CyPhERS
Cyber-Physical European Roadmap & Strategy

SEVENTH FRAMEWORK PROGRAMME

CyPhERS

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Research Agenda and Recommendations for Action

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Project Consortium Information

Participants	Contact
fortiss GmbH (Coordinator) Guerickestraße 25 80805 München, Germany	Bernhard Schätz Phone: +49 89 3603522 27 Email: `schaetz@fortiss.org`
Kungliga Tekniska högskolan (KTH) Brinellvagen 8 10044 Stockholm, Sweden	Martin Törngren Phone: +46 8 7906307 Email: `martin@md.kth.se`
Université Joseph Fourier Grenoble 1 (UJF) 621, Avenue Centrale, Domaine Universitaire 380410 Grenoble, France	Saddek Bensalem Phone: +33 0456520371 Email: `saddek.bensalem@imag.fr`
Università degli Studi di Trento Via Belenzani 12 38122 Trento, Italy	Roberto Passerone Phone: +39 0461283971 Email: `roberto.passerone@unitn.it`
The University of York Heslington Hall York YO10 5DD, UK	John McDermid Phone: +44 1904 325419 Email: `john.mcdermid@york.ac.uk`
Siemens AG (affiliate partner) Otto-Hahn-Ring 6 81739 München, Germany	Thomas Runkler Phone: +49 89 636 40010 Email: `thomas.runkler@siemens.com`

Authors

Name	Partner	Contact	
Responsible Author			
Bernhard Schätz	fortiss GmbH	+49 89 3603522 27	`schaetz@fortiss.org`
Contributing Authors			
Martin Törngren	Kungliga Tekniska högskolan	+46 8 7906307	`martin@md.kth.se`
Saddek Bensalem	Université Joseph Fourier Grenoble 1	+33 0456520371	`saddek.bensalem@imag.fr`
María Victoria Cengarle	fortiss GmbH	+49 89 3603522-29	`cengarle@fortiss.org`
Holger Pfeifer	fortiss GmbH	+49 89 3603522-10	`pfeifer@fortiss.org`
John McDermid	The University of York	+44 1904 325419	`john.mcdermid@york.ac.uk`
Roberto Passerone	Università degli Studi di Trento	+39 0461283971	`roberto.passerone@unitn.it`
Alberto Sangiovanni-Vincentelli	Università degli Studi di Trento	+39 335218403	`alberto@berkeley.edu`

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Executive Summary

Recent innovations in technological fields like embedded computing, communication, sensors and actuators, and informatics and control have enabled the implementation of complex systems that are able to *control and coordinate physical and organizational processes on a local and a global scale via the use of information and communication technology*. By their *inherently socio-technical character*, these systems – called *cyber-physical systems* – provide the potential for revolutionary changes, *bringing disruptive change to existing economical value-chains and societal processes*.

As this potential raises many questions – on a scientific, technical, and economical, but also legal and ethical level – the *CyPhERS* Support Action was initiated, co-funded by the European Commission, with the objective to develop a *European strategic research and innovation agenda for cyber-physical systems to ensure Europe's competitiveness* in this emerging field. To obtain these research challenges and derive recommendations, five *key areas of strategic importance to Europe – transport, energy, well-being, industry, and infrastructures* – where chosen to identify strengths, weaknesses, threats, and opportunities for Europe, based on the current state and and future technologies as well as market potentials of cyber-physical systems.

In these key fields, cyber-physical systems provide solutions for

- smart transportation, ensuring to meet the every-increasing demand for individual transport of goods and people in a sustainable and safe way, strengthening Europe's competitiveness in general as well as specifically as a mobility provider
- smart energy, enabling the decentralized and cooperative coordination of the electrical grid, facilitating stable integration of renewable energy resources, and enabling new, sustainable added-value services for operators and end customers
- smart health, offering personalized and proactive health support solutions for an aging society, keeping the well-being of the European citizenship affordable
- smart production, providing a shift from mass production to flexible, individually customized manufacturing, increasing Europe's competitive both in the production as well as in industrial automation

- smart cities, help to reduce the operation and maintenance costs for European city infrastructure as well as to provide for authoritative strategic planning, while optimizing the comfort and respecting the need of the individual citizen

However, to make these possibilities happen, several challenges have to be addressed:

Science: Integration of multiple paradigms affecting the construction of cyber-physical systems by specially considering their socio-technical aspects, facilitating multi-disciplinary collaboration, combining the related individual theories in a common systems theory, and establishing of a body of knowledge for multi-domain modeling

Technology: Up-scaling current engineering methods and technologies to the required level of complexity, by providing interoperable platforms/methods/tools, maturing the design and implementation of autonomous behavior, eliminating deficits in data privacy, methodically integrating safety and security to ensure dependability, and establishing a systematic approach to deal with uncertain information

Economy: Support for the establishment of new business models and value networks in markets disrupted through cyber-physical systems, by anticipating a shift from products to services, and being aware of the dominance of value-networks by new participants from the field of ‘cyber’-technology

Education: Provision of the required competences to the stakeholders in cyber-physical systems, by preparing education/training systems for the transfer of evolving knowledge, balancing theory and practice, and counteracting the lack of availability personell with the required skills and expertise

Legislation: Elimination of potential innovation barriers established by existing regulations inadequate for cyber-physical systems, by eliminating unclear interpretations or restrictive application of regulations, improving techniques and tools for the certification of systems, and Europe-wide harmonizing the fragmentation of regulations

Society: Management of change/risk-aversion in stakeholders from the public, industry, and politics, by raising awareness of the general public concerning the consequences of installing cyber-physical systems, and gathering support for acceptable risks during evolving these system from public, industry, and politics

Consequently, actions have to be taken by academia, industry, governments and administrations, as well as the public to *strengthen key research fields, accelerate the maturation of technologies, facilitate interoperability of technology, support open innovation,* *anticipate new business models, raise societal awareness, and ensure trustworthiness of those systems*.

Cyber-physical systems are influenced by several technological fields, and are of global strategic importance. Therefore, agendas compiled in neighbouring fields and other countries have been included in the preparation of this Research Agenda and Recommendation for Actions. In contrast to those other agendas, however, the Challenges and Recommendations identified here target a broader scope, especially concerning the interdisciplinarity needed to implement those systems, while they are specifically focused on the European potential of those systems.

1. Cyber-Physical Systems – Disruptive Change for Economy and Society

Information and communication technology has always been considered disruptive since it fundamentally changed the way of life, enabling a new degree of automation in organizational and technical processes not achieved before. However, it is also considered as a disruptive technology in the meaning coined by Clayton M. Christensen, since it enables new business models, thus establishing new markets and value-chains or -network, thus *overtaking and destroying an existing market, or economic network*. Therefore, to maximally draw on the potential of cyber-physical systems for our economic and societal benefit, we have to understand, anticipate, and exploit their impact.

Cyber-physical systems bring a *disruptive change on an economic level*, since their capability to link previously disjoint technical and organizational processes facilitates the provision of new products and – especially – services, thus creating new markets and not only incrementally changing them. While the speed of change – and therefore the power of disruption – in several of the application domains, for instance in mobility, and energy, depends on additional, non-economic factors like laws and regulations, the scale of impact *can be expected to exceed the already substantial changes initiated by the business information systems and embedded systems alone*.

In the mobility sector, for instance, cyber-physical technology allows the introduction of fleets of basic, highly automated, electric inner-city vehicles. Such form of mobility with a pay-per-use business model has the potential to open a niche for a new group of vehicle users currently favoring public forms of transportation, typical for a disruptive technology. However, it also establishes a substantially different form of value-network, since the focus on a high-end, massively-customized vehicle – which is a key selling point of the European OEMs and their Tier 1 and Tier 2 partners – is dropped in favor of a rather basic vehicle. The added value for the end-customer is in contrast produced by the automated driving functionalities as well as the optimal fleet management including maintenance and billing, generally not covered by the traditional automotive suppliers, thus radically changing the business model in this market.

In the energy sector, cyber-physical technology allows a change of similar substantial impact, albeit with a much more gradual transformation, by facilitating the management of many small-volume production and consumption loads in the electric grid. Such a form of grid can open the energy market to a new group of participants, opening their private, small-to-medium-volume – production, buffering, or consumption – installations to be managed by aggregators and thus participating in the value-chain. However, with a growing number of such new participants, the traditional business model of facilities of producing, transmitting, and distributing energy is gradually reduced to the management of a virtual grid with optimal balance of production and consumption, including the billing for services. The added value for the participants in this scenario is contrast increasingly provided on the level of the distribution grid, and covered by small or communal providers and established or emerging players dealing with customer-related services including billing, installation management, or aggregation, thus substantially changing the business models for the current large players in the energy market.

