout are close to \$6.4 billion<sup>1</sup>.

Although it is believed that the possibility of human interaction on shorter time-scales would result in a better performance in terms of fulfilling the upper-level goals, such interaction is presently not exploited since fast and reliable response of human operators cannot be generally assured. The multi-scale nature of the system dynamics plays crucial role in the way the grid is managed and how its behaviour is forecasted. Tools of static model-based simulation are in use where the simulation models consider the dynamic effects acting on much shorter (or longer) time-scales to be constant.

From the management viewpoint, one of the main features of the grid is the inherent stochasticity that originates from the inclusion of renewable energy and from the behaviour of the customers. Statistical tools for monitoring the network balance are utilized in order to forecast the future evolution of the demand and supply. To deal with the present challenges, several research and innovation projects were launched on modelling, simulation, control and optimization of the electrical grid. Presently, the modelling is commonly done both in physics-based and in data-based manner and includes attempts to model the behaviour of the “agents” in the grid. The challenges in

<sup>1</sup> ELCON The Economic Impacts of the August 2003 Blackout, 2004.

simulation include a deployment of hybrid (continuous-discrete) simulation tools, an adoption and reliable simulation of the models with various levels of abstraction at different decision-making levels (e.g. planning, operation), simulation of systems with many different time-scales and the coupling between physics of the grid, information flow and economy, as the politically-motivated regulations have a strong influence on the way how grid is operated.

Technological developments for overcoming the operational challenges in the grid include nonlinear, robust and distributed model predictive control and inclusion of new sensors and actuators. Current industrial and academic research projects orientate towards distributed multi-agent solutions of the management problems as these appear promising for reduction of effort and complexity compared to centralized control approaches and for natural resolution of the ownership issues of the equipment in the grid. In the field of optimization, stochastic optimization (risk management) and discrete decisions are seen as important fields of research.

Future technologies that will assist in mitigation of the challenges of the present currently in the engineering and management of the power grids comprise [2]:

- low-cost, practical electric and thermal energy storage;
- advanced (post-silicon) power electronics devices (valves) to be embedded into flexible AC and DC transmission and distribution circuit breakers, short-circuit current limiters, and power electronics-based transformers;
- power electronic-based distribution network devices with integrated sensors and communications;
- fail-safe communications that are transparent and integrated into the power system;
- low-cost sensors to monitor system components and to provide the basis for state estimation in real time;
- cost-effective integrated thermal storage (heating and cooling) devices;
- thermal appliances that provide “plug-and-play” capability with distributed generation devices;
- high-efficiency lighting, refrigerators, motors, and cooling;
- enhanced portability through improved storage and power conversion devices
- voltage stability by the distributed control of the DC/AC power converters embedded in solar panels and electric vehicles;
- DC network for the interconnection of solar arrays and storage to the AC grid;
- Intelligent substation for two-direction power flow between distribution and transmission grids

It is worth noting that the idea of smart grids is not limited to electric power but the principles, as well as present challenges, can be transferred to other resource infrastructures such as the ones for natural gas and for water distribution. In smart grids, autonomous/semi-autonomous entities coordinate their operations on an as-needed basis, following selfish goals, while the efficiency and stability of the overall system must be ensured by limited central authority. This is clearly a systems of systems design and management challenge.

### 3.1.2 Recent Research Projects in the Domain of Electric Power Grids

To complement the state-of-the-art analysis, an overview is given of research projects addressing the domain-specific needs as described above.

**GRID+** - The FP7-funded GRID+ project was launched in 2011 as a support action to help the European Electricity Grids Initiative (EEGI) to pass through the 2012-2014 period, critical for the EU’s internal energy market

objectives but also in terms of preparations for the first year of the EU's new research funding programme for 2014-2020 (Horizon 2020). The most relevant support tools delivered by GRID+ are:

- Knowledge sharing platform: the Grid Innovation Online platform is a dynamic virtual library structuring the new knowledge generated by R&I projects contributing to the EEGI roadmap
- Scaling and replicability factors assessment tool
- KPIs: Key performance indicators covering three levels (overarching, cluster specific and project level)
- RD&D gap analysis: the mapping of gaps in research, development and demonstration, feeding into the EEGI Roadmap and Implementation plans, but also the JRC's smart grid project database
- Interaction workshops between smart grid project representatives
- EEGI project labelling: providing more visibility for demonstration projects that are aligned with the EEGI's goals

**Meter-ON** - Meter-ON is coordination and support action funded by the EU's FP7 and designed to steer the implementation of smart metering solutions throughout Europe by collecting the most successful experiences in the field and highlighting the conditions that enabled their development. Meter-ON will provide all stakeholders with clear recommendations on how to tackle the technical barriers and the regulatory obstacles endangering the uptake of smart metering technologies and solutions in Europe. In more detail, the goal of Meter-ON is to, on the basis of the lessons learned, provide stakeholders with an open information platform. European distribution system operators (DSOs), regulatory bodies, smart metering manufacturers, operators, policy makers and other stakeholders in the European smart metering community, will all benefit from the results of the project. The public deliverables and outputs of the project aim to be used as comprehensive guidelines resulting from the most significant European-wide smart metering experiences.

**REservices** - The REserviceS (Economic grid support from variable renewables) is an FP7-funded project aiming to establish a reference basis and policy recommendations for future network codes and market design in the area of ancillary services from variable renewables. The outputs will be essential insights and economic elements to support the establishment of proper market mechanisms and grid code formulations in the EU, as well as to carry out a preliminary assessment to determine whether ancillary services can generate additional value for network operators by involving grid users, notably wind and solar PV generators. It is the first study to investigate wind and solar based grid support services at EU level. It will provide technical and economic guidelines and recommendations for the design of a European market for ancillary services, as well as for future network codes within the Third Liberalisation Package. REserviceS encourages the efficient and economic deployment of a large shares of renewable energy sources by exploring how wind and solar photovoltaic (PV) plants can provide such services in the future European power system.

**evolvDSO** - The FP7-funded evolvDSO project aims to develop the methodologies and tools for new and evolving DSO roles for efficient DRES integration in distribution networks. The evolvDSO consortium addresses the main research and technology gaps that need to be solved for DSOs to efficiently fulfil their emerging and future roles in the European electricity system. The new tools and methods will encompass a wide array of DSO activities related to planning, operational scheduling, real-time operations and maintenance. Selected methods and tools developed during the project will be validated in computer simulations and real-life testbeds to maximise their potential for deployment in various EU contexts. Beyond this holistic, top-down approach, evolvDSO is unique in that it brings together the key actors of the electricity value chain that are at the forefront of smart grid development, and with a clear common view on what is needed for further DRES integration in Europe. The consortium consists of 16 partners including DSOs, TSOs, renowned research institutions and new market players that provide unique expertise to achieve the stated objectives. evolvDSO will contribute to the transition to a more sustainable European energy system by maintaining and increasing the security and reliability of



distribution grids facilitating the increased feed-in of DRES. The results of evolvDSO will drive the implementation of the EEGI roadmap and ultimately provide a significant impetus for reaching EU climate targets.

**E-price** - E-Price is a three-year European research project aiming to develop a reliable, an efficient and a societal-acceptable control concept for the EU energy market. E-Price sets a new standard by introducing a feasible price-based control strategy. Its ambition is to be at the very heart of future developments that fully facilitate the increasing amounts of less-predictable renewable energy sources. E-Price uses expertise to develop innovative products and methods in co-creation with private and public parties. The interdisciplinary team of specialists from European universities and industry will look beyond present boundaries and fixed structures. E-Price will offer an integral solution, meeting European Union policy. This will bring about a market and control concept that gives incentives to all participants to follow their own interests and still satisfying the societal requirements on reliability, efficiency and transparency. It certainly affects the way electricity will be produced and used in the future, thus bringing about a structural change.

**SUNSEED** proposes an evolutionary approach to the utilisation of already present communication networks from both energy and telecom operators. These can be suitably connected to form a converged communication infrastructure for future smart energy grids offering open services. Geographical overlap of energy and communications infrastructures identifies vital DSO energy and support grid locations (e.g. distributed energy generators, transformer substations, cabling, ducts) that are covered by both energy and telecom communication networks. Coverage can be realised with known wireline (e.g. copper, fiber) or wireless and mobile (e.g. WiFi, 4G) technologies. For full utilisation of future network planning, the project will integrate various public databases. Applications build on open standards (W3C) with exposed application programming interfaces (API) to 3rd parties enable creation of new businesses related to energy and communication sectors (e.g. virtual power plant operators, energy services providers for optimizing home energy use) or enable public wireless access points (e.g. WiFi nodes at distributed energy generator locations). SUNSEED life cycle steps promise much lower investments and total cost of ownership for future smart energy grids with dense distributed energy generation and prosumer involvement.

**DYMASOS** - The project will develop new methods for the distributed management of large physically connected systems with distributed autonomous management and global coordination. The research will be driven by case studies in electrical grid management and control, including the charging of electric vehicles, and industrial production management. The properties of the distributed management and control techniques are investigated, and they are validated in large-scale simulations of case studies provided by industrial partners. From the validation for the case studies, general conclusions will be drawn about the suitability of the proposed distributed management and control mechanisms for certain classes of systems of systems. This will provide guidelines for the design of evolving systems of systems with respect to the interplay of local autonomy and global management. The project will include the development of methods and tools for the engineering and implementation of advanced management solutions for systems of systems.

### 3.1.3 Present and Future Challenges in the Domain of Electric Power Grids

The smart electricity grids discussed above are only part of the future energy landscape. There is a bidirectional interconnection with other energy carriers, for example the gas network, heat/steam networks, etc. This interconnection needs to be taken into account, when designing next generation electricity grids and optimizing their performance. This can be particularly relevant at the level of micro-grids, which can combine electricity generation and consumption with other energy sources, for example combined heat and power but it also addresses major prosumers such as industrial production facilities and big power plants.

The future fault management mechanisms, should not only consider the detection, but also the isolation and the recovery from a fault at all voltage levels of the grid. In particular at low voltage level no mechanisms are actually deployed. Techniques such as FDIR (fault detection isolation and restoration) and self-healing approaches could be adapted and deployed to address this challenge.

The security of the information being transferred over the grid represents another challenge. Existing approaches for achieving cyber-security are not applicable or may encounter problems because of the stringent timing requirements of message delivery in these domains. The generation, transmission and distribution domains require security solutions to not only protect information exchange, but also to meet the requirements for data communication and processing thereby posing a practical challenge for security designers [3].

With expected larger penetration of the electricity spot market in the member states of EU, market aspects may play a key role in the process. Producers and consumers of electricity, micro-grids, etc. will coordinate with each other to provide smart grid functionality either if forced (by introducing a legal framework), or if the right market mechanism makes it mutually beneficial for them to do so. Figuring out the benefits/costs of different behaviours and fairly allocating them to the different participants will be crucial for the latter approach. If a certain power consumption is requested (e.g. because a 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.

In addition to operational concerns, economic issues of course also arise in long-term decisions related to network development, capacity expansion, technology investment, etc.

For all these issues, optimization-based control methods, especially those building on distributed optimization concepts will be central. Dealing with uncertainty (e.g. about future demand and technology, operational uncertainty in the day-ahead markets, etc.) means that links to stochastic programming and randomized optimization should also be investigated.

Based on the preceding analysis, the specific challenges in the domain of electrical power grids include:

- Engineering
  - System integration of active distribution,
  - Requirements for the associated ICT systems such as latency, reliability, communication delays, etc.
  - Development of new approaches for verification of system stability
  - Data availability and new business models for their exploitation
  - Cyber-security (privacy)
  - Massive integration of inverter-based components (lack of inertia, synchronization issue)
- Management
  - Better use of measurements (network state estimation)
  - Distributed (decentralized) controls at substation level
  - Demand side management via artificial power plants
  - Application of advanced management solutions (e.g. MPC)
- Modelling
  - Modelling and simulation of distributed generation
  - Modelling the power system jointly with communication systems

- Modelling the human behaviour and interaction with the system
- Generic and automated model building
- Simulation
  - Simulation of large-scale systems
  - Reliable system simulation considering different abstraction depths of the models at each level
  - Variability of the nature of the models (static/dynamic, continuous/discrete) at different levels in planning and operation layers
- Optimization
  - Decentralized optimization at the distribution level taking into account market conditions, safety constraints and unit commitment
  - Optimization under uncertainty
  - Stochastic optimization

### 3.2 State of the Art in Smart buildings

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, water) interact by exchanging the 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).

