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Cyber-Physical European Roadmap & Strategy

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Characteristics, capabilities, potential applications of Cyber-Physical Systems: a preliminary analysis

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Executive Summary

The goal of this document is to profile the emerging research and industrial domain of Cyber-Physical Systems (CPS) and to organize a set of issues either suggested by external experts or discovered by us into a coherent framework for the potential launch of research programs. In particular, an initial definition of the CPS domain is presented based on existing surveys that were refined as a result of extended discussions with stake-holders and experts in the field.

As a basis for the systematic assessment of the domain, information has been gathered from several sources including existing surveys, and complemented by a workshop attended by stake-holders who were invited to participate to this effort. Around 30 individuals, including senior directors, managers, project managers to software engineers from the public and private sector, as well as academic experts, attended the workshop. This workshop was used as a means of elicitation and, at the same time, for validation of initial findings.

This first deliverable focuses on characterizing CPS by identifying their essential features, properties and capabilities, including understanding their inherent complexity. We discuss: technical characterisation, vision and value added, impact, trends and challenges, and economic ecosystems.

There will be a follow-on document where the insights gained during the performance of this aspect of the study will be collected and organized into a coherent framework.
1 Introduction

CyPhERS (“Cyber-Physical European Roadmap and Strategy”) is a project funded by the European Commission under the 7th Framework Programme and aims at combining and expanding Europe’s competence in embedded and mobile computing and in control of networked embedded systems. The main objective of the project is to develop a European strategic research and innovation agenda for Cyber-Physical Systems (CPS) to ensure Europe’s competitiveness in this emerging field.

To this end, CyPhERS employs an incremental approach. The starting point is a thorough characterisation and definition of the CPS domain. This will result in a solid and consolidated framework to be used as the foundation of and guidance for further investigations in the project, particularly with respect to analyzing and evaluating the societal, economic, technical, and scientific consequences of future CPS.

An essential ingredient in the CyPhERS work plan is the extensive and frequent involvement of relevant stake-holders in the CPS domain. The goal is to integrate a broad range of knowledge and views in the analyses that CyPhERS is carrying out, and to allow for expeditious feedback on, and validation of, project results. Therefore, CyPhERS has invited experts working in CPS-related fields in academia, technology transfer, and industry to join the project in a reference commission. This expert group plays an active part in eliciting the state of the art regarding CPS, and the members provide their visions concerning CPS and the potential evolution of such systems from their particular viewpoint.

The document at hand is the first deliverable of the project’s work package 2 Characterization of the CPS domain, which develops a systematic structuring of the CPS domain in order to provide the framework for further work in CyPhERS. It presents an initial framing of the CPS domain based on already existing surveys and refined by virtue of the discussions and insights obtained with the help of experts in the field. In particular, this document summarizes the results of the first European Experts Workshop, which has been organised by CyPhERS in Munich on October 14-15, 2013. This two-day event was targeted at key industrial and research representatives in the field of CPS with the goal of identifying the grand challenges posed by CPS and their associated causes and impacts.

Top-level researchers and strategists from leading companies came together and provided their vision on possible and desirable evolution of the field, and exchanged views and insights on
the state of the art in science and technology. Experts from eight countries and from the European Commission, representing a broad range of relevant CPS domains (including automation, business solutions, home appliances, innovation support [for healthcare, transportation & traffic, energy, telecommunication], internet of things, medical systems, transportation [avionics, automotive], wireless technologies), participated in the workshop. About two thirds of the participants were from academia, and one third from industry.

The workshop programme consisted in keynote presentations that highlighted both the policy aspects on the EU level and described related road-mapping experiences from Germany and Sweden, and presented insights from an industrial view to the new challenges that CPS present in certain domains. Interactive group work sessions formed the other major part of the workshop. In these sessions and at four tables arranged in a “World Café” setting\(^1\) each headlined with a specific theme, the workshop participants brainstormed and discussed topics ranging from the CPS vision and new opportunities, their added value and impact, and challenges in engineering, to acceptance issues and questions regarding economic ecosystems.