Besides affecting established business models and markets, cyber-physical systems will also bring a *disruptive change on a societal level*, changing societal processes including the governance of traffic or provision of energy. By addressing physical as well as organizational processes, they are *socio-technical systems*, leading to a new depth of interaction and collaboration between technical systems and their human users. Due to this socio-technical dimensions, a cyber-physical system one the hand defines how the *users of such a system interact with it* to control a technical system but also how *a cyber-physical system proactively collaborates with its users* to control a social system. For instance, a smart traffic system supports individual drivers to control the movement of an individual vehicle through advanced driving assistance functionality, but also provides governance of urban traffic as a whole through on- and off-board telematic functions guiding the flow of vehicles.

This thigh cooperation between its human users and the cyber-physical system has therefore a *disruptive potential on the societal level*, immediately raising *legal issues* – like regulations for handing over between manual and autonomous control in a smart traffic system – as well as *ethical questions* – like balancing the needs of the individuals as well as society as a whole in a smart energy system in case of a blackout – to be solved. Therefore, an open discussion shaping the general opinion about the use of those systems is needed, to ensure that Europe's competitive position in cyber-physical systems is not only the technologically feasible but also socially acceptable.

2. Cyber-Physical Systems – Fusion of the Physical and Digital World

Despite its wide-spread use, the term '*Cyber-Physical System*' does not come with a uniform meaning. It is often used as a synonym for 'system in which computing interacts with the physical world' or 'networked embedded system' on the one hand, or 'system of systems' on the other hand. While the use of computing devices, mechatronic components, and networking infrastructure in multi-hierarchical systems clearly is an essential property of cyber-physical systems, it fails to address their core characteristics, explaining their disruptive nature. In contrast, the interpretation that the term encompasses 'embedded systems (...), but also logistics-, coordination- and management-processes as well as internet services, and are 'interconnected (...) locally as well as globally', as suggested in the *agendaCPS* of the *acatech* indicates the complexity caused the wide spectrum of enabling technologies and application fields.

The main characteristic of cyber-physical systems used here – specifically the *possibility to control and coordinate physical and organizational processes on a local and a global scale via the use of information and communication technology* – explains why these introduce a new class of system complexity, and consequently provide a wide range of innovative usage potential but also pose new challenges for their engineering.

2.1. Enabling Technologies of Cyber-Physical Systems

Cyber-physical systems – and their capability to coordinate physical as well as organizational processes on a local and global scale – heavily depend on the availability of technologies, which allow to *interact with the physical world* as well as *process and communicate information* between the distributed elements of such a system. It therefore is the rapid improvements in fields related to these technologies – *predominantly microeletronics, communication and information technology, as well as informatics* – in the recent decades that have made the realization of cyber-physical systems possible:

Computation: Following Moore's law, the semiconductor industry manages to produce higher levels of integration of circuits in exponential fashion, raising computational speed of devices while reducing required size as well as consumed energy. This allows to raise the amount of computation done per device, and thus *increase the level of intelligence individual devices*, including mobile or in-field computation devices, as well as backend high-computation servers.

Sensor/Actutator: The production of miniaturized (electronic) structures provided especially by microelectronics – beside improved computation – also allows to provide smaller, more energy-efficient sensing and actuating devices addressing a wider range of applications, from small-scale accelerometers or detectors for biological and chemical substances to miniature light emitters or motors. This allows to *monitor and control a wider range of physical processes*, including biological, chancel, and mechanical processes.

Communication: Besides miniaturization, the production of communication solutions with increased variety – ranging from very energy-efficient to high-volume wired as well as wireless communication – and flexibility – concerning bandwidth, energy consumption, or frequency – enables the inter-networking of an increasing number of formerly isolated devices. This allows to *coordinate physical as well as organizational processes* on a local as well as globale scale.

Informatics and Control: The development of new methods and technologies in informatics (or computer science) and information technology – and specifically the engineering of software-intensive systems – has substantially improved the way how (software) systems can be efficiently built. This allows to *tackle systems of new ranges of complexity*, specifically cooperative and automated systems. Essential contributions include:

- frameworks and standards, platforms for multi-agent systems, or ontologies
- development methods, like front-loading of validation/verification techniques or synthesis of development artifacts
- algorithmic solutions, like the mining and fusing of data, or learning and adapting of plans or strategies

While these technologies enable the realization first versions of cyber-physical systems, further innovations are needed in all of these mentioned fields, as explained inn Section 4.

2.2. Cyber-Physical Systems – New Dimensions of Complexity

Cyber-physical systems are not only disruptive concerning their impact on economy and society, as shown in Section 1. While they are made possible by – as it seems – evolutionary technological innovations in the enabling fields discussed above, *the integration of these technologies allows to build systems of new dimensions of complexity* compared to the systems in those fields. Thus, *cyber-physical systems are also disruptive concerning the engineering knowledge* required to build these systems. In order to derive suitable Recommendations for Action in Section 5, it is therefore necessary to understand the complexity drivers of cyber-physical systems.

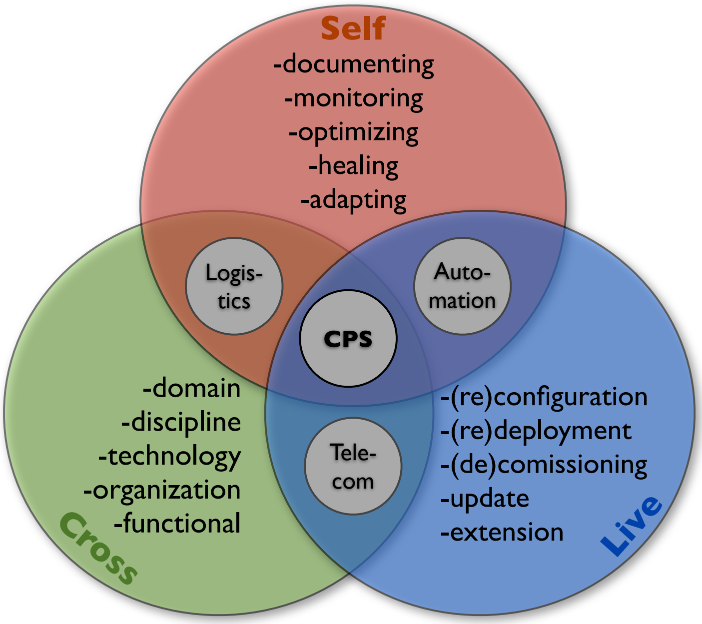

Figure 2.1.: Cyber-Physical Systems – Dimensions of Complexity

Taking a look at some example systems reveals that the complexity is caused by the need to simultaneously address the often contradicting requirements of physical and organizational as well as local and global processes. Examples for these new systems – as discussed in more detail in Section 3 – are

smart traffic systems encompassing the velocity control and distance measurement in the individual vehicle up to the traffic management of a large-scale telematic system

smart production systems encompassing the control of an individual machine performing a single production step up to the logistic resource-planing along the organizations of a production chain

smart health systems encompassing the movement monitoring of the individual patient up to the coordination of workflow through a clinical information system

smart energy systems encompassing the monitoring and control of a single household device or photovoltaic installation up to the trading of production and consumption volumes of complete regions at the spot market

These examples illustrate that systems capable of controlling physical and organizational as well as local and global processes exhibit specific characteristics complicating their realization. While *CyPhERS* Deliverable D5.1 provides a detailed spectrum of them, these characteristics can be classified into three groups, each group forming its own *dimension of complexity*, as shown in Figure 2.1:

‘*Cross*’-Dimension: As cyber-physical systems cover global-scale processes – both physical and organizational – these processes generally *go across borders, with respect to application domains, engineering disciplines, used technologies, governance, legal spaces, or involved organizations*, to mention a few.

‘*Live*’-Dimension: Additionally, cyber-physical systems generally support global mission-critical processes, making it impossible to turn off the system to make changes and therefore, for instance, *requiring (re-)configuration, (re-)deployment, (de-)commissioning, update, or enhancement during runtime*.

‘*Self*’-Dimension: Finally, being global-scale and mission critical, cyber-physical systems must cooperative with system engineers, operators, users, and also other systems by actively supporting their processes, *requiring capabilities of autonomously monitoring, control, adaption, optimization, and healing, as well as documenting itself.*

While single dimensions can already be found in existing systems – like being cross-domain and self-optimizing in logistics systems, or being self-documenting and live-reconfiguring in automation systems – their massive joint presence is typical for cyber-physical systems.

The example of a *smart energy system* from above – including components producing, consuming, and storing energy supports, as well as enterprises aggregating loads for spot market trade, and utilities with power stations processes – illustrates these principles. The complexity of the ‘*Cross*’-dimension is caused organization-wise, as its components are distributed over individual households, enterprise, or regions; technics-wise, as it provides services controlling batteries or photovoltaic installations as well as predicting consumption or production of energy; discipline-wise, as it addresses electricity issues like net frequency as well as economy issues like price bidding; and application domain-wise like home-automation as well as grid management. Similarly, in the '*Live*'-dimension: Live re-configuration and enhancement, for instance, is needed to add new equipment or installations without interrupting the operation of the grid; live update is needed when new control strategies must be implemented due to changed regulations. And finally in the '*Self*'-dimension: Self-optimization is required to improve scheduling of production, consumption, or buffering to ensure balanced grid operation; self-healing allows to minimize the impact of faults of sub-systems and their re-integration in the overall grid.