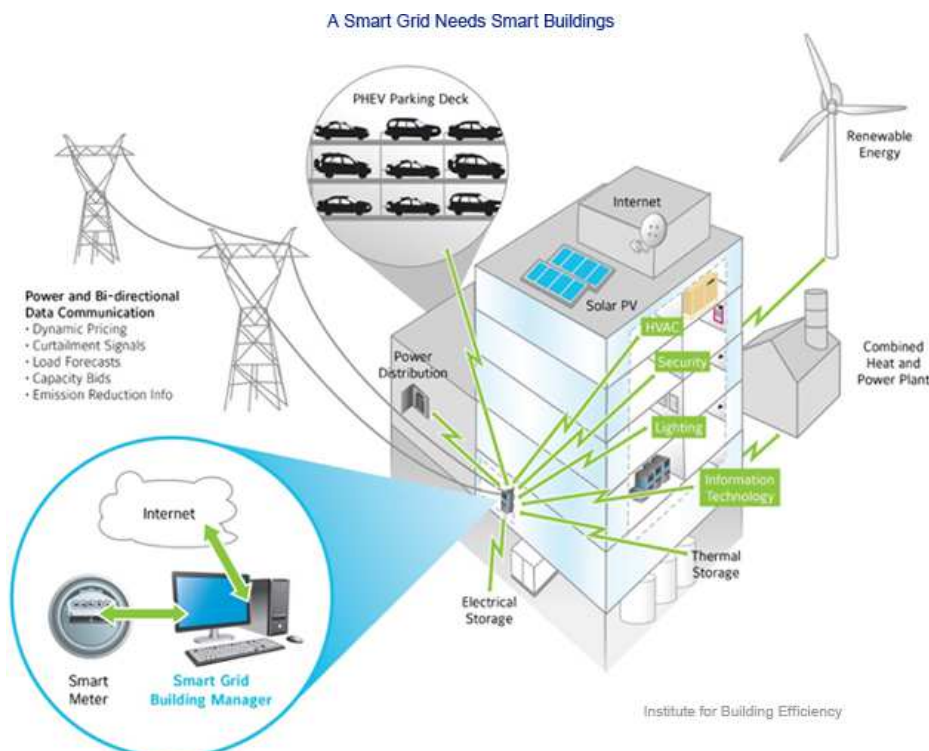


Figure 30. Integration of smart building within smart grids (taken from [4]).

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 become active participants in the electricity spot market. From the system 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 campus can include any type of local energy generation, distribution, consumption, and storage elements (see Figure 30). 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 as the production of electricity and thermal energy by CHP cannot be decoupled. 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, such as hot water (HW), chilled water (CHW) and electricity networks. The renewable sources of energy, such as solar radiation, play particularly significant role in both the supply and the demand side. This makes the efforts for proactive energy balancing challenging as these use the predictions on the future availability of the renewables-based energy whose quality depends on the accuracy of the weather forecast. Moreover, the smart buildings must meet the, possibly time-varying, comfort criteria, communicated from their occupants, by taking into account the number and the behaviour of the occupants.

Seeing the smart building as a prosumer in the electrical grid, the supply side feeds the grid with electric power that is generated locally by a variety of distributed generation elements. These can range from complex cogeneration (CHP) units to stand-alone generation units (wind turbines, photovoltaics, etc.) that utilize conventional or renewable sources of energy. Supplies also come from the main electrical power grid, which is operated by the respective system/network operator, and this connection can also serve for selling locally generated excess or green energy back to the main electricity network. In addition to electricity, the supply side includes also boiler plants and chiller plants for heating and cooling the building, which is required to maintain thermal comfort in the interior spaces. Heat is transferred to and from individual rooms or zones through available distribution networks – systems of ducts, pumps and heat exchangers – in which the hot water, chilled water and/or air are used as the three main energy carriers. The demand side of the building aggregates all devices that consume either electrical or thermal energy.

Energy storage is an important element that adds more flexibility, but it also increases the operational complexity. Energy storage elements can bring significant advantages particularly when the supply side includes intermittent renewable generation sources. In the future, when electric cars will be widely used, their storage capacity could be exploited in a similar way to smoothen energy consumption profiles.

### 3.2.1 Management of Smart Buildings

The present state of the art is to control and to optimize some of the subsystems independently of the others giving a rise to partial local autonomy so these subsystems must be coordinated using a certain set of management rules. Typically, all three, hot-water, chilled-water, and air distribution systems are operated so 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 which were specified during the system design. The current standard is to apply control schemes that are employed with rule-based control which commonly define supply set points using the current ambient temperature, adjusted dynamically after every measurement. Those techniques are, however, unable to dynamically respond to changing conditions, such as sunshine intensity, updates in forecast of the evolution of ambient temperature or the daily expectations on number and behaviour of occupants.

The management of the information that is available either as design specifications of the different components of the subsystems, e.g. parameters of the actuators such as pumps, valves, etc., or being gathered as

measurements from the available sensors does not allow the subsystems to exchange the relevant data. It is believed by domain practitioners that such exchange realized in efficient manner will result in improvement of the system monitoring and dynamic response to malfunctions and faults of the hardware.

Current building modelling software applications use static models with pre-determined parameters to model energy hold-up and exchanges, instead of realistic sensing data. Hence, they cannot model appropriately appliances, end-utility points, and occupants' behaviour, and, consequently, the simulation results exhibit low fidelity.

The majority of today's advanced management technologies require an elaborate model of the system to be available. In real-life applications though, these technologies usually turn out to be inapplicable due to absence of such system models, inappropriate modelling assumptions of the present models, computing limitations, complexity trade-offs and implied reliability of simulations. Modelling and efficient control of such systems – systems of systems – demands tedious work of specialized personnel and continuous tuning of the control and modelling parameters due to continuous evolution of real-life CPSoS dynamic behaviour and the subsystem interconnection dependencies.

Given the above shortcomings of the state of the art, there are large opportunities for improvements. Building energy systems should be operated in a predictive/proactive way while considering future demands (day-ahead predictions), weather conditions, and possibly also electricity prices/tariffs and other external parameters. Flow rates and temperatures in water and air distribution systems should be modulated to minimize the operating cost while interior comfort conditions are kept within a specified comfort range. The ratio between local generation and the purchased electricity should be optimized with respect to dynamic electricity prices and CO<sub>2</sub> footprint, while using various storage mechanisms to accommodate variations. Recent research suggests that the application of model predictive control (MPC), as an advanced management solution, outperforms the standard control schemes while reducing energy consumption of the buildings and enhancing the internal thermal comfort. The advantages of MPC include [5]:

- Incorporation of the disturbance predictions (occupancy profiles, weather changes, etc.)
- Full exploitation of the building's thermal mass compared to the conventional controllers (such as PID, weather-compensated or rule-based control)
- Ability of taking into account the energy price variations into control problem formulation
- Responsive tuning capabilities, e.g., for shifting and minimization of the energy peak loads that can be handled within a definite time period due to the selection of the tariff and least operational cost
- Potential for deployment of distributed control strategies together with flexible parameterisation of the (distributed) agent-based controllers

The application of these advanced solutions is presently restricted because of the lack of:

- accurate models that would reliably predict the behaviour of the buildings and that could be standardized (e.g. for different types of buildings),
- information exchange models and solutions that would allow to process the available measurements, gathered in different subsystems, and pass the newly obtained information to all the monitoring and control systems present in the building,
- adaptive mechanisms that can automatically incorporate the measurement information can into the prediction models for increasing their accuracy,
- incentives from the legislation and economics

### 3.2.2 Recent Research Projects in the Domain of Smart Buildings

To complement the state-of-the-art analysis, an overview is given of research projects that are addressing the domain-specific needs as described above.

**REEB** – The project aims to facilitate creation of a Strategic Research Agenda (SRA) and a supporting Implementation Activity Plan (IAP) for sustainable and energy-efficient smart building constructions by the establishment of and federation of dialogues between interactive and complimentary communities of practice from energy, environment, and building construction domains. REEB will establish a community operating method that will allow these communities to act as breeding and nurturing grounds for innovation in bringing together the relevant organisations and stakeholders for the purpose of starting up "innovation cycles in ICT-based environment management and energy efficiency" in smart building constructions. The main outcomes will be: (i) a SRA and detailed IAP for R&D and innovation in ICT supporting energy-efficient smart facilities, (ii) a comprehensive coordination of information exchange and dissemination between energy-related ICT projects in various EU, national, and global programs/initiatives, in terms of on-going research, developed solutions, standardisation efforts, etc.

**MSP** - The central objective of the MSP-project is the development of a highly competitive technology and manufacturing platform for the 3D-integration of sophisticated components and sensors with CMOS technology. The MSP project is focused on the development of essential components and sensors for the realization of smart systems capable for indoor and outdoor environmental monitoring:

- Gas sensors for detection of potentially harmful or toxic gases
- Sensors for particulate matter and ultrafine particles
- Development of infrared sensors and UV-A/B sensors
- Development of highly efficient photovoltaics and piezoelectrics for energy harvesting
- Development of components for wireless communication within sensor networks and to handheld devices

The major goal is the development of smart multi sensor platforms for intelligent air conditioning systems in building technologies and for implementation directly into smartphones to detect harmful environmental gases.

**BESOS** is an EU Research and Development project funded by the EC in the context of the 7<sup>th</sup> Framework Program that proposes the development of an advanced, integrated, management system which enables energy efficiency in smart cities from a holistic perspective. To that end, the energy management systems deployed in a typical district that are consuming or producing energy, and which nowadays normally expect an isolated IT management solution, will be able to share data and services through an open trustworthy platform among themselves and to external third party applications.

**INTRPID** is an FP7-ICT project that aims to develop technologies that will enable energy optimization of residential buildings, focusing initially on the optimal control of internal sub-systems within the Home Area Network (HAN), but then also providing adequate mechanisms for effective interaction with external world, including other buildings, local producers, or electricity distributors, enabling energy exchange capabilities.

**DIMMER** - The project focuses on:

- Interoperability of district energy production and consumption, environmental conditions and user feedback data

- Exploitation of effective visual and web-based interfaces to provide pervasive and real-time feedback about energy impact of user behaviours
- Integration of Building Information Models (BIM) with real-time data and their extension to the district level, leading to District Information Models (DIM)
- New business models for energy traders and prosumers.

The DIMMER system integrates BIM and district level 3D models with real-time data from sensors and user feedback to analyse and correlate buildings utilization and provide real-time feedback about energy-related behaviours. It allows open access with personal devices and Augmented Reality (A/R) allowing the visualization of energy-related information to client applications for energy and cost-analysis, tariff planning and evaluation, failure identification and maintenance.

**PEBBLE** (FP7 project) – With the belief that maximization of net energy produced (NEP) for Positive-Energy Buildings is attained through Better Control dEcisions (PEBBLE), a control and optimization ICT methodology that combines model-based predictive control and cognitive-based adaptive optimization is proposed. There are three essential ingredients to the PEBBLE system: first, thermal simulation models, that are accurate representations of the building and its subsystems; second, sensors, actuators, and user interfaces to facilitate communication between the physical and simulation layers; and third, generic control and optimization tools that use the sensor inputs and the thermal models to take intelligent decisions. Building occupants have a dual sensor-actuator role in the PEBBLE framework: through user-interfaces humans act as sensors communicating their thermal comfort preferences to the PEBBLE system, and in return the PEBBLE system returns information with the goal of enhancing energy-awareness of the users. The generality of the proposed methodology affords a universality that transcends regional, behavioral, environmental or other variations. For this reason, the PEBBLE system will be demonstrated and evaluated in three buildings possessing a variety of design and performance characteristics, located at different places across Europe.

**ICT 4 E2B Forum** – The project is aimed at bringing together all relevant stakeholders involved in ICT systems and solutions for Energy Efficiency in Buildings, at identifying and reviewing the needs in terms of research and systems integration as well as at accelerating implementation and take-up. ICT 4 E2B Forum intends to promote, through community building activities, a better understanding, a closer dialogue and a more active cooperation between researchers, end-users/practitioners, building owners, technology-suppliers, and software developers as regards the use of ICT to support informed decision-making (both human and automated) in the current delivery and use of sustainable and energy-efficient buildings and districts. The ICT4E2B Forum project aims at the following objectives:

- Bring together relevant stakeholders to identify and review the needs in terms of research and systems integration
- Update the REEB research roadmap
- Promote the use and further development of ICT for improved energy efficiency of buildings

**CAMPUS21** – The project focuses on energy-efficient operation of public buildings and spaces. CAMPUS21 develops, deploys, and tests a Hardware-Software Platform for the integration of existing ICT-subsystems supporting energy, building, and security systems management. The key technological innovations of CAMPUS21 are:

- Integration concepts for energy management systems including the related middleware components
- Development of methodologies for intelligent and optimized control of building services systems

- Development of algorithms and tools to support load-balancing between renewable micro-generation, storage systems, and energy consuming devices in buildings and public spaces

Those components are complemented by the development of key business elements, including:

- New business models for integrated energy management and the underpinning novel procurements schemes
- The development of Performance Metrics and a holistic Evaluation Concept for Systems Integration

**Local4Global** – The main objectives of the project are to develop and extensively test and evaluate in real-life technical SoS (TSoS), a generic, integrated and fully-functional methodology/system for TSoS with the following attributes:

- The TSoS constituent systems are operating as fully autonomous units that react and interact depending only on their local environment in order to optimize the TSoS emerging performance at the global level.
- There will be no need for an elaborate and tedious effort to deploy the Local4Global system or to re-design/re-configure it in cases of changes in the topology, environment or hierarchy of the TSoS.
- Moreover, there will be no need for an elaborate, “expensive” infrastructure that provides each and every constituent system with information coming from all over the TSoS.