2.3. Cyber-Physical Systems and the Technology Landscape

Despite of their disruptive nature, cyber-physical systems evolve from a wide range of technological fields. So while cyber-physical draw upon the contributions from many of these fields, they are not just a mere new phrase for some of these fields, or a straightforward combination of these contributions. To illustrate that cyber-physical systems are a complex research and innovation field in its own right, partly overlapping or even encompassing them, in the following their differences to the most closely related fields are briefly illustrated:

Embedded Systems: Embedded Systems generally refers to the integration of software and electronics part of system embedded into a physical environment, and including aspects of control and communication engineering. Cyber-physical systems target a larger scope, including additional aspects of the collaborative governance of generally distributed, physical and especially organizational processes.

Mechatronics: Mechatronics is usually understood as synergistic combination of mechanical and electrical – including control – engineering, potentially including computer science, with the core topic of co-design of mechanical and electronic control systems. Thus, while mechatronic systems – per definition – have an emphasis on electro-mechanical systems, cyber-physical systems furthermore target other, large-scale physical as well as organizational processes, and their automated and distributed control.

Internet of Things: Internet of Things generally focusses on the sensing of the physical world and the (internet) connectivity, emphasizing individual things providing data over the net to steer (usually organizational) processes. While sensing physical data and communicating it – not necessary via internet – is generally also required for cyber-physical systems, these systems also target the control of combined organizational and physical processes, and therefore specifically address tight human-machine interaction, mostly not addressed in Internet of Things.

Big Data: Big Data mostly refers to the use of large-volume data, including capture, communication, analysis, storage, and visualization. While cyber-physical systems to to their distributed and heterogeneous nature require the processing of a large volume of data, they also covers the aspect of the often highly autonomous control of – specifically physical – processes generally not associated with Big Data, adding further limitations.

System of Systems: System of systems usually addresses the construction of evolving, large-scale systems and the coordination among those systems, specifically focussing on the integration and optimization existing and new systems to satisfy a wide range of objectives. While many cyber-physical systems will in fact also be systems of system, the field of cyber-physical systems is not concentrating on the large-scale aspects of evolving and integrating those individual systems, but also has to address the full technological and disciplinary spectrum from sensing physical data to autonomous collaborative control.

As these terms often have a wide range of interpretation, a much more in-depth discussion of these differences in provided in the *CyPhERS* Deliverable D5.2.

3. Cyber-Physical Systems – Scenarios of Future Potential

The disruptive nature of cyber-physical systems has the potential to substantially change the way how we can address the key questions of modern societies, and specifically the European challenges including Well-Being, Clean Energy, Integrated Transport, and Resource Efficiency, by providing smart answers to these questions.

In the *CyPhERS* project, the following five key areas were therefore chosen to illustrate the potential of cyber-physical systems using future scenarios of 2030, and identify strengths, weaknesses, threats and opportunities of Europe:

Transport: Smart Mobility

Energy: Smart Grids

Well-Being: Smart Health Systems

Industry: Smart Production

Infrastructures: Smart Cities

These scenarios are also used to identify open research and innovation challenges in the following chapter, which have to be addressed to materialize these scenarios. An in-depth description and analysis of these scenarios can be found in the *CyPhERS* deliverable D5.2, including opportunities and weaknesses. Here, for each of these key areas we briefly illustrate why they are of importance for Europe, and how the technologies of cyber-physical systems – and especially its characteristics of the three dimensions *Cross*, *Self*, and *Live* identified in Section 2.2 – help to address the challenges in these areas.

3.1. Smart Mobility

Transportation is the foundation of any modern society – forming the backbone of the supply chain for internal and external markets, and providing the necessary mobility of people. Thus, besides forming a substantial industry with more than €500 billion of

Gross Value Added, contributing about 5% of the Gross Domestic Product (GDP) and directly employing around 10 million people – the European transport industry and services sector – with many world leaders in infrastructure, logistics, traffic managements, and transport equipment – is a key element for Europe's competitiveness. European transport relies on an infrastructure of increasing complexity – with more than 5 Mio. km of paved roads and more than 200.000 km of railroads exceeding even the U.S. and China, as well a complex air space with a transport volume only topped by U.S. – requiring careful management to ensure economic competitiveness as well as meet the societal demand for sustainable growth.

Transportation services in general, and the increasingly necessary services of tightly connected, inter-modal transport, require the coordination of processes across different sectors – like automotive, aerospace, rail – influenced both by the corresponding vehicles – cars, trucks, airplanes, trains – and infrastructural components – roads, airports, railroads – with obvious differences including speed, capacity, cost, or governance. With logistics begin an integral part of industrial and societal processes, the shift from mobility as the provision of vehicles to mobility as a service is accelerating. Correspondingly, modern mobility solutions will increasingly focus of highly automated forms of transport, *addressing the need for individual transport without the need for an individually owned vehicle*. This holds for the mobility of goods – from long-distance, mass transport by plane, rail, ship, or truck to last-mile, individual transport by small automated guided vehicles like areal drones or holonic vehicles – as well as the mobility of passengers – with public, shared, or private means of automated transportation. These means of highly automated mobility are not only necessary to cope with the increased demand for mobility, but also address the additional societal goals of increased safety – including reducing fatalities – and sustainability – including supporting optimized intermodal, fleet-oriented vehicle use – while ensuring reliability in face of increasing climate-change induced disturbances.

The cyber-physical system of a smart transportation system can provide the necessary solution to support this scenario of automated control and coordination, by enabling cooperative logistic processes across individual vehicles or even organizations, integrating the necessary set of sensors and actuators, in the vehicles themselves as well as in the infrastructure, and interconnection between vehicles, the infrastructure, and coordinating backend services. By coordinating the overall traffic flow, but also the immediate cooperation between highly automated vehicles – supported by a traffic prediction based on the itinerary and requirements of the individual transport processes – the smart-tragic cyber-physical system allows a much more efficient use of the available road or rail infrastructure as well as airspace.

By enabling the realization of smart transportation systems, cyber-physical systems can help to achieve the challenges of a sustainable and efficient economy as well as of an aging and increasing urbanized society. With Europe still being a technology leader in transportation technology, they can also strengthen Europe's competitive position in this field. Nevertheless, to allow the implementation of such a system in Europe, the necessary technological and – specifically concerning autonomy – legal conditions must be provided, as well as investment in an extendable, safe and secure cross-border infrastructure, supporting the substantially different life cycles of vehicles and infrastructure.

3.2. Smart Energy

As any highly industrialized society, Europe is built on an infrastructure that depends on the reliable provision of energy, and in particular of electric energy. Currently, Europe's annual demand of primary energy is about 22 PWh, with 20% electric energy. It is essential for any aspect of daily life, from the individual household via production and manufacturing processes up to mass transportation. As electric energy cannot easily be stored and buffered, it takes a complex production, transmission, and distribution system with a meticulous balance between the volume of energy produced and consumed to ensure such a reliable provision to all end users. Failing to reliable provide electric energy when needed can result in a substantial economic loss. For example, in Germany for more then 60% of the regions, a non-availability of 1kWh will result in the loss of more than 5€ in production. Traditionally, such an electric grid is implemented asymmetrically by a small number of high-volume facilities like fossil or nuclear power plants, often complemented with hydro-power plants, on the production side and large number of generally low-to-medium volume installations like households or enterprises on the consumer side. As the consumption of these installations varies substantially during the course of a day – with a factor of four between lows and peaks – the production of those facilities have to managed accordingly, based on assumptions about future demand. An upcoming surplus in demand – *but also in production* – has to be compensated on short notice by additional providers or consumers, who sell their capacities on a European energy spot market like EPEX SPOT.

Europe – with its leading global role concerning climate control and the reduction of CO_2 emission – has adopted the strategic decision to reduce greenhouse gas emissions by 20% compared to 1990 and increase the use of renewables by 20% in 2020. In contrast to the traditional energy resource, the renewable energy resources – specifically wind turbines and photovoltaics – are generally produced by a larger number of – often privately or communally owned and run – facilities. Furthermore, the volumes produced by these facilities are extremely volatile, and not in synch with the requested consumption. Therefore, with an growing amount of renewables, the traditional asymmetric and centralized management scheme of the electric grid becoming increasingly inadequate and must be replaced by a more distributed approach.