The Local4Global methodology/system will be applicable to generic TSoS that comprise highly heterogeneous TSoS. Moreover, it will, by its very nature, be totally scalable and computationally efficient.

All the advances of the project will lead to a fully-functional and ready-to-use system (Local4Global final product) - delivered in the form of an embedded, web-based, “plug-and-play” software system for generic TSoS, mountable locally to each constituent system. This system will be deployed and extensively tested and evaluated in 2 real-life TSoS Use Cases, a Traffic TSoS Use Case and an Efficient Building TSoS Use Case.

### 3.2.3 Present and Future Challenges in the Domain of Smart Buildings

Recent studies show that for substantial savings in building energy consumption, no static assumptions should be made about a building's state and operation and that the dynamicity is an essential property to achieve energy efficiency in buildings [6]. In parallel to optimizing energy consumption and performing automated adaptations, user comfort continues to be an essential success criterion for ICT-based solutions in order to improve user acceptance of the system.

To overcome the above presented shortcomings novel technologies and methodologies for optimal management are needed. Such approaches should encompass adaptability, flexibility, stability, and interoperability properties building upon the distributed operation of the system taking into account uncertainty in the modelling of the system, variability of the occurring disturbances (e.g., accuracy of weather forecast and occupancy prediction, availability of renewables-based energy) and socio-technical aspects (interaction with humans) of the system.

In this respect, modern adaptive mechanisms have to be extended towards the reduction of computational demand and control complexity, the ability to handle thousands of parameters in an efficient manner and, as a consequence, towards the increase of the efficiency of the response of real-time control schemes. Self-learning mechanisms can be considered as a concrete basis for future research in order to embed easily, appropriate aspects of adaptive system identification schemes within the control mechanism, so as to directly construct an internal accurate enough model, capable of assessing the effect of control decisions on the real system.



The complex interplay of an extremely large number of parameters together with the fact that the system behaviour is subject to frequent changes (due to e.g., weather changes, human behaviour, incidents or changes in the system infrastructure) render the transformation of "what the human wants" into "how should the CPSoS control and calibrate the large number of parameters so as to do what the human wants" an extremely difficult and complex task. This task becomes significantly more complex when the human operator needs to intervene in the systems in a real-time and dynamic fashion, i.e., "on-the-fly", while the system is in operation. The future research goals should lead towards an integrated, inexpensive, straightforwardly deployable (plug-n-play) application software which will embed conventional cheap infrastructure with a highly intelligent mechanisms for assisting the customers in significantly reducing their energy bills and will enable the human operator to control and adjust CPSoS of high complexity, scale and heterogeneity in a simple yet very efficient manner.

For the (campuses of) smart buildings to become active players in the future energy infrastructure, any of the following smart building-related Information regarding smart grid functionalities should be used and exploited by the automatic management platform:

- Real-time information about current as well as future electrical energy tariffs (if variable tariffs are implemented).
- Real-time information concerning local generation and storage information.
- Real-time information concerning local or grid-connected renewable sources status.
- Real-time information concerning distribution network operator requirements.
- In cases of micro-grids, real-time information regarding the status and the needs of all the micro-grid actors.
- Real-time information concerning current voltage and frequency levels.
- Micro-grid connection mode (connected to the grid mode or islanded mode) so as to be able, in the case of islanded mode of operation and in order to prevent blackout, to achieve load balancing in order the available generation added to the power can be extracted from storage devices to meet the demand.

Occupants of the buildings play a critical but poorly understood and often overlooked role in the building environment [7]. 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. Personalized behavioural strategies need to be further studied and the factors and incentives affecting user behaviour need to be better understood. Privacy is an important matter in this respect. There is a need to respect the privacy of occupants and avoid exposing details about their habits or lifestyles to the third parties in order to increase the trust in the system and to make human-building interaction effective.

Based on the preceding analysis, the specific challenges in the domain of smart buildings include:

- Engineering
  - Communication framework that allows for effective exchange of the information and deployment of self-adaptive solutions
  - Multi-dimensional visualization of parameters of building operations and data sharing from technical systems
  - Privacy and cyber-security
- Management
  - Better use of measurements for state and parameter estimation
  - Performance analysis and optimization by the use of the information collected during the monitoring

- Adaptive control mechanisms that can automatically incorporate the measurement information into the prediction models for increasing the prediction and monitoring accuracy
- Intelligent sensor-based data monitoring
- Development of energy optimal coordination algorithms between applications such as HVAC, lighting, security, etc.
  
- Modelling
  - Modelling of the human behaviour and interaction with the system
  - Generic and automated model building and standardization of the models
  
- Simulation
  - Reliable system simulation considering parametric uncertainties of the employed models
  - Stochastic simulation
  
- Optimization
  - Optimization under uncertainty
  - Development of algorithms that learn tenant behaviour and derive optimal control decision based on this information

### 3.3 State of the Art in the Process Industries

Integrated large production complexes in the chemical and in the petrochemical industry are major consumers of energy and raw materials in Europe and a major source of employment and income. They produce virtually all raw materials for convenience products in modern industrial society. The ecological and economic viability of the production depends crucially on the careful management of the ensemble of different units which in many cases are simultaneously producers and consumers of intermediates and carriers of energy (see Figure 31). These sites host a large number of autonomously operated production plants, nowadays often owned by different companies, with complex energy and material stream interconnections among them to ensure operational excellence and competitiveness of the production. The plants belong to competing value chains inside one company or to different owners. Complex networks of carriers of energy and of various chemicals are operated to make the best possible use of energy, materials and intermediates and by-products.

The flexibility of production is limited by many different constraints on individual units which must not be violated in order to prevent, e.g., accelerated equipment degradation or plant trips. Each unit operates most efficiently in terms of economics and energy and resource consumption under specific conditions which often are not compatible with the global state of the production system due to the interconnections and limited resources. The main goal of the site-wide management is to achieve an optimal global performance. The main degree of freedom to achieve this goal lies in ability to vary the production intensity in order to compensate for changing utilities availability and market prices. Essentially each plant operates autonomously, i.e. as an independent agent that tries to reach its production objectives as part of the value chain. Therefore this is an area with an enormous potential for the use of a systems of systems approach leading to better coordination and hence better economic and ecological performance.

The prototypical case study of an integrated chemical production site is a petro-chemical complex (Figure 31) that uses naphtha as a main feedstock. Naphtha is cracked into simpler chemical compounds which are then used to synthesize higher-value products in different subsequent production units. These plants which belong to different business units with their individual economic goals and contractual obligations are interconnected by the

networks of steam with different steam pressures, off-gas, electricity, water, compressed air, nitrogen, hydrogen, raw materials, intermediates, and products. The networks that connect the production units usually have only very small buffer capacities so that the mass and energy balances must be met on short horizons.

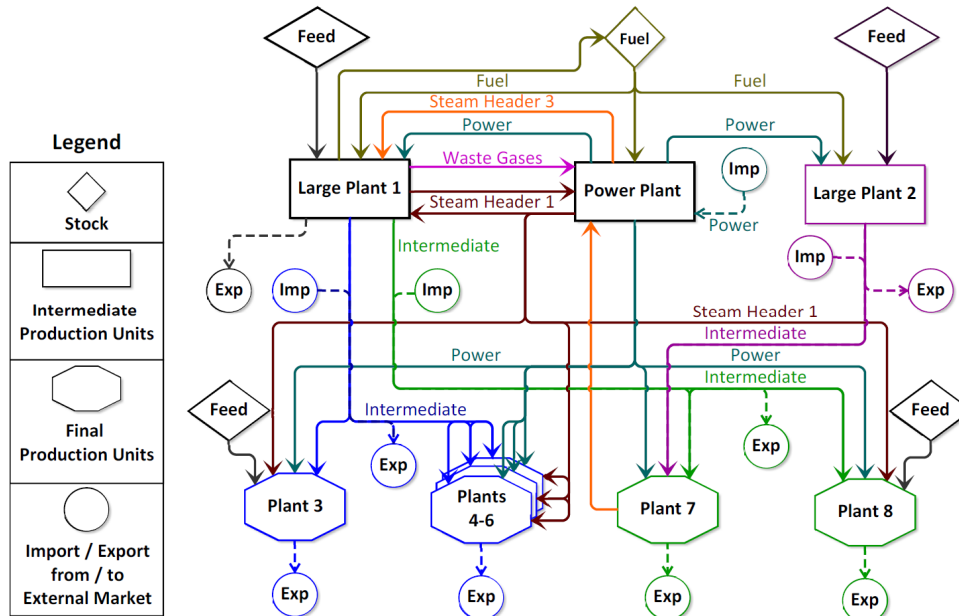


Figure 31. A schematic representation of an integrated chemical production complex.

Along the production chain, several by-products of little economic value are produced. A power plant is employed to burn those waste products that can be incinerated to produce some or most of the electrical power and steam needed by the production plants. Further complexity is added by production plants that feed different steam grades into the headers produced by auxiliary boilers (superheated steam) or by reactor cooling (often saturated steam). Thus, the management of the plants 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 auxiliary boilers on and off.

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 may cause severe restrictions to other units, and in particular the cracker products (intermediates) must be used on the site or fed into pipelines at the contractual rates to avoid severe economic losses. The individual units strive at optimizing their operation economically and ecologically for given production targets and the connections to the other units and to the steam network are constraints in this endeavour.

Characteristic features of integrated production sites are:

- Complex networks of energies and chemicals are operated to enable the proper 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 comprise little to no 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. Therefore, the degrees of freedom to optimize the operation of a complete value chain are limited. The primary

degree of freedom is the variation of the production intensity on a real-time frame in order to compensate for e.g. changing utility prices.

- A global optimum is hard to identify and can only be achieved by optimal coordination of individual production units.

### 3.3.1 Management in the Process Industries

The cyber-physical aspect of the industrial systems lies in tight integration of physical plant with computer-based management tools such as Enterprise Resource Planning (ERP), Manufacturing Execution System (MES), Supervision, Control & Data Acquisition (SCADA), Distributed Control System (DCS), Human-machine Interfaces (HMIs), Programmable Logic Controllers (PLCs) that constitute a hierarchical system, the so-called automation pyramid. These systems interact with the site on different levels and time scales and, thus, employ conceptually different viewpoints on the site and its parts. The models used by these systems differ in temporal granularity (some models are partially or completely steady state), degree of abstraction of the occurring phenomena (static models are commonly used for simplification of some higher-level tasks despite the dynamic nature of the modelled processes), and reliability as the model parameters might be uncertain or changing with the aging or replacement of equipment and dynamic reconfiguration of the site.

Generally, very simple models are employed for production planning (site-wide and unit-wide) and for prediction of the future plant and market behaviour. The industrial state of the art is the use of static planning tools and network balancing based on meetings between the different operating teams and the use of buffers in the system to smoothen short-term variations. Dynamic variations, such as unplanned shut-downs, forced production reductions, intermittent restrictions on the use of electrical power or steam, and fluctuations of raw material and utility prices, are only addressed on an ad-hoc basis. Rarely an automatic mechanism is installed on site which detects changes in operation conditions and coordinates and adapts production targets of all production plants in real time in order to respond to the disturbances listed above. Site-wide optimization is performed mostly by discussion processes between the managers of the production units. Similarly to the management of electrical grids, the governmental policies, regulations and incentives play a strong role for the decisions taken for site management and these can lead to behaviour which is counterproductive from an energy saving point of view.

The process industries have for many years pioneered the application of advanced control strategies. Model predictive control (MPC) penetrated as an industrial standard for control of large chemical plants (reactors, distillation units) mostly in petrochemical industry. This is due to the ability of MPC to effectively handle operation of multi-input multi-output constrained dynamic systems that represent a core of chemical production site. Industries report that the major success points of MPC lie in increased throughput, improvement of process stability, reduction of energy consumption, increased yield of more valuable products, reduction of quality giveaway, reduction of down times and better use of raw materials [8]. Despite its tremendous impact on the process industries, due to presented advantages, application of MPC faces challenges when applied to nonstationary (batch) processes and processes with distributed autonomy and decision making. The application to batch processes is limited due to unavailability of the appropriately detailed dynamic models which creation and maintenance comprise in many cases a tedious effort. The return horizon of such investment is rarely known which results in batch production to be standardly managed by human operators who apply (mostly) suboptimal recipe-driven operation and rely on experience.

The optimal management of the process industry site is a complex optimization problem that spans multiple time scales and layers of decision making. It starts, in the upper layer, with the planning of the production and supply chain optimization that allocate the levels of production to respond to the market conditions and to meet the contracts with the customers. This information is passed to the lower layer where production scheduling takes place and where RTO (real-time optimization) adjusts the set points for operation of the particular plants. MPC or

other standard control technique is then used for meeting the demand as set by scheduling and RTO by passing the control signals to the actuators (pumps, valves, boilers, etc.). The models, used along this hierarchy, vary largely in the depth of abstraction of the physical plants, the employed formalism (as they are used for different purposes) and nature (first principles models are preferred for modelling of physical plants but are difficult to employ for modelling at higher levels), time scales of execution, etc. For example, scheduling of the batch production exploits static models which do not involve any information about the uncertainties being present at the plant (status of equipment, quality of raw materials) or the experience and actions of the personnel. This affects the feasibility of the decisions taken at the upper level, as many effects of dynamics and uncertainties are not taken into account, and restricts a penetration of the automated solutions for fully-autonomous production planning and execution.

### 3.3.2 Recent Research Projects in the Domain of Process Industries

To complement the state-of-the-art analysis, an overview is given of the research projects addressing the domain-specific needs as described above.

**AUTOPROFIT** - This project aims at improving the operational efficiency of large-scale dynamic plants as found in petrochemical, chemical and other process industries. Costs related with industrial implementation of current model-based operation support systems, like Model Predictive Control, Real-Time Optimization and soft-sensors for these complex processes are currently very high. Moreover it is widely recognized that life-time performance of these systems is rather limited, particularly due to the fact that the underlying dynamic models need to be adapted/calibrated regularly, requiring expensive dedicated measurement campaigns. It is proposed to develop model-based operation support technology that enables control and model calibration at a considerable higher level of autonomy than currently possible. The technology enables autonomous maintenance by automated surveillance, continuously monitoring the process' and operation support system performance. If performance degradation is anticipated then proactive adaptation of the model-based operation support system is initiated. Industry is specifically involved to guide research in an industrially relevant direction and to ensure industrial validation of the technology to be developed.

**DYMASOS** - The project will develop new methods for the distributed management of large physically connected systems with distributed autonomous management and global coordination. The research will be driven by case studies in electrical grid management and control, including the charging of electric vehicles, and industrial production management. The properties of the distributed management and control techniques are investigated, and they are validated in large-scale simulations of case studies provided by industrial partners such as plant-wide optimal management of the petro-chemical complex. From the validation for the case studies, general conclusions will be drawn about the suitability of the proposed distributed management and control mechanisms for certain classes of systems of systems. This will provide guidelines for the design of evolving systems of systems with respect to the interplay of local autonomy and global management. The project will include the development of methods and tools for the engineering and implementation of advanced management solutions for systems of systems.

**LOCIMAP** - The LOCIMAP Project focuses on a closer integration of industrial parks in Europe, thereby increasing their efficiency and lowering their emissions. While the project will partly focus on the technological possibilities and requirements for the design of integrated plants, local communities form a significant part of the equation. Industrial parks and local communities are often highly interdependent, with the local community potentially benefiting from heat, power and employment opportunities, whereas the parks benefit from access to workforce, infrastructure and other resources, as well as a way to change previous waste and by-product streams into useful resources. Closer integration with the local community can further strengthen these synergies.

Given this close interaction, an important part of the project is to identify the most important socio-economic aspects involved in realizing closer integration of the parks; in other words, how closer integration of the parks can help meet the needs of the community, and overcome possible barriers. To this end, the project will conduct surveys and ask for input, as well as look at best practices. One of the end results of the project will be a white paper with recommendations to European producers and policy makers, to ensure that industrial parks and local communities complement each other.

**MORE** - The goal of MORE is to monitor resource efficiency during daily operations of large production plants and to influence the operational decisions such that the plant efficiency is optimized and the environmental footprint is constantly minimized. Towards reaching this goal, indicators will be defined that provide meaningful information about the resource efficiency over short periods of time like hours or days, and new analytical measurements to provide the necessary data will be screened and tested. Based on the new indicators, decision support for the operating staff will be developed to guide the decisions towards higher resource efficiency.

**PAPYRUS** - The first objective of the project is plant-wide application of asset management. It lifts the focus from single-component diagnostics to a plant-wide view of both asset performance and asset condition. Secondly, because diagnostics need to result in actions, diagnostic information (asset information) is used to generate control actions. Control refers to all levels of the automation pyramid, i.e. production control, plant maintenance, as well as field level control. A third and necessary objective is to achieve and maintain this in a modular and efficient way. A decision support system will also be developed that maps plant information, together with constraints and requirements, in order to generate and propose plant actions that satisfy production and other requirements.

### 3.3.3 Present and Future Challenges in the Domain of Process Industries

Industrial production encompasses complex dynamic nonlinear systems whose engineering and management are challenging given the integrated, tightly-coupled nature of the production sites, management on multiple time scales and with distributed authorities, and inherent uncertainty in the matching of the models with the reality and in the behaviour of human operators of the involved processes.

The uncertainty present in the form of inadequacy of the models, that are employed for advanced control purposes (e.g., for realization of model predictive control), plays an important role. The maintenance of these models is expensive and is rarely addressed to a sufficient extent. Many of the employed models are built for particular application (simulation, optimization, planning, etc.) based on specific assumptions and simplifications which restricts the reusability of these models for other purposes. Presently, when the information obtained from these models is passed to other management level, the information on its reliability, given the employed level of abstraction of the model, is not communicated which creates the propagation of uncertainty and false assumptions in the system. It is a present challenge to develop automatic modelling procedures that would construct high-fidelity models for various purposes from the basic design sheets (P&I diagrams) that represent the most detailed technical model of the instrumentation and connections at the plant.

Another significant source of uncertainty is present via human interaction with the system. The human operators take many real time decisions that influence the dynamic response of the site to the command signals received from upper layers. In order to decrease the risk of potential industrial accidents, people and the reliance on their decisions should be eliminated from the operation; this is particularly important for the night shifts. Moreover, the demographic and societal trends in Europe suggest that, in the future, the number of people working as operators of the chemical plants will decrease. For these reasons a certain level of the dehumanization of processes supervision must be established.

The dehumanization of the plant operation is, however, not applicable everywhere. Methodologies for reducing the effect of the uncertainties are required. On the one hand, a good practice is the exploitation of operator training simulators whose usage became well-established in the industry and which are needed to close the gap between the educational level of many control-room operators and the increased complexity of the processes and to establish operator-awareness of the plant behaviour. On the other hand, the models for building these simulators are often costly to develop and maintain or are not available which results in the simulators that do not cover the site with all its interactions and aspects. Prototypical solutions for optimization and handling the uncertainties are currently missing or are rarely in use due to the costly maintenance of such solutions.

Beside the uncertainties in human decisions or models inadequacies, the plants on the site can be driven into abnormal operating regimes by faults and disturbances causing a deterioration of the site performance and a decrease of the plants safety. Such situations occur as consequences of the malfunction of the components of some system but might happen also during the (un)planned shutdowns of some plants or during the start-up procedures and change of operating points of the major plants, i.e. those which produce intermediates or consume a substantial amount of raw materials. An early recognition (in the case of unplanned events) and thorough diagnosis could lead to a better coping with these situations without requiring a deterioration of the site performance. Handling of these situations is however usually based on the experience of the management personnel and negotiation between plant operators in real-time. In more severe cases, a set of rules would be and followed which might, for example, define the order in which the plants are shut down on the site such that the safety is guaranteed. Although it is well known that these procedures are rather slow and conservative, an automatic solutions that would result in optimal response to the faults are rarely implemented because of the complexity of these problems and missing solutions that would turn the past experiences gained during the abnormal events into a model-based decision-support platform.

An increased focus on energy management will arise in the future. A more energy efficient process design is often more integrated and as such intrinsically harder to control. The major challenge for an existing chemical site is the optimal medium and long term planning, especially if the production, as for example in chemical parks, cannot be influenced directly and the profit and losses are not shared. Increased productivity requires tighter integration between the automation layers (ERP, MES, APC, etc.) which is only partly a technical problem, and to a very large degree also a cultural/organizational challenge. Today these automation levels are typically handled by different departments often in different geographical locations using different software tools with limited or no interaction. A challenge lies in creating an efficient integration of supply chain management, scheduling, and control systems together with asset management and condition monitoring by establishing a proper flow and sharing of information and a coordination (e.g. via automatic negotiation) of the decisions taken in the these management systems.

The problems of production planning result in moving horizon scheduling problems of large size without the guarantee that the solution will be feasible and applied. Firstly, the technical implementation of the calculation might not be sufficient to handle the problem adequately (i.e., simplifications would need to be applied). The physical implementation of the results in the real world might be cumbersome as well considering that the solution does not take into account many human decisions in the process management. In this respect the implied uncertainty in these decisions should be taken into account which might even further prohibit the effective resolution of the planning problems.

Significant challenges for the technical implementation of the optimal production allocation lie in the employed models and communication. Even when the models are available and the appropriate communication channels are established, there exists a mixture today of different open and proprietary protocols whose configuration often takes more time than the implementation of the optimiser. If models could be easily and simply created for existing and new plants and communication between the different layers of plant operation was standardised,

easy and safe, adding advanced solutions to existing plant management would be relatively easy. New platforms have to be developed that allow the interchange of the information available to different engineering teams providing appropriate representation of the information and information security.

If such global solutions existed, it would still be a challenge to implement the results in the plants on a site. Within one company this is already difficult, on an industrial park with many companies this is close to impossible. One possible way to cover both situations is to influence the price of utilities and create internal exchanges that define the prices according to availability and demand. In this respect, market-based mechanism can be employed and automatic coordination of the site can be established by exploiting suitable algorithms that would apply principles of negotiation and price-adjustment in order to steer the site towards the global optimum.

In the future we will see tighter integration of the production and electrical systems including connection to the power grid. This is a challenge since most engineers are expert in one of the areas of process and electrical engineering, but few master both. There will also be an increased need to integrate the different levels in the automation hierarchy making, for example, modelling a more difficult task. Automation of automation, i.e. to automatically generate more and more of the control solution and simulation models directly from a CAD description of the system like P&I diagrams, will become a challenge in industrial systems.

Based on the preceding analysis, the specific challenges in the domain of process industries include:

- Engineering
  - Integration of supply chain management, scheduling, and control
  - Standardization of interfaces on the higher automation layers
  - Integrity, security and trust
  - Cyber-security and information security
  - Plug-n-play solutions for harmonization of the communication among the different layers of decision making processes
  - Standardization of the solutions for their re-use
- Management
  - Dynamic reconfiguration
  - Industrial demand response
  - Autonomous abnormal event (fault, disturbance) recognition, diagnosis, and compensation
  - Automatic validation of new observations with data and comparison to historical models
  - Coordination of the large-scale plants with distributed decision making
  - Dehumanization of the decision making
  - Decision support systems for human operators supporting impact-awareness
- Modelling
  - Modelling the human interaction with the system
  - Reduction of the modelling effort , generic and automated model building
  - Creation of a modelling framework for control which combines data-based models and first-principles models
  - Re-use of the single-purpose models for different purposes
- Simulation
  - Simulation and co-simulation of large-scale systems
  - Scenario-based simulation



- Reliable system simulation considering different abstraction depths of the models at each level
- Optimization
  - Decentralized optimization
  - Large-scale mixed-integer optimization
  - Optimization under uncertainty

## 3.4 Commonalities and Overarching Research and Innovation Issues

### 3.4.1 Identified Commonalities and Challenges

This section has considered the power grid, smart buildings and process industries sectors. We identified the challenges, technological bottlenecks and relevant future research topics. The main challenges involve modelling and model management, humans in the loop, handling of information in systems and systems integration.

The challenges in modelling include the high cost for building and maintaining models and the difficulty of model re-use, modelling, simulation and analysis of stochastic behaviour, coupling tools of different strengths without the need for re-modelling, the consistency of detailed and abstract models, and the effort needed for setting up models that include failure states and the reaction to these for validation and verification purposes. The interactions between different automation layers (e.g. error handling and global task scheduling) are currently handled in systems design only by heuristic reasoning.

Analysis of the behaviour of humans in the loop stresses the need of the identification of the capabilities of humans and machines in real-time monitoring and decision making and suggests a challenge of optimal cooperation between human and machine decisions. Acceptance of advanced solutions by human users or operators is often a problem. If systems are sold in large numbers, like cars, a high development effort can be invested to make them completely automatic and/or robust against wrong behaviours of the human users and operators. This is not possible in domains where solutions are one of a kind and human intervention is needed to react to unforeseen situations and faults and to monitor the behaviour of the overall system. Humans may introduce an additional nonlinearity and uncertainty in the system and future research on the monitoring of the actions of the users and anticipating their behaviours might be a promising direction of progress.

Issues identified in handling the information are concerned with availability and processing of the increasing amount of data which is available as more sensors are placed in the systems that can communicate and share the information among different parts of the system of systems. Hand in hand with presence of the information comes a responsibility for making the information available to the relevant systems and protect the data flow to the systems which might be, for example, vulnerable to cyber-attacks. Data security is of a concern for engineers of systems of systems especially when it comes to data from which behaviour of human users of the systems (e.g. smart houses) could be identified by some third parties.