Here, the cyber-physical system of a smart grid offers a solution to this need for change, by enabling the decentralized and cooperative coordination of technical and organizational processes, from the control of a photovoltaic installation to the billing and trading of energy. The increasing amount of installations of smart meters allows to monitor and predict individual consumptions on a fine-grained level, which, together with a dependable prediction of the renewables production, facilitates a more reliable short-term balancing of demand and supply. Additionally, the installation of low-volume energy buffers, as well as the use of intelligent devices and managed installations supporting load-shifting enabling the shift from a supply- to a demand-side management of the grid, additionally facilitates short-term balancing. The highly-automated control of a cyber-physical system – supporting the self-adaption to load-changes – allows to scale these processes – via cross-organizational processes including the individual household via the communal distributor – to the required number of participants. By combining these means with suitable tariffs and market models, providing suitable incentives, the integration of the physical and economic processes strengthens a balance within the distribution grid, thus offering an alternative to massive investments in new transmission lines.

By enabling the realization of smart grids, cyber-physical systems do not only help to address the societal challenge of sustainable energy, but also position Europe to export those systems in particular to countries currently developing or updating their energy infrastructure. However, to enable the effective implementation of such a system in Europe, the necessary technological and – at least of equally importance – regulatory prerequisites must be established.

3.3. Smart Health

Europe has defined the well-being of its citizens as one of its societal major challenges. In a overall aging society – like Europe – this is not only an important societal goal, it is also a goal of important economic impact, both with respect to the productivity of Europe's workforce in an increasing competition with low-cost countries, but also with respect to the macro-economic issues of the costs of the healthcare system. Overall, in 2005 Europe spent on average 8% of its Gross Domestic Product on healthcare for the well-being of its citizens.

In Europe the availability of best treatments for acute cases is at an extremely high standard. However, especially in urban regions, there still is a need for a more individualized treatment of patients, selecting the best available options at the best possible times. Furthermore, specifically in context of an aging population, the importance of preventive care – including basic aspects like monitoring daily exercise or consumption of nutrition – as well as post-treatment care – including the monitoring recommended recuperation therapy after acute treatment – is increasing, to avoid the costs of necessary (re-)treatment caused by neglecting these possibilities. With the emergence and – as shown by the increasing popularity of wearables – acceptance of a wide range of sensors – including constantly worn devices measuring basic physical parameters of the patient, as well as advanced breath sensors for detecting metabolic anomalies, or even sensors analyzing consumed nutrition – a closer monitoring of the physical health of patients becomes possible, substantially improving the confidence on the therapy to be chosen. With the substantial improvements of sensor and even actuator technology, consumable or implantable devices can provide further, unprecedented benefits.

The above-mentioned need for a *personalized and proactive health support* can be addressed by a smart health cyber-physical system, exploiting the increasing amount of individually available date. By automatically monitoring this data, fusing and evaluating it as well as providing it when requested, such a system can help choosing the appropriate treatment. Furthermore, complementing the monitoring, it can assist – especially in pre- and post-care – the patient with recommendations, increasing the effectiveness or even avoiding the necessity of acute treatment. Additionally, it can support coordinating the corresponding organizational processes, including the workflows of clinical information systems as well as emergency calls. Thus, such a cyber-physical system can facilitate in-home treatment, avoiding to rely only on services at the hospital. Finally, besides selecting – and even detecting – optimal forms of treatment, the monitored data can also help to evaluate the effectiveness of therapies, supporting the provision of treatments that are as beneficial as they are cost-effective.

By supporting these forms of personalized and proactive therapies, cyber-physical systems can help to ensure the well-being of the European citizens, counter-measuring the increasing costs caused by an aging population. Nevertheless, the possibility of realizing such a systems in Europe depends on – besides many technological prerequisites – the public acceptances of such systems and therefore, in turn, on the protection and ownership of personalized data and regulations of its fair use.

3.4. Smart Production

A modern industrialized society without the highly-automated production of goods is literally unthinkable. The transition from craft production to mass production by the increased use of mechanization defines the beginning of industrialization. However, while the original focus of automated production was *mass production* of few product variants with a high production volume per product – in the automotive sector initiated by the assembly-line production of the Ford T-model in 1915 – the demand for a larger variety of products initiated a transition – in the automotive marked by a peak in volume in the US production in 1955 with as little as 30 products on the market – to *mass customization* – to be coined as the new production paradigm in 1980 – with more product variants of less volume per product. One European premium automotive manufacturer currently offers 19 different series with more than 20 different models for some of the series, and thus – considering options like color, interior style, or infotainment packages – virtually offers a distinct product for each customer.

Therefore, today the adequate production paradigm is *adaptive production*, not only addressing the possibility to customize a product to individual needs, but also the need to do so in a timely manner, realizing the ‘lot-size zero’ production typical for craft production. Furthermore, societal goals – most specifically a sustainable economy – require the inclusion of further considerations like the resource-efficient production. Altogether, these requirements demand a way of *smart production*, merging the physical manufacturing process with multi-concern virtual business process. By moving from ‘classical’ production to this smart approach, Europe can turn around the trend of deindustrialization and off-shoring, while still 195 of the Top-500 manufacturing companies are headquartered in Europe, and the manufacturing industry accounts for 28.4% of the GDP of Europe.

To realize achieve smart production capabilities, the deep integration of a physical manufacturing process with a virtual management process provided by a cyber-physical systems enables adaptive and flexible manufacturing. The increasing availability of machines or robots equipped with a wide range of sensors, and offering standardized connectivity and interoperability, as well as more flexibility and intelligence on the level of the individual machine, offers two essential improvements: A deep integration of the production floor with manufacturing execution systems and enterprise resource planning systems – allowing a fast and automated live reconfiguration of the manufacturing process and plant based on individual demands – as well as improved forms of man-machine interaction – allowing a high physical collaboration between planning, working, or maintenance personnel and the production systems – to provide the required capability of adaptive production. Additionally, self-monitoring and self-optimization reduces production cost and equipment failure. Furthermore, the inherent capability of cyber-physical systems of supporting distributed but integrated processes, enables new business models by putting the individual customer even more into the focus. It also allows a strong integration of the end-users into the manufacturing process, offering the possibility to integrate them in the design-process by providing them a virtual workbench with a large component library – custom-made by use of technologies like 3D printing – thus simplifying a built-by-order-oriented, cross-organizational business process.

By enabling the realization of smart production, cyber-physical systems will not only enable Europe to compete in a market driven by increasing cost-pressure, for example by increased resources efficiency, but also bring back off-shored production by offering flexible production with high market responsiveness and individualized products, as well as position Europe as a leader in exporting these production technologies in other markets. However, to enable the implementation of such systems, the necessary technological prerequisites as well as eco-systems and value-networks – under specific inclusion of small and medium enterprises – must be provided.

3.5. Smart Cities

The European Union has a significant number of global cities and contains 13 of the 60 cities that compose the 2008 Global Cities Index. Already more than three quarters of Europe's population live in urban regions, with still-increasing tendency, thus posing substantial challenges concerning the management of these regions – including management of energy, water, waste, and transportation – but also their future development. Scientific evidence suggests that labour productivity in urban agglomerations of the size of Paris or London is on average around 20% higher than in an urban agglomeration of 50,000 inhabitants – making the successful management of large cities not only a social but also an economic goal for Europe.

With the complexity of urban infrastructure, its efficient and sustainable management becomes a huge challenge – as exemplarily illustrated by a leakage loss of more than 25% of the public water supply in several European countries – requiring support for affordable up-keeping of (critical) infrastructure – ranging from the water pipe system to roads and bridges – and *reducing the operation and maintenance costs* while ensuring its availability. City management also plays a decisive role in ensuring the well-being of the urban population – including the daily management of air pollution as well as the incidence management in emergency cases – which in turn also impacts its productivity.

Finally, with urban areas being growing and changing structures that require massive, long-term investments, the *provision of data for authoritative strategic planning* must be supported.

The necessary solutions and services to implement such scenarios of smart cities can be provided by cyber-physical systems. They offer the infrastructure and processes to support a large-scale collection of operational data, ranging from the use of low-cost wide-spread sensing technology – including physical stress, air quality, or traffic flow – to the support for easy uptake of information and feedback directly or indirectly provided by citizens. This data enables additional operational services, including to measure and calculate tear and wear of infrastructure, pin-pointing or even predicting problems, thus reducing the operation and maintenance cost. Such a system can indirectly influence the operation of urban areas by automatically suggesting actions like necessary maintenance tasks or even directly and automatically controlling it via actuators, like the redistribution of water flow to circumvent failures or bottlenecks. Finally, the gathered information can also be used to provide reliable data for planning the change and growth. To that end, the cyber-physical system of a smart city will also specifically interoperate with those of smart energy and smart mobility to implement these services.

Cyber-physical systems allow to implement of smart cities and help to provide solutions for a efficient and sustainable and efficient management of urban areas. While Europe currently is extending existing urban areas with cyber-physical technology to implement smart cities in contrast to Asia building them from scratch, their implementation in Europe can also open up a new competitive position in the emerging – and rather U.S. and Asia lead – market of smart cities, making Europe a solution provider in this field. However, to implement such a cyber-physical systems in Europe, especially the necessary interdisciplinary technological and engineering solutions must be provided, accompanied by a substantial public investment in a robust and secure infrastructure.