The increased integration of the systems has been also identified as a present challenge. The main concern lies in physical interconnection of the systems that are govern by different authorities. It is clearly pointed out by the representatives of the industry that such decentralized decision-making system must be coordinated but there exist very few automated solutions for doing so.

### 3.4.2 Issues Identified

A public workshop „Engineering and Management of Cyber-physical Systems of Systems“ was organized by the CPSoS project in order to discuss the findings of the above presented state of the art analysis of physically connected systems of systems. A report from this workshop is publicly available on [CPSoS website](#). The workshop was attended by 39 participants who represented a broad spectrum of domain experts, researchers, developers and industrial practitioners from the domains of electrical power grids, smart buildings and process industries. The findings, of the state of the art analysis were presented as an input for the discussions.

A set of research challenges was identified in the discussions that strongly supports and elaborates on the findings presented above. More concretely a list of issues was discussed for the domains of electric power grids and smart buildings:

- Modelling and simulation:
  - Modelling the power system jointly with the communication system
  - Modelling and simulation of distributed generation
  - Reliable simulation (What depth should be simulated at which level?)
  - Simulation of large-scale systems
  - Generic and automated building of dynamic models
- Information systems and systems integration:
  - Data availability and new business models
  - System integration of active distribution
  - Better use of measurements (estimation)
  - Distributed (decentralized) controls at substation level (MPC, setting less protection, ...)
  - Remote control of substations
  - Demand side management via virtual power plants (subsidies to big consumers; how to do it optimally?)
  - Negotiation between market and technical system for the feasibility when planning
  - Massive integration of inverter-based components (synchronization issue, lack of “inertia”, ...); Cultural change of frequency management due to renewables
  - Multi-stage decision making under uncertainty (decisions changing the structure of the system, policies or control/protection schemes, the operating points of the system)
  - Requirement for the associated ICT systems (latency, reliability, communication delays)
  - Cyber-security (privacy)
  - Revision of the communication protocols
- Other topics:
  - Spatial complexity (from Pan European power grid to active distribution grids)
  - Temporal complexity (from decades to milliseconds)
  - Stochastic complexity (from failures, weather conditions to grid users’ behaviours)
  - Aging of grid assets
  - Taking advantage of high performance computing
  - Mixed integer non-linear programming, “Convexification” of ACOPF (scalable implementation for large SDP)
  - Robust optimization (bi-level programs and semi-infinite programs, chance constraint programming)
  - System stability (“Lyapunov like” approach, sum of squares, flatness, ...)
  - Dynamic reconfiguration and re-engineering while performing a migration from the existing grid to the optimal one
  - Synchronization without using GPS
  - DC transmission and distribution

A list of issues discussed for the domains of process industries included:

- Modelling:
  - How to go quickly from P&ID to high-fidelity simulation of a process? Need to simulate different possible equipment (e.g. pumps) and automation systems (different vendors)
  - How to handle incomplete information in simulation?
  - Exchange of information between models on different levels
  - Doubts on application of co-simulation for large-scale systems
  - Modelling with incomplete or generic information
  - Model building and maintenance is time-consuming; very detailed models needed for control purposes; very hard task for batch plants (hybrid data-based + first-principles models did not penetrate to industry)
  - Information on models -> Limits-aware models
- Full Automation and modelling of human behavior:
  - People and their interaction with the system is the biggest challenge
  - Model the human behavior and decision process; planning is very hard otherwise
  - Building near-autonomous system management because of the demographic changes in Europe
  - People should be taken out of the real-time operation; need to build trust in system and software
  - Decision-support systems (e.g. to support people who decide on the maintenance of equipment)
- Information systems and systems integration:
  - Big data handling at different levels (SAP(ERP)/MES/APC)
  - Plug-n-play solutions to harmonize the communication across SAP(ERP)/MES/APC, data synchronization
  - Each layer (planning, scheduling, control) uses different model; how to link and integrate these?
  - Integration of different software tools used at different departments (engineering vs. automation and control)
  - Information security – where does the information go (model the flow of information); cyber attacks
  - Integrity, security and trust
- Other topics:
  - Degree of reliability of academic solutions is unknown
  - Need for “non PhD” tools
  - How to control the modules in modular plants; there should be a joint effort of vendors of control systems to develop plug-n-play solutions for those plants
  - Integrity, security and trust (Lack of understanding in commercial structures, making people aware of benefits, economic benefits for coordinated work in industrial parks)
  - Lack and inconsistency of models on higher hierarchical levels, e.g. on the supply chain and production planning layer (possible to build up high level models from lower level models? model simplifications?)
  - Standardization (using developed models for several needs)
  - Feasibility of set-points provided by high level models is unclear for lower levels
  - Supply chain and production should be modelled and optimized simultaneously
  - Industrial demand response
  - Unmanned operation / remote operations / maintenance
  - „Data mining“, using historical data for process monitoring, e.g. Baseline calculation from historical data, debottlenecking

- Integration of supply chain, production scheduling, demand planning, and control
- Standardization of model interfaces

### 3.4.3 Research Priorities

The identified challenges within the domain of physically connected systems of systems were prioritised into short term (<4 years), medium (from 4 to 8 years) and long term (>8 years) issues according to the expectations of the participants of the public workshop „Engineering and Management of Cyber-physical Systems of Systems“ about the availability and deployment of the solutions to the challenges.

#### Short term:

Smart grids and smart buildings:

- System integration of active distribution
- Massive integration of inverter-based components
- System stability
- Data availability and new business models

Process industries:

- Modelling, optimization and simulation tools
- Standardization of interfaces on the higher automation layers
- Integrity, security and trust
- Industrial demand response

#### Medium term:

Smart grids and smart buildings:

- Requirement for the associated ICT systems
- Better use of measurements (estimation)

Process industries:

- Dynamic reconfiguration
- Validation and verification of the proper functioning of systems
- Handling of disturbances, faults and abnormal situations

#### Long term:

Smart grids and smart buildings:

- Cyber-security (privacy)
- Distributed (decentralized) controls at substation level

Process industries:

- Integration of supply chain management, scheduling, and control
- Reduction of the modelling effort

A recommendation of this part of the document is to address the presented research topics in a European research agenda for development in physically connected systems of systems in order to increase sustainability of the resources and to secure employment opportunities in Europe in future.

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## 4 Methods and Tools for the Engineering and Management of Cyber-physical Systems of Systems

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In this section the state-of-the-art is described with respect to the methods (and tools) that are currently used for cyber-physical systems of systems. Cyber-physical Systems of Systems are cyber-physical systems which exhibit the features of systems of systems:

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

This definition has been taken from the working paper [1] that was used as an input document for CPSoS Working Groups Kick off Meeting which took place in Düsseldorf/Germany on January 31st, 2014 [2].

### 4.1 Engineering of CPSoS

The engineering of cyber-physical systems of systems is a challenging activity as it has to deal with changing requirements (both functional and performance requirements may change over time), changing available constituent systems. On top of that the cyber-physical system of systems is large and complex.

In T-AREA-SoS [3] a number of aspects have been put forward that complicate the engineering of systems of systems. These aspects are also present in cyber-physical systems of systems.

- Representation of constituent systems is not easy as these vary over time as well
- Gain of participation in system of systems is unclear from a constituent systems perspective
- Risks of unintended behavior
- Reluctance (by stakeholders) to make changes to constituent systems that are needed from a system of systems point of view

A large number of methods and tools have been proposed for the engineering of cyber-physical systems. Below we mention some examples that are used in industrial practice. It is impossible to deliver a complete list.

- Simulink ([www.mathworks.nl/products/simulink](http://www.mathworks.nl/products/simulink)) is a block diagram environment for multi-domain simulation and Model-Based Design. It supports simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with MATLAB, enabling you to incorporate MATLAB algorithms into models and export simulation results to MATLAB for further analysis. MATLAB/Simulink is the most widely used platform for computing in industrial applications.

- Stateflow ([www.mathworks.nl/products/stateflow](http://www.mathworks.nl/products/stateflow)) is an environment for modeling and simulating combinatorial and sequential decision logic based on state machines and flow charts. Stateflow allows one to model how a system reacts to events, time-based conditions, and external input signals. With Stateflow you can design logic for supervisory control, task scheduling, and fault management applications. Stateflow offers state diagram animation, state activity logging, data logging, and integrated debugging for analyzing the design and detecting run-time errors, static and run-time checks for transition conflicts, cyclic problems, state inconsistencies, data-range violations, and overflow conditions.
- Modelica [4] is a relatively new language for hierarchical object oriented physical modelling. The language has been designed to generate efficient simulation code automatically. The language supports exchange of models and the use of model libraries.
  - Dymola ([www.3ds.com](http://www.3ds.com)) is a Modelica simulator that is used for modelling and simulation of integrated and complex systems for use within automotive, aerospace, robotics, and other application areas. Dymola supports multi-engineering solutions for modelling and simulation. The Dymola environment uses the Open-Modelica modeling language which means that the users are free to create their own model libraries or modify existing model libraries to better match the users' needs.
- SysML ([www.sysml.org](http://www.sysml.org)) [5] is a standardized general purpose graphical modeling language for capturing complex system descriptions in terms of structure, behavior, properties and requirements. SysML offers systems engineers several noteworthy improvements over UML, which tends to be software-centric. SysML reduces UML's software-centric restrictions and adds two new diagram types, requirement and parametric diagrams for requirements engineering and for performance analysis and quantitative analysis. SysML is able to model a wide range of systems, which may include hardware, software, information, processes, personnel, and facilities. SysML furnishes flexible allocation tables that support requirements allocation, functional allocation, and structural allocation. This capability facilitates automated verification and validation and gap analysis. SysML model management constructs support models, views, and viewpoints. These constructs extend UML's capabilities and are architecturally aligned with IEEE-Std-1471-2000 (IEEE Recommended Practice for Architectural Description of Software Intensive Systems). SysML is gaining acceptance in industry.
- MARTE (Modeling and Analysis of Real-Time and Embedded Systems, [6], <http://www.omgmarTE.org>) provides support for specification, design and verification/validation stages. The formalism is supported by the OMG group, that also maintains the Unified Modelling Language UML (which is one of the leading software development languages), and many industrial and academic institutions.
- SCADE (<http://www.esterel-technologies.com/products/scade-suite/>) is a model-based development environment dedicated to critical embedded software. With native integration of the SCADE language and its formal notation, SCADE Suite is an integrated design environment for critical applications spanning model-based design, simulation, verification, qualifiable/certified code generation, and interoperability with other development tools and platforms, including requirements traceability.
- Microsoft Excel is the de facto standard for the purpose of data management. For different domains more dedicated solutions are available such as Osisoft PI (<http://www.osisoft.com>) and AspenTech IP21 (<http://www.aspentech.com>). Such tools provide data exchange interfaces to which external tools can connect.

Other tools that have been mentioned several times by industrial contacts include SAP, FEM tools such as Comsol, and very specific simulation tools for physics (e.g. AMESIM, KULI), and for modelling of software control Rhapsody, Rational Rose RT, and SysML. It is noteworthy that in many (larger) companies tools are used that are developed by the company itself. These are also used typically for a very specific purpose and therefore are mostly restricted to a single or a small number of aspects.

These tools are offering very useful and important functionality to support the engineering process. However they are mainly restricted to conveniently model a small number of the relevant aspects. These tools provide functionality for design-time activities and seem to lack proper functionality for managing and engineering the run-time engineering aspects associated with reconfiguration and evolution. Also, keeping in mind that cyber-physical systems of systems are mostly modelled in a rich palette of different modelling formalisms (even for the same aspects), these tools currently cannot deal with this heterogeneity.

### 4.1.1 Modelling and Simulation

To enable assessment of system-wide performance properties of a cyber-physical system of systems it is needed to represent all relevant (contributing) systems in a system-wide model. This is not always possible. There may be different reasons for the lack of appropriate models:

- The efforts needed for obtaining a detailed model are not in line with the anticipated gain of having these models. This may result in models that only approximate the behavior of the system coarsely. In industry the use of informal models such as sketches of the system on a piece of paper is commonplace.
- Different (legal) entities are involved that may not desire or are not allowed to provide an accurate model of the system.
- Scientific knowledge has not reached the level of understanding in order to explain the causalities that result in the behavior anticipated as emergent. As an example of these we may consider the human as a system in a system of systems.

From the working paper “Cyber-physical Systems of Systems – Definition and core research and development areas” [1] the characteristic of large-scale systems with complex dynamics is explained as follows: Cyber-Physical Systems of Systems consists of a *significant* number of *interacting* components that are (partially) physically coupled and together fulfill a certain function, provide a service, or generate products. The components can provide services independently but the performance of the overall system depends on the “orchestration” of the components. Complex dynamics refers to systems having continuous-time behaviour that is described by means of systems of differential equations that are hard to solve or approximate algorithmically. Such examples arise among others in the domain of chemical batch processes. Complex dynamics also arise in systems having many different modes of continuous behaviour with complex switching between these, and in large-scale systems where the geographic (or functional) distribution requires communication mechanisms that introduce information loss and time delays.

In order to assess the functional and performance properties of a cyber-physical system of systems model-based methods are used that allow one to model and simulate the complex dynamics on a system-wide level. For model-based analysis it is needed to have models that are capable of expressing complex dynamics. There are several approaches towards the description of such complex dynamics. With respect to the continuous dynamics of such systems these are dominated by methods that use differential and difference equations. It is well recognized that in cyber-physical systems (of systems) besides dynamics also the switching between different



dynamics needs to be considered. This has resulted in many academic formalisms with well-established semantics such as hybrid automata [7], hybrid Petri Nets [8], and other hybrid process theories [9] [10].

Simulation of cyber-physical systems of systems suffers from computational challenges such as the numerical integration of very complex continuous behavior, execution of discrete model parts, and re-initialization of continuous quantities after discrete events [11] [12] [13]. Commercial tools such as Dymola (<http://www.3ds.com>) and gPROMS (<http://www.psenterprise.com/gproms.html>) are available and used in industry for simulation of dynamic behavior.

Modelling and simulation of large-scale systems with complex dynamics is theoretically possible. However, severe practical limitations are the complexity of the construction of the models, computational efficiency, and the heterogeneity of these models in different dimensions. Construction of the large number of involved models is time-consuming and needs deep domain knowledge (from very different areas). Models that are encountered in a cyber-physical system of systems are different in modelling paradigm that is used (continuous-time, discrete event, stochastic, computation, ...) as well as in formalisms that are used for expressing models within a certain paradigm (e.g. automata-based descriptions versus process algebraic specification languages).

In a presentation for the Modelica Conference, 2011, Peter Schwarz has provided a list of items that are needed in order to be able to efficiently simulate a heterogeneous system. In a condensed form these are

- Model interfaces for model exchange between different simulation environment based on the same modeling language. The FMI is a well-recognized example of this.
- Co-simulation for coupling simulators of different modeling languages and for embedding special simulation algorithms.
- Co-existence of different modelling languages such as Modelica, VHDL-AMS, Verilog-AMS, MATLAB/Simulink/Stateflow, SystemC-AMS.

There is a large variety of modeling formalisms and simulation tools around, which are often designed specifically for particular domains [14] [15] [12] [13] [16] [17] [18]. Besides these formalisms, in industry also domain-specific languages are used for modelling specific aspects of the behavior of systems in a formalism that is conceptually aligned with the domain.

Following [18], aggregate models can be obtained either via automated model transformation or via co-simulation. Automated model transformation requires a semantics-preserving mapping between different formalisms which can be executed by means of an algorithm. Such transformations may then be used to map models to the same modelling language. Limitations of the applicability of this approach on cyber-physical systems of systems are the very different uses of time in the modeling formalisms, and the very rich palette of modeling constructions offered by the modelling languages such as Modelica [19], gPROMS [20] and EcosimPro [21] encompassing object-orientation, hierarchical modeling, and complex dynamics (Integral/Partial Differential Algebraic Equations), and algorithmically specified computations. A number of languages have been developed that aim to provide a common model exchange format:

- DEVS (Discrete Event System Specification) [22] is an exchange format for discrete event models
- SysML [23] is a customization of UML for systems engineering applications with hierarchical high level models
- UML extensions [24] with hybrid model representations
- ModelCVS [25] enables ontology-based tool integration

- Modelica [26] [27] for exchange of equation-based models
- CIF (Compositional Interchange Format) [28] for hybrid systems modeling with complex continuous DEA dynamics, hierarchy and modularization

Industrial use of such model exchange formats for the purpose of simulation of aggregate models is rather limited though in several industries, such as those developing high-tech systems, interest in and use of model transformations is growing and facilitated by management to a larger extent.

In many cases [18] model transformation is not an option. In these cases co-simulation may be applied. Co-simulation is the synchronized simulation of different models in their original formalisms and with their own simulation tools. Since each of the contributing realms to cyber-physical systems of systems design has its own specialized and mature simulation tools, it seems appropriate to combine domain-specific tools into one that utilizes the best features of individual simulators.

There are many academic and commercial co-simulation frameworks. Examples of academic co-simulation frameworks are the Simantics Open Simulation Platform, TrueTime, CHEOPS, and SIMCAN. These lack industrial relevance and/or are focused on a very specific domain. The Crescendo tool combines 20-sim for continuous-time modelling and uses the VDM notation for discrete-event modelling [10] [11]. Also the commercial frameworks dSpace SystemDesk, qTronic Silver, SKF, CAPE-OPEN, OPC and TISC are targeted for specific domains. The following are a number of co-simulation frameworks that are both industrially relevant and general purpose. These frameworks are more used because they built on tools that are already common-place in industry or because they are supported by relevant standardization bodies.

- FMI (Functional Mockup Interface) is developed in the EU project MODELISAR and provides an open tool-independent standard for co-simulation of hybrid dynamic models [36] [37]. The FMI only supports continuous dynamics in ODE form. Well-established tools such as Dymola and OpenModelica [38] support FMI.
- Simulink is a tool for the modeling and simulation of nonlinear dynamic systems [39]. Discrete event models can be integrated using Stateflow and SimEvents and acausal components can be added using the SimScape toolbox. Simulink uses the s-function interface that must be implemented by external software components to be integrated into Simulink models.
- HLA (High Level Architecture) [40] is an IEEE standard for distributed simulation. HLA establishes a framework in which simulation components interact via services from the Runtime Infrastructure (RTI).

Co-simulation platforms for simulation of physical systems and communication systems, which adapt already existent tools, can be classified as follows [29]:

- Extending physical systems simulators to also simulate the events and dynamics of communication networks. Examples are the original TrueTime [30] version that is based on Simulink, the more recent Modelica-based versions of TrueTime [31] and VisualSense [32]. These tools lack support for routing, transport, and application protocols.
- Extending a network simulator to support physical systems simulations. An example is Agent/Plant [33]. Physical dynamics and control algorithms are modeled explicitly by differential–algebraic equations (DAEs) that are to be solved within the simulation script or via a call to an outside utility such as Matlab.

- Marrying a full-blown network simulator with a full-blown physical systems simulator. Examples include the ADEVS/ns-2 integrated tool [34], the Simulink/ns-2 combined tool [35], and the Modelica/ns-2 integrated tool [29].

One important aspect in the use of co-simulation are the different time scales in which the different models operate. In chemical processing the time delays introduced by a communication network can much easier be neglected or abstracted from than in applications in mechatronic systems where the time scales of the physical processes and the communication systems are much more aligned. In these applications the influence of abstractions on the time delays introduced by the communication system cannot be neglected that easily.

Limitations of co-simulation are the poor performance (efficiency of the resulting simulation) of the co-simulation frameworks and the efforts needed for connecting the simulation tools appropriately.

It is expected that ongoing research will generate improved methods and tools for simulation of cyber-physical systems of systems, but given the current state of the art it may not be expected that these are applicable immediately to the heterogeneous large-scale systems, involving also computational and communication elements that fall within the scope of cyber-physical systems of systems. Given this observation, the need arises for abstraction and approximation methods that only consider the details of the system that are of relevance to the analysis questions at hand.

#### 4.1.2 Model and Tool Integration

The systematic consideration of interactions between management and control layers in the design and validation of cyber-physical systems of systems requires a methodology for the management of models and requirements which enables engineers

- to identify and capture interdependencies between the elements on different automation layers and of different constituent systems
- to trace dependencies between requirements, models, control code, simulation results, etc.,
- to deal with changes of these artefacts during the lifetime.

Existing approaches for models and requirements management from the field of model-based design in software engineering focus on models and requirements for software, often in the sense that the models are a representation of the requirements which are then refined during the design [41]. Models of physical processes and systems usually are not considered in this domain. If they are, management most often only refers to version control, translation using exchange formats, tool integration, and similar activities [42] [25].

CyPhy [43] is a model integration language which integrates models from different domains in a semantically sound manner that enables reasoning for correctness of models. The language is supported by the META design flow and a tool suite. The goals of the CyPhy tool suite development effort were to

- support design flow through levels of abstraction with early, incremental, and continuous analysis of designs and design spaces that enable system designers to efficiently navigate the design trade-space,
- provide system and subsystem verification at different levels of abstraction including probabilistic analysis, and

- enable semantic integration, through the lifecycle, of compositional design tools and design verification tools, and the generation of detailed manufacturing directives spanning machine instructions, human work instructions, and logistics flow. This semantic integration ensures a seamless and coherent design flow.

CyPhy has been under evaluation since January 2013 through multiple design exercises in which teams worked to design drivetrain, suspension, propulsion, chassis, and structural elements and associated subsystems for an amphibious infantry fighting vehicle. Insights from such efforts are being used to improve language, methodology and tools. Currently these efforts are still to find their way to industrial application.

Derived from computer science and engineering, meta-modelling is the activity that describes the permitted structure to which models must adhere [44]. It entails the analysis, construction and development of the frames, rules, constraints, models and theories applicable and useful for modelling a predefined class of problems. As such meta-modelling may be used to capture the specific structures of an application domain. The availability of a meta-model may be used beneficially for construction of model editors (textual and graphical), parsers, and in cases where semantics are attached to the models to obtain simulation and verification tools. Meta-models may be used to capture relevant levels of abstraction for defining model transformations (for example a code generator). In industry meta-modelling (in combination with the Eclipse framework ([www.eclipse.org](http://www.eclipse.org))) is used for developing and maintaining domain-specific languages.

According to a recent state of the art in meta-modelling [45] research is needed as to what methods are appropriate and intuitive in attaching semantic information to meta-models. The expected benefits of semantic attachments are among others documentation, verification benefits, and automatic translations between tools. In [46] meta-modelling is used to relate models from different domains which is beneficial in capturing the correspondence in model elements of the different views. The authors claim that ensuring consistent relationships between various system models is an important part of an integrated design methodology. An architectural approach to reasoning about relations between heterogeneous system models is provided.

In industrial practice the most used model-management systems are version control systems such as SVN. These systems do not offer functionalities, such as consistency checking of models. Consistency of models is an issue, that is very much recognized by industry, for which support is needed in terms of more advanced model-management systems. An example of such a model-management system is the Design Framework (<http://df.esi.nl>) that links all design activities to concrete design artefacts and to track consistency of these artefacts in a multi-disciplinary environment. The Design Framework is a prototype and has not reached sufficient industrial adoption. These model-management systems fall short of charting semantic relations between modelling artefacts. For meaningful analysis of the models the semantic relationships of the concepts that are exchanged over interfaces must be made unambiguously clear.

The tool Artshop [47] [48] provides a framework for managing artefact dependencies. The analyses cover consistency and conformity checking of related artefacts while management operations include traceability, variant management and auditing of persisted models. Each artefact and its containing elements can be annotated with arbitrary meta-information, such as the results of test cases, comments, simulation parameters or other information. Other

Tool integration can be divided into either conceptual or mechanical [49]. Research efforts at the mechanical level of tool integration has resulted in standardization of middleware efforts that suffer from high maintenance overheads and poor scalability [25].

ModelCVS [25] is a system which enables tool integration through transparent transformation of models between different tools' modelling languages based on their meta-models. ModelCVS provides versioning capabilities. The integration of tools is based on ontologies to express the semantics of modeling languages. In order to specify the bridging between two meta-models ModelCVS offers the following functionalities:

- Meta-model lifting: creation of an ontology, which entails a mapping of elements in the meta-model to concepts in the ontology.
- Ontology-level integration: based on relations between concepts in an ontology relations between concept in the meta-models may be deduced.
- Derivation of bridging: provide operators that express the desired integration behavior on the meta-model level. The bridging operator may be used express semantic correspondence and translation.
- Derivation of transformation: bridging is used to obtain transformation code.

The authors report that integration of ontologies which are very heterogeneous is challenging. Thus far, application of ModelCVS to the engineering of CPSoS is largely missing.

### 4.1.3 Requirements Engineering

Requirements engineering of cyber-physical systems of systems is faced with the following challenges [50]:

- New requirements engineering processes, management methods, techniques and tools that can dynamically respond to continually changing requirements are needed. Emphasis will need to be placed on handling competing stakeholder demands, dynamic evolution and impact of emergent behaviors on the stability of requirements
- Effective requirements engineering methods, tools and techniques for managing emergent effects with predictable results are required.

As a step in this direction [51] proposes a content model that facilitates collaboration between stakeholders. Reported benefits of the approach are consistency and eased communication between stakeholders. In [52] it is concluded that the approaches towards security requirements engineering lack explicit support for managing the effects of software evolution.

In [53] factors in systems of systems that complicate requirements engineering are reported to be (i) scale, in terms of number of constituent systems, number of interactions, number of stakeholders, (ii) multi-domain, (iii) varied operational context, (iv) decentralized control, (v) rapidly evolving environments (vi) multiple life-cycle phases. In the paper a requirements engineering approach for systems of systems is proposed that consists of identifying the system of systems context, identification of system-wide and constituent system goals, understanding interactions, identifying individual system capabilities and constraints, and analyzing the gap between capabilities offered and capabilities required for system-wide goals. Concrete examples of the application the approach and mentioning of tool support are missing.