4. Cyber-Physical Systems – European Challenges

While the disruptive nature of cyber-physical systems offers substantial potential for Europe concerning its economic and societal goals, as illustrated by the five key application areas in Section 3, the realization of such systems is by no means a straightforward process, which will result naturally from advances of the enabling technologies identified in Section 2. Due to the socio-technical nature of cyber-physical systems, rather the coordination of progress in a wide range of fields is required. Therefore, the challenges for research, innovation, and advances have been categorized in six topic fields:

- **Scientific Challenges**
- **Technological Challenges**
- **Economic Challenges**
- **Education Challenges**
- **Legal Challenges**
- **Societal Challenges**

For all these topic fields, the most important ones from the challenges identified using the scenarios of the five key application areas have been selected. Special attention has been given to challenges common to all key application areas. Challenges were prioritized based on their European focus and strategic character. An more comprehensive collection can be found in the *CyPhERS* deliverables.

As the challenges considered here directly *focus on overcoming barriers to the realization of cyber-physical systems*, more lateral challenges potentially affecting other societal goals – like the environmental sustainability of installing such systems or the social sustainability of changing labour relations – are not addressed.

4.1. Scientific Challenges: Multi-Paradigm

Europe has a well-established, pronounced scientific landscape covering many key fields of cyber-physical systems. However, these systems by nature are cross-domain and cross-discipline, involving aspects from biochemistry and mechanics via microtechnology and informatics to economics and social sciences. All of these domains and disciplines come with their own established paradigms of ontologies, foundational theories, as well as modeling approaches. Since, however, cyber-physical systems simultaneously touch these fields, a *scientific approach integrating these multiple paradigms at the required breadth and depth* is essential.

Challenge ‘Multi-Disciplinarity‘: To understand the functionalities and services provided by cyber-physical systems, the chain of processes along all the involved disciplines has to be considered. However, with few exceptions – for instance systems engineering – scientific research is mainly organized according to disciplinary schemata linking few, and generally neighboring fields – for instance mechatronics or business informatics – leading to scientific silos. The *resulting scientific landscape lacks the necessary instruments to facilitate multidisciplinary collaboration* concerning methodical aspects – like common ontologies – as well as organizational ones – like joint funding schemes – thus complicating cross-fertilization.

Challenge ‘Socio-Technical Character‘: As cyber-physical systems address both physical and organizational processes, the provided series of such systems are performed in a close interaction with its human users and operators. However, while research in the field of human-machine interaction has increased, the *systematic treatment of socio-technical aspects is not yet sufficiently advanced, most specifically the explicit consideration of the capabilities and limitations as well as the active management of the intensions and expectations of human users by those systems*.

Challenge ‘Foundational Theories‘: To adequately describe and reason about the cross-domain and cross-discipline aspects of cyber-physical systems, corresponding foundational theories must be provided, allowing to address these aspects, including the physical, technical, organizational, and social processes. Currently, those theories only exist in various states of maturity, depending on the addressed domain. However, more critically, these *individual theories are not combined in a common integrating systems theory*, thus lacking the necessary link between these theories and thus complicating reasoning across process-chains of such systems.

Challenge ‘Multi-Domain Modeling‘: Besides an integrating systems theory, there is *no established body of knowledge on how to adequately model all the relevant aspects of cyber-physical systems* – especially with respect to useful combinations of those aspects and the required level of abstraction – to effectively reason about its physical, technical, or organizational properties. Specifically, methodical guidelines are missing how to use suitable abstractions of (parts of) a cyber-physical systems at varying level of detail to enable the engineering of those systems with a sufficient level of confidence concerning the quality of the implemented systems.

4.2. Technological Challenges: Complexity

Europe has a long-standing tradition of engineering complex systems, providing excelling in the provision of high-quality technology. However, as discussed in Section 2.2, the realization of cyber-physical systems challenges engineering technologies with a new level of complexity – this new level of complexity is not only caused by the size and heterogeneity of those systems including cross-technology and cross-organization aspects, but also issues like self-configuration and self-optimization as well as life-update and life-extension. However, *current engineering methods and technologies are not yet read to scale to this level of complexity, to deal with unintended and undesirable emergent effects* resulting from the orchestration of the complex behavior in those systems.

Challenge ‘Interoperability‘: The large-scale, long-life character of cyber-physical systems requires the capability to integrate components from different suppliers, and especially to integrate them with legacy parts to address the continuos update of such systems. This form of integration requires a degree of *interoperability in a wide range of aspects, including communication protocols, interpretation of data, use of ontologies, or complex cooperative behavior exceeding the standards of current technology*. This interoperability is not only *required for technologies like platforms, infrastructures, and frameworks but also for methods and tools* used to realize cyber-physical systems.

Challenge ‘Autonomy‘: Cyber-physical systems are self-controlling or even self-adapting and self-optimizing systems, leading to increasing levels of highly automated or even autonomous behavior in the components of those systems, as well as in their collaboration. However, *the state of the involved technologies – to enable the implementation of such systems, but also to predict their complex, evolving behavior to exclude emergence of unintended situations – has not yet reached the maturity needed* to ensure the required trustworthiness of cyber-physical systems.

Challenge 'Privacy': Cyber-physical systems generally implement cross-organization chains of services, and therefore data collected and processed along this chain becomes available to participating parties of these services. Furthermore, this data is highly sensitive, both for individuals like in healthcare, or enterprises like in manufacturing processes – making their protection from unwanted access an essential prerequisite of the general acceptance of cyber-physical systems. *Current infrastructures often demonstrate substantial deficits concerning the protection of data privacy*, and specifically concerning features like transfer, restriction, or revocation of access rights.

Challenge 'Dependability': By providing services along chains of physical, technical, and organizational processes, cyber-physical systems are exposed to faults or attacks, threatening the integrity of the provided services. However, the *necessary dependability technology to avoid propagation of those threats* along these chains – for instance the erroneous or malicious modification of power measurements in a grid leading to a shift of loads resulting in a blackout – and to support the mixing of different levels of assurance as well as specifically *the methodical integration of safety and security aspects* has not been established to the required extent.

Challenge 'Uncertainty': To operate in its environment, a cyber-physical system has to inherently deal with imprecise or incomplete information, threatening a high confidence in the adequacy of the function provided. However, while advances in the treatment of imprecise and incomplete data have been made, *a systematic approach to collect, aggregate, and apply uncertain information thus ensuring the provision of its service with a sufficient level of confidence– specifically in the interaction with its human users – has not yet been established* in the current state of technology.

4.3. Economic Challenges: Disruption

Europe's industry has a strong tradition of establishing stable value-networks involving medium and large enterprises to manufacture complex products. However, these *established networks may prove inadequate for the new business models and dynamic* *value-chains implemented by cyber-physical systems* and the flexibility of the technical and organizational processes supported by them.

Challenge 'Service vs. Product': While cyber-physical systems require substantial investments in equipment and infrastructure, at the same time they facilitate the establishment of business models focusing on the provision of a service rather than manufacturing of a product. Here, services supplied to either the end-customer – for instance the brokerage of an available autonomous electric vehicle – or to a partner in a value-chain – for instance the optimal process control of a manufacturing step in industrial automation – provided the added value to the customer. *Current business processes – including the organizational set-up of value-networks – are often more focussed on the traditional, product-oriented market models*.

Challenge 'Disruptive Dominance': In cyber-physical systems, an added value can be provided by adding organizational processes – for instance the optimized management of power facilities – to the orchestration of technical and physical processes – like the control of power production – thus creating a new marketable service. However, such a disruptive business model facilitates the *invasion of value-networks by new participants from the field of 'cyber'-infrastructure*, who then are dominating the business models of cyber-physical systems over established participants.

4.4. Education Challenges: Competence

Europe's investment in education and training ensures a well-educated and highly specialized workforce. However, stakeholders in cyber-physical systems require competences in key disciplines – specifically science, technology, engineering, and mathematics – combined with the capability of extending and applying their knowledge in an interdisciplinary and evolving field. Current *education systems endanger the transfer of the required competences to a sufficiently large group of stakeholders, including the future workforce*, to implement and evolve cyber-physical systems.

Challenge 'Knowledge Excellence': The cross-disciplinary nature of cyber-physical systems requires a wide – and growing – scope of necessary skills and knowledge, not only for the engineering workforce, but also for a broader span of stakeholders including end-users, as well as decision-markers in industry, management and public administration responsible for the realization of these systems. Furthermore, the evolution of science and technology of these systems requires a constant update of these skills and knowledge. However, *current education and training systems are often not focused on and prepared for the transfer of evolving knowledge*.

Challenge 'Balanced Education': The still evolving body of science of cyber-physical systems requires a sufficient breath of knowledge in the key disciplines across the physical, technical, and organizational process chains combined with the necessary depth in the area of specialization. Furthermore, because of this evolutionary nature, also the set of of necessary skills including the pragmatic competences or best practices identified in industrial application, must be integrated into this body of knowledge. However, *current educational systems often lack the necessary balance between theory and practice, supporting a cross-fertilization between academia and industry in both directions*.