To make good use of requirements in the engineering process it is important that requirements are explicitly formulated and that they ways in which they are realized in the designs are tractable. Currently, most requirements are formulated informally using a text document or graphical representations. These requirements are mostly used for documentation and not so much for an analysis of the system.

#### 4.1.4 Analysis and Verification

It is well known that verification of (discrete) systems is computationally tractable unless the involved (models of) systems become too large. Progress is made in the development of methods, algorithms and tools for the verification of both discrete event and continuous-time systems [54]. In [55] the authors report a new method (continuization) for computing accurate over-approximations of reachable sets of states for hybrid systems which may have a large number of discrete switching.

UPPAAL (<http://www.uppaal.com>) is an integrated tool environment for modelling, validation and verification of real-time systems modelled as networks of times automata. It has been applied in (safety-critical) industrial applications (see <http://www.uppaal.com> for a list of applications). The tool is commercially available. Extensions are available for schedulability analysis, synthesis of schedules and executable code, and black-box conformance testing among others. UPPAAL is currently the most used verification tool for timed discrete event systems.

The SpaceEx tool platform (<http://spaceex.imag.fr>) implements a number of algorithms for reachability and safety verification for continuous and hybrid systems. Currently, development and application of SpaceEx are mostly of academic nature. Potential scalability has been demonstrated on a helicopter controller (more with more than 100 variables) [56].

The tool KeYmaera [57] is a formal verification tool for cyber-physical systems. It has seen many real-world applications, e.g. verifying non-collision in the European Train Control System. KeYmaera's capability comes from Platzer's differential dynamic logic [58]. Differential dynamic logic generalizes very elegantly to dynamic logics of multi-dynamical systems. Multi-dynamical systems, which are systems that combine multiple dynamical aspects such as discrete, continuous, stochastic, nondeterministic, or adversarial dynamics, generalize hybrid systems and provide the dynamical features of cyber-physical systems that hybrid systems are missing.

ASD is a component-based modelling formalism for automation design in which for each component model also interface models must be specified for verification purposes. In order to guarantee correctness, each of the components in a complex system is verified with respect to the described specification on its interface models. The strength in the ASD:Suite resides in the capability to compare the actual behavior of the design models with respect to the expected behavior that is defined in their interface models. Upon successful verification of an ASD specification code can be generated. Applicability of ASD:Suite is restricted to software models.

Although promising techniques are developed for the verification of multi-dynamical systems as well as for probabilistic and stochastic models, currently the size of the systems to which verification by means of model checking can be applied successfully is still very limited and not adequate for application on heterogeneous large-scale systems. This reflects in the very limited use of verification technology in industry.

In the context of design of embedded systems contract-based design [59] has been coined as a technique that addresses some of the concerns in the design of cyber-physical systems of systems. In this sense a contract represents both the assumptions on the environment and the guarantees of the system under these assumptions. The use of contracts supports open system development as contracts abstract from details from the possibly unknown aspects of the environment and focus on the properties that the context is supposed to deliver. Contracts are useful in managing requirements and in fusing viewpoints. Finally, contracts, at least in principle, enable the use of contract composition and successive refinement steps in a design process. Assume/Guarantee contracts were developed in the SPEEDS project [60] and the CESAR project [61]. They have been extended to real-time and stochastic settings in [62] and [63], respectively.

### 4.1.5 Emergent Behaviour

There is much debate on the use and abuse of the term emergent behaviour [64]. The point of view adopted in the CPSoS project is that the emerging behavior is to be restricted to the occurrence of patterns, oscillations or instabilities on a systems level and the formation of structures of interaction in a way that had not been anticipated in the construction of the subsystems and in the design of their interactions.

In the context of the AMADEOS project [65], in [64] work is done on emergent phenomena in a system-of-systems. Reasons for the occurrence of such phenomena are presented. It is shown how emergence manifests itself in an SoS and elaborated on the diverse causes of emergence. Guidelines for the system designer that should reduce the occurrence of detrimental emergent phenomena in a System of Systems are presented.

Emergent behavior is not so much a property of the cyber-physical system of systems, but rather a mismatch between expected and understood consequences of the cyber-physical system of systems and the actual behavior it displays. This mismatch is closely related to a lack of a complete enough understanding of the system and the complexity of the cyber-physical system of systems (both in terms of size and complex dynamics). In other words, it indicates absence of adequate models or methods to synthesize models of the systems into its system-wide consequences.

In [66] it is argued that clearly defining system-to-system interfaces is key to understanding emergent behaviour. It is currently unclear how this approach extends to the realm of CPSoS, with its complex dynamics. Another method to deal with emerging behaviour not at design time but rather at run time is to equip the cyber-physical system of systems with monitors which may then be used to reconfigure or adapt the system behaviour [67]. Run-time monitoring and verification is discussed previously.

### 4.1.6 Dynamic Reconfiguration

Dynamic reconfiguration refers to the addition or removal of components on different time scales, depending on the nature of the system and the reasons for the changes of the structure and changes of the way the system is operated. It includes systems where components come and go (like in air traffic control) as well as the handling of faults and the change of system structures and management strategies following changes of demands, supplies or regulations.

The presence of possibilities for dynamic reconfiguration as defined above implies that quality of service can only be guaranteed insofar the services that are needed to guarantee this QoS are present in the system of systems, and can be located and used by the requesting system.

To guarantee safety of the system of systems one needs to specify the allowed or disallowed global system states in terms of global concepts. It is not useful to state safety in terms of local system states since these systems may be removed.

Approaches advocated in the engineering of computer systems address dynamic reconfiguration at the architectural level and mostly assume that a centralized control is available for monitoring arrival and removal of components [68]. In computer science much research has been performed in dynamic reconfiguration and this has resulted in many commercially available solutions that aid in the engineering of such systems such as CORBA, Java RMI and DCOM [69]. It is uncertain that, and how, these techniques can be transferred to the engineering of CPSoS.

In computer science literature, there is a distinction made into foreseen reconfigurations, and unforeseen ones. The latter type is much harder to deal with in engineering of CPSoS as these are not anticipated at design-time. Engineering of CPSoS in which unanticipated reconfiguration appears, requires that accurate models of all potential components of the CPSoS and their interconnections are maintained at run-time in order to assess functional and performance properties of the system as a whole.

Dynamic reconfiguration techniques are widely used for designing efficient System-on-Chip (SoC) architectures. Many promising reconfiguration methods exist including dynamic scaling of processor voltage levels, reconfiguration of cache hierarchy and communication architectures to improve both energy consumption and overall performance in SOC architectures. Although they receive considerable attention in various domains recent years, dynamic reconfiguration techniques haven't widely been employed in real-time systems. This is due to the fact that such systems consist of tasks with time constraints and missing task deadlines may lead to catastrophic effects in safety-critical systems. Dynamic reconfiguration normally will change the task's execution time. Moreover, additional computation required for making decisions at runtime may adversely affect the task schedulability. The problem is further aggravated in the presence of aperiodic or sporadic tasks where task attributes are not known in priori. The goal of this research is to exploit the advantages of dynamic reconfigurations in real-time embedded systems. See <http://esl.cise.ufl.edu/reconfiguration.html>.

A consequence of reconfiguration is also that the higher level control layers such as system-wide supervisory control and optimal control need adaptation at a similar time scale as the (possible) occurrences of the reconfigurations in order to guarantee that the QoS of the system as a whole remains within acceptable levels. For this it is needed to have means, either inside or outside the CPSoS of detecting that reconfiguration occurred.

#### 4.1.7 Continuous Evolution

Cyber-physical systems of systems are systems that evolve continuously over long periods of time both in terms of the purpose they serve as the means they have for achieving those. As a consequence the engineering of such a system has to be performed at run-time. The waterfall paradigm “Requirements – modelling – model-based design – verification – commissioning – operation - dismantling” is not applicable to systems of systems where the requirements change during operation.

A systematic review of software architecture research [70] identified that most methods and tools that are developed for the purpose of software evolution are not widely established in industrial practices. Currently, evolution of system evolution are mostly ad hoc and lack a systematic approach, such as clean sheet designs. Among others, the development of foundation theories with practical value to software architecture evolution is identified as a research challenge. Novel methods and tools are needed to design ultra-large-systems that integrate and orchestrate the evolution of thousands of platforms, decision nodes, organizations and processes.

In the DEECo project [71] a framework is presented for software engineering in the context of smart cyber-physical systems and addresses the characteristics autonomy, dynamic reconfiguration and continuous evolution to some extent. Component (software units of development and deployment) may be assembled dynamically into collaboration groups. Interaction between components is handled by a centralized execution environment. Global system invariants are maintained by component coordination and are decomposed into component processes or collaboration group interactions. This approach is referred to as the Invariant Refinement Method [72]. Reported unresolved issues in the use of this framework are uncertainty of knowledge and verification in the presence of dynamicity.

An option is to perform validation and verification “on the fly”. This strengthens the role of models in the engineering processes. Up-to-date (because continuously updated) models of the running operation can be used



for both purposes. If they are adapted to the real operational practice, they reflect reality better than the original engineering models and can be used to investigate options for modifications as well as improved operational policies without modifications.

The behaviour of cyber-physical systems of systems depends heavily on the environment and changes over time, which makes their behaviour hard to analyse prior to execution. Runtime verification [73] is a lightweight verification technique which is performed in runtime and as such may suffer less from the evolutionary aspects of a cyber-physical system of systems. By means of a monitor process it is decided whether expected and actual behaviour are well enough aligned. Runtime verification may be an interesting technique in cases where certain information is only available at runtime, in cases where precise models are not available, and in safety-critical systems for increasing confidence that the system behaves safely. Run-time verification continuous signals is studied in [74]. Runtime monitoring for stochastic cyber-physical systems is discussed in [75]. Compared to other verification approaches, runtime verification is able to operate on concrete values of system state variables, which makes it possible to collect statistical information about the program execution and use this information to assess complex quantitative properties. More expressive property languages that will allow us to fully utilize this capability are needed.

Partly due to the presence of evolution of a cyber-physical system of systems both in terms of the functionality offered and in the means available for delivering the requested functionality with appropriate performance, the focus must shift from the use of models in the design and implementation phase to the operation and maintenance phase [76].

## 4.2 Management and Control of CPSoS

*System-wide management and control* of large-scale, distributed processes has been an important topic in research and industrial application for many years. The main challenge that is considered in this area is how to operate a wide-area physical system to maximize overall performance measures under operational constraints, drawing from a broad range of information sources, and to ensure a robust and stable operation even in case of failures of subsystems. The performance measure typically describes socio-economic and environmental criteria, while the constraints are related to dynamical restrictions of the system, limitations of equipment and resources, and the legislation (e.g. safety codes and emission limits). Communication between the constituent systems takes place both between the physical sub-systems by exchanging material and energy and at all levels of the control hierarchies that are in place via sensors and actuators and communication channels.

The high degree of complexity of such large-scale physical systems makes centralized management infeasible and requires management and control architectures that are motivated by the basic engineering principles of separation of concerns and encapsulation of functionality to reduce complexity. Consequently, the management and control systems of such processes are virtually always structured *hierarchically* in layers or can be organized in a *distributed* manner such that independent “agents” (i.e. local control algorithms) control the subsystems and exchange information among each other or with a central coordination mechanism. Simple representations of both of these management architectures are given in Figure 32.

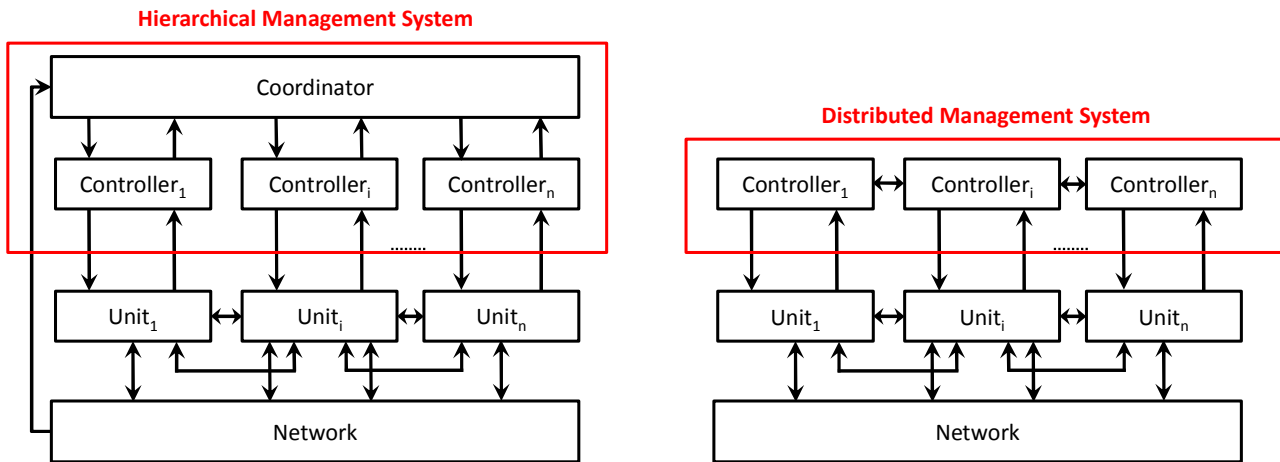


Figure 32. Management and control architectures.

Methodologies for the design of management and control systems that specifically target the distinct properties of CPSoS, such as partial autonomy, dynamic reconfiguration, continuous evolution, and a high degree of uncertainty (see [1]), have received attention only much more recently, and mature, practically applicable methods are not yet available. However, several of the CPSoS methodologies that are currently under development draw strongly on the mature results that have been developed in the areas of hierarchical and distributed management.

This section provides a brief overview of the state of the art in hierarchical and distributed management and control in the following two subsections and briefly summarizes the current efforts towards CPSoS-targeted methodologies in subsection 4.2.3. This overview is partly based on the surveying efforts of the FP7 Network of Excellence HYCON2 (<http://hycon2.eu>).

### 4.2.1 Hierarchical Management and Control

A hierarchical management system consists of several interconnected control layers [77]. A simple hierarchy with only two layers is shown in Figure 32, but several additional layers are often present. A typical industrial control hierarchy is shown in Figure 33.

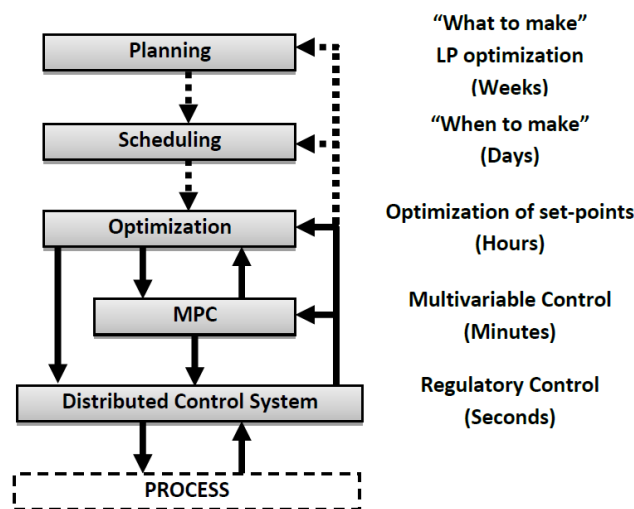


Figure 33. Industrial control hierarchy (taken from [78]).

Only the lowest level directly interacts with the physical system (regulatory real-time control), while the higher levels perform optimization, scheduling, and planning tasks on longer time horizons that influence the lower levels to maximize performance indicators.

The highest levels (planning and scheduling) operate on time scales from days to weeks. On these levels, optimal plans and schedules are computed for the complete physical system based on abstract models. The lower levels perform optimizations on more detailed models and usually only target single systems of the overall CPSoS. Here, the optimization layer (also called *real-time optimization* or *RTO*, see [79]) typically employs steady-state models to compute optimal setpoints for the lower-level controllers while the multivariable (optimizing) control layer computes optimal trajectories for the input variables of the physical process using dynamic linear or nonlinear models.

In industrial practice, all of these management system elements are usually designed separately using suitable (model-based) design methodologies. As examples, mature methodologies for the design of automatic scheduling algorithms are available that are based on mixed-integer programming (MIP) optimization techniques (see e.g. [80]) or timed automata [81], and a comprehensive survey of real-time optimization methods is provided in [78]. Multivariable optimal control (and in particular *model-predictive control* / *MPC*) has received wide attention for decades, and a large number of different algorithms are available (see e.g. [82], [83], [84]). An important sub-area is model-predictive control that is robust to uncertainties, which is an important prerequisite for their application in a CPSoS context, see e.g. [84].

Since a separate design of management and control algorithms on different hierarchy layers does not guarantee the desired performance and safety of the overall system, over the last years new methods have been developed to generate integrated hierarchical management and control systems. In the following, an assortment of methodologies that was developed for the integrated design of hierarchical control schemes is described. These methodologies have been applied to a wide range of practical case studies and simulations, including factories, energy and material networks, and chemical processes.

Several methodologies have been developed that implement hierarchical extensions to model-predictive control algorithms, see e.g. [85], [86], [87], while in [88], a formal framework is proposed that ensures consistency between different layers of a management hierarchy for systems with timed dynamics. Mechanisms were proposed to integrate the *real-time optimization* (*RTO*) layer with the *model-predictive control* (*MPC*) layer, see e.g. [89]. In [90], a method is proposed that integrates the scheduling layer with low-level discrete batch control, and [91], [92], [93] describe hierarchical supervisory control algorithms for discrete-event and hybrid systems.

Price-based coordination and control methods are very interesting for CPSoS applications since they are able to take partial autonomy into account. While several methodologies have been developed for price-based scheduling mechanisms, price-based methods have so far only rarely been investigated in a control context, see e.g. [94], [95].

#### 4.2.2 Distributed Management and Control

In contrast to hierarchical control where the uppermost layer usually influences the complete system, in distributed management and control the problem is divided into a set of local problem formulations of smaller size without a central coordinator. The local controllers cooperate by communicating certain data entities with each other, such as optimal local predictions, local state measurements, or local decisions. Each controller is based on a local model of the overall dynamics, possibly neglecting existing dynamical interactions, and the global performance objective must be suitably mapped into local objectives for each of the local problems.

Due to the strong reliance of distributed control applications on communications, research on *networked control systems* [96] is an important topic in this area. This research mainly focuses in the following areas [97]: (1) evolution and research in networking technologies, (2) effect of network delays (modelling and analysis, compensation for delays), (3) fault-tolerant control, (4) bandwidth allocation and scheduling, (5) network security, and (6) integration of components.

There are two major types of distributed control: *non-cooperative distributed control* (in which local controllers do not share a common objective function, but might share some information, e.g. on state values of local subsystems) and *cooperative distributed control* (in which all local controllers use the same global objective function). By far the most common type of distributed controller is based on the extension of model-predictive control approaches to a distributed setting (*distributed model-predictive control, DMPC*). [98] describes the different types of distributed controllers and provides a comprehensive survey of distributed control approaches.

### 4.2.3 CPSoS Management and Control

The area of CPSoS management and control is still in its infancy; CPSoS pose several challenges that the approaches described in the previous sections do not yet address. CPSoS cannot be managed in a strict hierarchical top-down manner with one authority tightly controlling and managing all the subsystems. Instead, there is a significant distribution of authority with partial local autonomy, i.e. partially independent decision making, which must be considered explicitly in CPSoS automatic management strategies.

Furthermore, the approaches described above require a centralized off-line design phase which requires the knowledge of the whole system already at design time, and adaptations to dynamic reconfigurations and system evolutions are usually done manually at run-time. A promising candidate to overcome this problem is *Plug-and-Play control* [99]. The method has been applied amongst others to the design of the AGC layer in power networks.

However, this methodology is still far away from productive use and does not cover all aspects of CPSoS. Currently, there are several research and innovation projects running within FP7 to develop new methodologies that are tailored for complex CPSoS (under the umbrella of the *European Systems of Systems Research Cluster*).

The EU FP7 project *Local4Global* (<http://local4global-fp7.eu>) aims to develop and extensively test and evaluate a generic, integrated and fully-functional methodology/system for technical systems of systems (TSoS) with

- a self-learning mechanism for the identification of the TSoS dynamics
- a situation-awareness mechanism for the constituent systems
- a distributed optimizer to determine local control actions
- a control-for-learning and learning-for-control mechanism

The system will be deployed and tested for a traffic case and an efficient building case. Related projects are *AGILE* (rapidly-deployable, self-tuning, self-configurable, nearly-optimal control design), *HYDRA* (middleware platform for heterogeneous devices), *BEAMS* (buildings energy advanced management system), and *EPIC-HUB* (fully interoperable middleware solution).

The FP7 project *DYMASOS* (<http://www.dymasos.eu>) is currently developing three new methodologies which are based on existing approaches for large-scale systems management and control, but which explicitly target the

additional challenges posed by CPSoS. Examples of practical cases where such mechanisms may be applied are chemical production sites, electric vehicle charging nets, electric distribution grids.

*Population control methods*, which are inspired by ecology and are mainly motivated by biological applications, refer to systems that comprise a large number of semi-independent subsystems, which are viewed macroscopically in terms of their emergent behavior. Several engineering applications can profit from a population control perspective, as they are concerned with the control of the emergent behavior of large collections of semi-autonomous subsystems and are suitably flexible. There are many practical examples that can benefit from this new methodology, e.g. power networks, including real-time demand-response schemes implemented either through the aggregation of large numbers of small thermostatically controlled electrical loads, or through the aggregation of large numbers of plug-in electric vehicles.

*Economics-driven coordination and market-based management methods* are based on the market coordination mechanisms described above, but are extended in DYMASOS to fit the requirements of complex CPSoS. Market-based distributed mechanisms lend themselves naturally for the coordination of complex systems of systems. Market-based mechanisms are inherently decentralized and can thus be mapped directly to systems with autonomous subsystems, no transfer of information about the “internals” of the subsystem is required, and only bids and prices must be communicated. Furthermore, these mechanisms can directly handle varying numbers of subsystems, since the optimal coordination can be done separately for different intervals of time, independent of the number of bidders.

Like other distributed management methods, *coalition management schemes* consider the overall system as a set of subsystems that are controlled by local controllers or agents which may exchange information and cooperate. However, they do not assume that the structure of the system is fixed, which enables quick reactions to dynamic reconfigurations or system evolutions. Different agents cooperate when there is enough interaction between the controlled systems. When the interaction is low, they work in a decentralized fashion. Moreover, for the CPSoS considered here, the coalitions can be established not only based on the dynamic interconnections but also because of subsystems sharing common objectives or competing with other subsystems.

### 4.3 Future Research Challenges

The results of the above state of the art in methods and tools for management and engineering of CPSoS have been discussed in the “Workshop on Tools and Methods for CPSoS” and in a breakout session organised as part of the Second WG2 meeting. The findings of these consultations are reported in Deliverable D2.3 [100] of the CPSoS project.

Both the state of the art and the research challenges drawn from it have been discussed in consultations with industry, varying from well-established tool vendors such as The Mathworks to SMEs such as Verum Software Tools and across several domains such as automotive and high-tech systems. These consultations have shown support for the research challenges and confirm the prioritization of these.

This has resulted in the following research challenges in the area of tools and methods for the management and engineering of CPSoS.

- **(Efficient) Modelling and simulation of large-scale heterogeneous complex systems**
  - Formulation of detailed models of the constituent systems, incl. human operators and environment.

- Availability of simulation engines capable of dealing with the scale dimension of CPSoS. This requires clear interfaces between heterogeneous models and abstraction methods that can be used for representing complex models with adequate simplified ones.
- System-wide simulation techniques that allow to assess the properties of the system prior to effectuating of evolution steps (in case these can be controlled). These should also aid in detecting emerging behaviour.
- **Abstraction and approximation methods** for reducing model complexity for system-wide functionality and performance analysis. This includes methods and tools for the verification of heterogeneous models including dynamic behaviour, discrete event behaviour and stochastic behaviour
- **Development of control strategies and methods for decision making**
  - that deal well with reconfiguration and partial autonomy of parts of the CPSoS
  - for which reconfiguration and evolution have less impact on the system-wide behaviour
  - including methods to detect significant evolutions in the CPSoS in order to react timely with adapted control
- **Techniques for modelling and analysing threats** to system functionality and performance induced by communication infrastructure
- **Model-based systems engineering approach** is needed that does full justice to the shift from design-time to run-time engineering.
- **Tools for the management of models** and relationships between models that allow to keep track of past, current and planned system configurations at the architectural level and provide linkage with the associated models. These tools should be able to deal with semantic linking of concepts among collections of heterogeneous models.

### 4.3.1 Research priorities

The identified challenges for methods and tools for the engineering and management of CPSoS have been prioritized into short term (less than 4 years), medium (from 4 to 8 years) and long term (more than 8 years) issues according to the expectations of the participants of the public “Workshop on Tools and Methods for Cyber-physical Systems of Systems” on September 12<sup>th</sup>, 2014, at the University Residential Center, Bertinoro, Italy and from a breakout session that was organised as part of the second meeting of Working Group 2 (Physically Connected Systems of Systems) which was organized as a public event jointly with STReP DYMASOS (Dynamic Management of Physically Coupled Systems of Systems) in Zürich on October 1<sup>st</sup>, 2014.

#### Short term horizon:

1. Tools for the management of models
2. (Efficient) Modelling and simulation of large-scale heterogeneous complex systems
3. Model-based systems engineering approach

#### Middle term horizon:

1. Development of control strategies and methods for decision making
2. Model-based systems engineering approach
3. Tools for the management of models



4. (Efficient) Modelling and simulation of large-scale heterogeneous complex systems

**Long term horizon:**

1. Model-based systems engineering approach
2. Tools for the management of models
3. Development of control strategies and methods for decision making



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