Challenge 'Future Workforce': The complex nature of of cyber-physical systems requires a highly skilled and knowledgable workforce capable of building, operating, maintaining, and extending those systems. However, already now *the availability of personell with such set of skills and expertise is already considered as being too low, with only limited possibility of additional mobilization within or outside Europe* without additional actions taken.

4.5. Legal Challenges: Innovation Barriers

Europe has a well-established culture of proactively setting up legal frameworks to balance and protect individual interests. The socio-technical nature of cyber-physical systems mandate such framework to regulate the implementation and use of those systems. However *their economically and societally disruptive nature renders existing – and especially inhomogeneous – regulations in part inadequate for their application to cyber-physical systems*, potentially turing them into innovation barriers.

Challenge 'Regulatory Environment': Due to the adverse effects of unintended functionality of cyber-physical systems, legal measures – including the application of established regulations from affected domains like medical devices or road vehicles – have to be taken. However, *unclear interpretations – for instance the delegation or sharing* *of liability – or restrictive application – for instance the exclusion of autonomous behavior – of these regulations may hinder innovative solutions* and advances of the state of technology by significantly increasing the necessary investments.

Challenge 'Certification': To implement cyber-physical systems with regulatory frameworks, certification approaches are needed to ensure the necessary dependability in the functional integrity of those systems. However, *current techniques and tools for certification are not immediately applicable to the requirements of those systems*, lacking – for instance – the capability to efficiently scale to the requires size or to allow the runtime change of evolving systems.

Challenge 'Harmonization': As the chains of technical and organization processes coordinated by cyber-physical systems range across organizations or domains, different regulations – for instance concerning the protection of data, dependability of service provision, or liability – may apply due to differences between national laws or domain-specific standards. However, such *an inhomogeneous fragmentation of regulations leads to uncertain – economic and legal – risks*, posing a substantial innovation barrier.

4.6. Societal Challenges: Change-Aversion

Europe has set itself ambitious societal goals concerning sustainable growth, and cyber-physical systems can substantially contribute to the achievement of these goals. However, *the necessary steps as well as resulting consequences of implementing these systems affect a wide range of often risk-averse stakeholders from the public, industry, and politics, and require a clear and deliberate commitment*.

Challenge 'Public Awareness': The socio-technical nature of cyber-physical systems – reflected in the collaboration between these systems and its human users – requires a public understanding of the possibilities and the limitations of these systems, and – consequently – of the responsibilities of the users concerning evolving risks and threats to safety or security. Currently, *the general public is not sufficiently aware of consequences of installing those systems*, including ethical and derived legal aspects to ensure a positive reception of these technologies.

Challenge 'Public Support': Since the engineering of cyber-physical systems requires the use of technologies that, in part, are not yet available or mature and can only be improved by the experiences gathered from implementing those systems, publicly acceptable risks have to be taken for their evolution to stimulate and promote innovations in that field. Without *explicit support for taking agreed-upon risks from public, industry, and politics, materialization of unexpected risks may lead to a rejection of these innovations*.

5. Recommendations for Action

Chapter 4 has identified a set of research and innovation challenges to be essential for Europe's competitiveness in the field of cyber-physical systems. To provide the necessary prerequisites for addressing these challenges, *strategic fields for actions* have been selected, and elaborated with *suggestions for concrete actions in* these fields.

Depending on the time needed for set-up (from commitment until implementation of action – for instance the definition of a funding program, or the initiation of a standard or regulation) and impact (from implementation until first materialization of effect – for example the dissemination of a funded technology, or the passing of a standard or regulation), actions recommended are classified as

Short-term (S): Little set-up time and impact time up to two years

Mid-term (M): Set-up time of up to two years and impact time of up to three years

Long-term (L): Set-up times of up to three years and impact times of up to five years

The classification does not represent a prioritization with respect to importance or urgency – in all cases the *'window-of-opportunity' of implementing these actions to strengthen the competitiveness of Europe is considered to be limited to the near future* given the competition from Asia and Northern America.

The recommendations address a wide range of different stakeholders in research, industry and management, regulations and politics, as well as education. As a consequence, the implementation of these recommendations require the cooperation of many institutions and bodies on the national and European level.

As cyber-physical systems draw upon many different fields of technology, non-surprisingly there is a partial overlap of the identified challenges and recommendations with strategic roadmaps from these domains, most specifically those targeting complex embedded and networked systems like the SRIA of ICT Industries [1], the Major Challenges of ARTEMIS [2] and the ITEA/ARTEMIS High-Level Vision [3]. However, unlike those, here a broader look is taken on the involved disciplines and technologies, leading to a broader set of challenges and recommended actions, specifically concerning interdisciplinarity.

Furthermore, as cyber-physical systems are internationally considered of strategic importance, there is also a partial overlap concerning these challenges and recommendation with other national agendas, most specifically the recommendation from the US CPS Summit report [4], and the German agendaCPS [5]. However, the specific European focus leads to some divergent findings, with respect to the former for example concerning the challenges from smart production and smart cities, or concerning the recommendations on education, regulation, business models, and societal issues; with respect to the later including European-level challenges like transport and cities, as well as providing recommendations specific to transnational European actions.

5.1. Strengthen Key Research

Due to the cross-technology character of cyber-physical systems, their advancement depends on a large spectrum of enabling technologies, and the necessary research required to achieve innovations in the respective fields. This implies to ‘strengthen existing strengths’ – like the excellent research in many technological fields relevant for cyber-physical systems – but also to ‘overcome existing weaknesses’ – like the missing cross-fertilization between the engineering sciences and the humanities – as each contributing field in return also is a limiting factor. Consequently, on a European level the identified *research and innovation challenges must be addressed in integrated programs, including and balancing both established and evolving fields*, complementing and linking national programs.

Recommendation ‘Intensify Enabling Sciences’ (M): Since cyber-physical build on scientific results and technologies found in the different fields of complex and large-scale technical and organizational systems in general, and in the field of ‘self-X’ and ‘live-X’ systems in particular, the innovations in those fields are also boosters or ’technology push’-factors for them. Those fields specifically include

- the physical level, specifically micro system technology for sensor and actors,
- the information and communication level, specifically highly dependable and efficient technologies for processing and wirelessly communicating information,
- the data and knowledge level, specifically robust technologies for fusing, mining, learning, and predicting
- the system level, specifically scalable technologies for distributed configuration, control, and adaption

Therefore, the *research and innovation activities in these core fields should be intensified, with specific requirements from their integration in cyber-physical systems added as 'technology pull'-factors for these fields*.

Recommendation 'Address Human-Machine Interaction' (M): Cyber-physical systems closely interact with a wide range of human users – including specially educated personell like traffic operators as well as common end-users like traffic participants – to coordinate and control in an often highly automated fashion technical and organizational processes. To enable an acceptable interaction, these systems therefore need to be aware of the capabilities and limitations as well as intentions and expectations of their human users. Therefore, to address the issue of human-machine interaction, *the integration of behavioral science and technical disciplines – ranging from multi-modal ergonomics to modeling human behavior – must be a key field* of research in the engineering of cyber-physical systems.

Recommendation 'Foster Cross-Disciplinary Research' (M): To provide system-level services in cyber-physical systems, functionalities rooted in several different disciplines along the value-chain for this services have to integrated and orchestrated, ranging from micro system technology via software and systems engineering to macroeconomics. Each of these disciplines generally apply their own languages, models, and methodologies. To provide a framework allowing these disciplines to cooperate, *research programs should specifically address the the integration of the participating disciplines*, and specifically the homogenization and integration of ontologies, domain models and languages. Furthermore, flanking cooperation and support activities fostering the exchange and disseminating the integrated ontologies, models, and languages should be implemented.

5.2. Accelerate Maturation of Technologies

The adoption of key technologies of cyber-physical systems will depend on their maturity or technology readiness level, requiring their application in real-world and large-scale installations. As cyber-physical systems are of cross-domain/discipline/technology-nature, many *technologies matured within one domain or discipline can be directly used or adapted for different kinds of those systems*, thus boosting their realization in general. Furthermore, the new level of complexity introduced by cyber-physical systems prohibits a detailed a-priori identification of most suitable scientific and engineering technologies required to realize those systems, *mandating an experimental and incremental approach* to complement the anticipated roadmap. Both aspects suggest to *strengthen Europe's economic position using public-private partnerships an instrument for large-scale implementation of specific cyber-physical systems*, like a European Smart Grid or Smart Traffic System. This will not only result in the development of dedicated exportable solutions, but also improve the general competitiveness in different fields of application.

Recommendation 'Support Maturation Initiatives' (S): The complexity of cyber-physical systems requires the development of technologies – including platforms and frameworks as well as tools – that are convincingly proven to be mature in contexts that, without already forming a large-scale cyber-physical system, demonstrate the requirements of a relevant technological sub-field. To push the maturation of technologies to Technology Readiness Levels of 6 or 7, and to demonstrate their practical application, *public-private partnerships should be installed to jointly set up 'technology demonstrators' or 'show cases' accessible to a wider audience*.

Recommendation 'Promote Available Infrastructure' (M): In cyber-physical systems, information and communication technology is the central backbone for the large-scale coordination of technical and organizational processes. Consequently, the availability of performant information and communication infrastructure in the urban as well as rural regions is a core limiting factor for their implementation. Therefore, especially to ensure the large-scale installation of those systems required to address societal-scale challenges, *public-private partnerships are needed to ensure the availability and affordability of dependable and trustworthy information and communication infrastructure*.

Recommendation 'Coordinate Installation of Key Systems' (L): While cyber-physical systems, like smart energy or smart transport systems, are able to address Europe's key societal challenges, their nature of large-scale systems transcending national boundaries generally require substantial investment in public and private infrastructure, like communicating and cooperating stations and sub-stations in the electric transmission and distribution grid, or road-side installations. Therefore, *trans-European large-scale public-private partnerships should be formed to implement those systems in key fields of societal importance*, to address these challenges and also position Europe as a key player in cyber-physical systems.

5.3. Facilitate Interoperability of Technology

Cyber-physical systems provide their system-level functionality by the collaboration and orchestration of services both vertically – across a stack of disciplines from microsystems via middleware platforms to cloud solutions – as well as horizontally – across a range of domains from mobility via assisted living to energy management. To avoid innovation-barriers and enable new value-networks, *public incentives and support actions are needed facilitating the cross-domain as well as the cross-discipline interoperability* of these technologies, specifically focusing trans-European solutions.

Recommendation 'Provide Reference Platforms' (M): To support the integration of services in cyber-physical systems, defined levels in the stack of disciplines have to be provided. Here, reference platforms with a Technology Readiness Level of 4 or 5 – like a reference controller board supporting safe process control as well as secure communication, or a reference implementation of a service-oriented architecture supporting the operating, monitoring, and reconfiguration of real-time processes – provide the means to support innovation by building upon them as well as facilitate maturation by providing a benchmark. Therefore, *research activities should target the provision of medium-TRL reference platforms along the stack of disciplines with a potential to be applied in several domains*, enabling the commercial exploitation and industrial application.

Recommendation 'Homogenize Interoperability Standards' (M): As cyber-physical systems provide system-level functionality via the collaborative – and often cross-component or cross-organizational – coordination of processes, the necessary technical and regulatory prerequisite for such collaboration must be provided, without over-constraining potential applications. While standardized functionality is often provided between at least the lower layers of vertical stack within a domain ecosystem, the – specifically higher – layers are generally vendor-, domain-, or market-specific silos. Therefore, to enable new value-networks, *interoperability standards facilitating the cooperation between components from different domains and organizations must be established and homogenized*, ranging from services providing reflective services including status information of single components up high-level functionalities of sub-systems including the emergency shut-down protocol of a subnet in a smart grid.

Recommendation 'Define System-Level Design Methodologies' (L): Many innovative added-value services provided by cyber-physical systems results from the crosssubsystem-orchestration of more basic services implementing chains of physical, technical, and organizational processes. Therefore, in the design and realization of such services a large spectrum aspects – including those of application domains, of the used platform technologies, and involved organizations – must be considered. However, current methodologies mainly address the design flow only concerning a sub-spectrum and generally limited to an integrated software/hardware unit, not supporting cross-component process chains. To enable the efficient realization of cyber-physical systems, therefore *design methodologies including the corresponding tool support must be defined that facilitate the modular development of system-level services implementing causal chains of physical, technical, and organizational processes*.

5.4. Support Open Innovation

Cyber-physical systems provide the capability to realize value-added services based on more basic services already controlling technical and organizational processes, and thus offer the potential of disruptive innovations. While the basic services in general rely on and are provided by established, cost-intensive, and domain-specific infrastructures – like physical equipment for the electric grid, automation, and transport, or IT solutions for market trading, resource planning, telematics – innovative services can be realized by orchestrating these more basic ones across those domains, bringing a substantial additional value for the end user. As these innovations are generally cross-domain, and often targeted by small or medium enterprises, they are rooted in easy access to those services in these domains, *making the openness of these domains the limiting factor of innovation*.

Recommendation 'Provide Open Standards' (S): European funding programs related to Cyber-Physical Systems should specifically *promote the definition, provision, and evolution of open – both pre-normative and normative – standards,* making this a funding criterion, specifically for Coordination and Support Actions. For normative standards, specifically the cooperation with European non-profit Standard Organizations like ETSI should be addressed supporting easy access to standards.

Recommendation 'Promote Open Source and Open License' (M): As cyber-physical systems support the realization of value-added services via the orchestration and extension of more basic services, access to interoperability platforms supporting such orchestrations and extensions are a key requisite to fast innovation and are of specific importance for small and medium enterprises. European funding programs related to Cyber-Physical Systems, specifically Innovation and Research Actions, should specifically *promote the provision of open-source or open/free license results* covering general or infrastructure functionality of cyber-physical systems and not infringing competition-relevant outcomes. Furthermore, the sustainability and open availability of these results, as through the establishment of an open-source community or a dedicated (profit-oriented) organization providing additional services, should be included in those actions.

Recommendation 'Increase Open Data' (S): In order to optimize technical and social processes, cyber-physical systems make intensive use of data for coordination and cooperation purposes. To accelerate the implementation of innovative governing schemes – especially key challenges in the public domain of well-being, transport, or energy – the availability of open data should be increased by supporting activities *facilitating the access to open data* in European funding programs related to Cyber-Physical Systems, for example by providing funding for the provision of interfaces to data sources. Here, specifically the *availability of live data* should be supported.

5.5. Anticipate New Business Models

Cyber-physical systems offer the potential of enabling new value-added services – like the trading of small private energy-volumes on a bulk energy market – by means of new organizational processes – like the coordinated aggregation of available small volumes to tradable bulk volumes – relying on services of existing infrastructure services – like managed private energy installations – and requiring only system-level knowledge. Such end-user services will become as important 'products' in the context of cyber-physical systems as their tangible assets, however requiring the *implementation of new business models ranging from the necessary regulatory frameworks to accessible basic business services* like platforms providing billing or service brokerage.

Recommendation 'Activate Networks for Open Innovation' (L): Cyber-physical systems allows the provision of value-added functionality for the end-user by orchestration and extension of existing services and exploiting system-level knowledge. This will create an ecosystem of value-networks, where innovative services provide economic benefits not only for the end-user and the innovator, but also for the providers of the existing services, including extension of client base, increased use, better utilization, or even new use-cases. However, to realize these value-networks by means of open innovation, *forums should be provided facilitating the initialization of contacts between innovators trying to enter the service ecosystem of a cyber-physical system and existing providers of services*, including Idea Challenges or Pitching Competitions.

Recommendation 'Facilitate Business Service Infrastructure' (M): In cyber-physical systems end-user services will be provided via the collaboration of more elementary services, potentially provided by a 'virtual enterprise' of organizations formed temporarily for the duration of this service from a pool of competing service suppliers, like in case of a 'Lot-Size One' production in smart production. In contrast to 'classical' business services, the fusion of technical and organizational processes requires the inclusion of service-level agreements covering aspects like tolerance of measurements or precision of actions to traditional ones like availability and cost of a service. To enable the establishment, execution, and finalization of such services, the *set-up of the necessary technological and regulatory service infrastructure for providing highly dependable services must be supported*, facilitating the brokerage of suitable providers as well as the establishment of – potentially temporary – contracts between the involved partners including end-users and service-providers and also handling the billing for these services.

Recommendation 'Provide Clear Liability Frameworks' (L): Malfunctions of services offered by a cypher-physical system can result in substantial economic or in case of liability, presenting a substantial risk for any organization participating in the value-chain of a such a service offered, which can be an existential threat especially for small and medium enterprises. This becomes especially relevant in the provision of services through orchestration of sub-services from different supplier organizations collaborating temporarily to provide this service. To avoid that this threat becomes an entry barrier for innovative enterprises, suitable *liability regulation frameworks and corresponding supporting technologies must be put into place that help to clearly, explicitly, and non-refutably identify – both continued but also temporary – acceptance and delegation of responsibilities for services* provided.

5.6. Foster Enabling Education and Training

The engineering of cyber-physical systems – due to their cross-discipline and cross-technology aspects – require cross-cutting knowledge of these aspects, as well as skill to cooperate and communicate in these heterogeneous worlds. Therefore, the establishment of education and training programs and methods is needed that *enable the current and future workforce to acquire these skills and knowledge, but also are prepared to continuously update them*, accompanied by the recognition of their importance for Europe in the – often more research-focused – academic institutions.

Recommendation 'Stimulate Collaboration in Education' (M): The innovative nature of cyber-physical systems – not only with respect to each of the technologies involved, but also specifically with respect to the engineering-challenge of systems of that scale and heterogeneity – requires advances in both theoretical foundation and pragmatic engineering. Besides the foundational scientific knowledge, engineers require practical engineering knowledge including state-of-art technologies and tools and established best practices. Incentives for academic and industry stakeholder should be provided to *stimulate the cross-fertilization of pragmatic and theoretic knowledge* by including corresponding courses in the academic curricula.

Recommendation 'Promote Life-Long Learning' (M): Due to the disruptive nature of cyber-physical systems and the fast innovation cycles in the information and communication technology, the half-life of state-of-the-art knowledge in several involved disciplines and technologies is extremely low. To ensure the necessary re-qualification, an academic-industrial alliance should *engage established engineers in life-long learning* through alumni-programs or training courses offered by academic and industrial educational institutions and supported by industry.

Recommendation 'Support T-Shaped Education' (L): Many innovative services of cyber-physical systems are implemented via cross-domain and cross-displine value-chains. Therefore, education must avoid silos of disciplines to create engineers capable of building cyber-physical systems. Study programs and training courses should be improved and revised to not only provide the necessary depth in a specific discipline, but also the *necessary breadth in cross-cutting knowledge, and combined with core communication and cooperation skills*.

Recommendation 'Provide Educational Platforms' (M): Due to their rich infrastructure and set of basic services, future cyber-physical systems can accelerate the construction of innovative added-value services. However, to be ready for this kind of service-engineering, engineers must experience practical, cross-discipline technologies to familiarize themselves with the necessary – often more technical and practical than theoretical – capabilities to enable these innovations. There, the *establishment of private-public cooperations for the operation of educational platforms must be supported, facilitating experimentation with new technologies and interdisciplinary learning*, including ’open labs’, ’hacker spaces’ and ’maker spaces’.

5.7. Raise Societal Awareness

Due to its technical and social components, the pervasiveness of cyber-physical systems in everyday life – like autonomous vehicles in self-coordinating traffic, home installations in a self-balancing grid, or cooperative machines in individualized production processes – will lead to more disruptive changes than its individual enabling technologies including the use of embedded systems and the internet. To avoid a technology-illiteracy *a broad understanding and consensus of the potentials – and threats – of these systems is required* to ensure the adoption of cyber-physical systems.

Recommendation ‘Enable Decision Makers’ (S): Decision makers – most specifically in politics and management – must be *able to understand the impact of cyber-physical systems on society and markets* to be capable of making informed decisions, to ensure the sustainable competitiveness of Europe. Coordinated actions between European academies of engineering and science, European societies of engineers, management organizations and political parties fostering the transfer for knowledge should be initiated.

Recommendation ‘Stimulate Public Discussion’ (M): Societal acceptance of new technologies is a prerequisite to obtain the public support for necessary measures including the necessary investment in public or private infrastructures, change of education systems, and adaptions of laws and regulations. To avoid resentments about the introduction of cyber-physical systems, to ensure an understanding of the necessary responsibilities of their users in the resulting socio-technical systems, and to avoid a ‘digital divide’ , *dedicated dissemination activities addressing the wide public outside the scientific community* should be established.

Recommendation ‘Achieve Societal Consensus’ (L): As any socio-technical system inherently poses risks of material and financial loss, also for cyber-physical systems an acceptable balance between the economy and efficiency of eliminating these risks must be found. As the public acceptance of residual risks forms the basis of legal regulations affecting the liability of suppliers and operators of cyber-physical systems, the sciences of engineering and humanities must initiate and moderate a process for *defining the publicly acceptable responsibilities of the suppliers and users of technology* to form the foundation for corresponding standards and regulations.

5.8. Ensure Trustworithness

The pervasiveness of cyber-physical systems implies that the malfunction or misuse of them can have as dramatic negative effects on the society and economy, as the correct function and use has positive ones. Therefore, measures ranging from updating existing installations up to establishing new regulations for safety and security of cyber-physical systems must be taken, to *ensure that the implemented systems are sufficiently trustworthy in application*.

Recommendation 'Harden Infrastructure' (M): Cyber-physical system make use of open information and communication technology – especially the global Internet – to coordinate the control of critical technical and organizational processes, including the electric grid with its switches and power stations as well as the marketplaces for energy trading, or telematic systems with their road-side installations as well as traffic control centers. Joint public and private investments are needed to *assess and improve the security of both public and private information and communication technology* to protect these critical infrastructures from cyber-attacks.

Recommendation 'Protect Data Ownership' (M): By means of their deep embedding in socio-technical environments, cyber-physical systems acquire a substantial amount of sensitive data, ranging from profiling of individual traffic participants or patients to closely monitoring sensitive production processes. To avoid misuse of this data and consequently hinder the adoption of cyber-physical systems, the *establishment of legal regulations clarifying the treatment of data ownership* including granting and revoking access, as well as *corresponding technical implementations* are necessary.

Recommendation 'Adapt Dependability Regulations' (L): Cyber-physical systems – due to their characteristics like large-scale, cross-organization, and multi-user – rather follow maintenance-and-update schemes common in information and communication technology – like continuous delivery – rather than the classical design-implement-certify-commision-decomission cycle commonly found – and mandated by current regulations – in the domain of dependable systems. Furthermore, characteristics like self-control/adaption/optimization contradict current regulations focusing on human control with little automation. To ensure that cyber-physical systems can be operated, maintained, and extended, the *provision of suitable mechanisms for highly automated operations as well as the live update of dependable systems* must be addressed in upcoming research programs and the relevant standards and regulations must be adapted accordingly.

A. Project Description

A.1. Project Implementation

The *CyPhERS* (Cyber-Physical European Roadmap and Strategy) project was implemented a 20-month Support Action co-funded by the European Commission with the objective to develop a European strategic research and innovation agenda for cyber-physical systems (CPS) to ensure Europe's competitiveness in this emerging field.

Members of the *CyPhERS* consortium were

- fortiss GmbH, Munich, Germany (Co-ordinator)
- KTH Royal Institute of Technology, Stockholm, Sweden
- Université Joseph Fourier, Grenoble, France
- University of Trento, Italy
- The University of York, UK
- Siemens AG, Munich, Germany (affiliated partner)

The project systematically surveyed, analyzed, and evaluated the economic, technical, scientific, and societal significance of Cyber-Physical Systems for Europe by dedicated work packages

- providing a systematic classification of the CPS domain (WP2);
- modelling of the markets and their players relevant for CPS (WP3);
- developing a structured analysis and assessment of core technologies and the current state in science and technology related to CPS (WP4);
- analysing the future technological, economic and social implications of CPS, and assessing challenges, bottlenecks and risks for research and development in CPS (WP5).

In the course of the project, three *Expert Workshops* were held to collect input and feedback of industrial and academic participants active in the field of cyber-physical systems:

- *CyPhERS* 1st Experts Workshop, Munich, October 14-15, 2013.
- CPS20: CPS 20 years from now - visions and challenges. *CyPhERS* 2nd Experts Workshop, collected with CPSWeek 2014, Berlin, Germany, April 14 2014.
- *CyPhERS* 3rd Experts Workshop, Stockholm, Sweden, September 22-24, 2014

Besides the input and feedback collected through the expert workshops, a *CyPhERSReference Commission* was installed, to ensure the soundness of the results. The members of this commission participated in dedicated reviews as well as in the Expert Workshops of the *CyPhERS* project. They moreover provided feedback on the subject addressed by the respective workshop.

Members of the Reference Commission were

- Manfred Broy, Technische Universität München
- Karl Henrik Johansson, KTH Royal Institute of Technology
- Ulf Andersson, MAQUET
- Roberto Zafalon, ST Microelectronics
- Marco Di Natale, University of Pisa
- Joseph Sifakis, Centre de Recherche Intégrative, Grenoble

A.2. Project Funding

This project was funded as a *Coordination and Support Action* of the European Commission Directorate General for Communications Networks, Content & Technology by the European Union's Seventh Framework Programme (FP/2007-2013) under Contract Number 611430

A.3. Public Deliverables

The *Research and Innovation Challenges* identified as well as the *Recommendations for Action* given in Chapters 4, 3, and 5, respectively, are based on a much more in-depth description and analysis of the characteristics of cyber-physical systems, of their market-related disruptive potential, of enabling technologies, and of their status and potential than discussed in Chapters 1, 2, and 3. The following deliverables providing the additional information leading to the results presented here can be publicly accessed via `http://cyphers.eu/project/deliverables`:

WP2 Characterization of the CPS domain

- **D2.2** Structuring of CPS Domain: Characteristics, trends, challenges and opportunities associated with CPS
- **D2.1** Characteristics, capabilities, potential applications of Cyber-Physical Systems: a preliminary analysis

WP3 Markets

- **D3.2** Market and innovation potential of CPS
- **D3.1** Structured CPS market model

WP4 Technologies

- **D4.2** CPS Technologies
- **D4.1** CPS Methods and Techniques

WP5 Status and Potential

- **D5.1** CPS: State of the Art
- **D5.2** CPS: Significance, Challenges and Opportunities

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