The outcomes of these discussions are summarized and presented in the subsequent sections. As the title of the document suggests, this presents an initial synthesis of the material, and will form a basis for the systematic assessment of the CPS domain. Following CyPhERS’ iterative approach, the document will be further refined and extended during the course of the work package towards the final deliverable of this work package, D2.2 *Structuring of CPS Domain.*

\(^1\)World Café is a method based on the hypothesis of a collective knowledge that is to be elicited via a structured conversational process in which groups of people discuss at several tables a topic associated with the table, and where individuals switch the table periodically and are supposed to visit all the tables.
2 Definition and characteristics

In this chapter, we begin by summarizing the history of the Cyber-Physical Systems research agenda, and provide our working definition of Cyber-Physical Systems (CPS). We then discuss the drivers that helped the evolution of conventional systems into CPS and enumerate a (non-exhaustive) list of properties that characterise these systems.

2.1 Definition

The original definition dates back approximately 8 years when a group of academics in the United States realized that embedded systems were evolving into systems where physical aspects played a fundamental role. The interaction between the intelligence provided by distributed processors that were interconnected with networks of growing complexity AND the physical world where they were immersed could not be ignored or considered of secondary importance.

The definition of the research field described by the term Cyber-Physical Systems (CPS) came from a series of discussions of Berkeley faculty (Henzinger, Lee, Sangiovanni-Vincentelli, Sastry and Tomlin) who were the PIs for the Center of Hybrid and Embedded Software Systems (CHESS) funded for five years by NSF. The actual name is due, to the best of our knowledge, to Professor Shankar Sastry. A steering group was formed in 2006 to provide CPS strategic directions for funding agencies of the United States and to the White House. The initiative yielded an Executive Summary sent to the President’s Council of Advisors on Science and Technology (PCAST). This action resulted in the introduction of CPS in the agenda of PCAST (see the 2007 PCAST report [Fed07] submitted to the National Coordination Office that highlights CPS as the “number one” Priority for Federal Investments in Networking and Information Technology) and of NSF. The group included (in alphabetical order): Helen Gill, National Science Foundation (NSF), Bruce H. Krogh, Carnegie Mellon University, Edward Lee, UC Berkeley, Insup Lee, University of Pennsylvania, Scott Midkiff, NSF, Al Mok, UT Austin, George Pappas, University of Pennsylvania, Raj Rajkumar, Carnegie Mellon University, Alberto Sangiovanni Vincentelli, UC Berkeley, Lui Raymond Sha, UIUC, Kang Shin, University of Michigan, Jack Stankovic, University of Virginia, Janos Sztipanovits, Vanderbilt University, Wayne Wolf, Georgia Institute of Technology, Taieb B. Znati, NSF. The group had participants coming from a rather diverse background: from real-time systems to control, from design methodology and tools to computer...
architecture and networking. In 2008 a letter was sent to The Honorable Bart Gordon Chairman Committee on Science and Technology (enclosed) outlining the relevance of the field for the interest of the United States. The definition used in the report was simple to make sure the message could be delivered to the policy makers with great strength: “The integration of physical systems and processes with networked computing has led to the emergence of a new generation of engineered systems: Cyber-Physical Systems (CPS). Such systems use computations and communication deeply embedded in and interacting with physical processes to add new capabilities to physical systems. These CPS range from minuscule (pace makers) to large-scale (the national power-grid).”

In 2010, acatech (German National Academy of Science and Engineering) started the development of an Integrated Research Agenda for Cyber-Physical Systems that was published in 2011 [GBC+12]. The definition provided there is more detailed and encompassing compared to the US counterpart (see [GBC+12]): “A Cyber-Physical System (CPS) is a system with embedded software (as part of devices, buildings, means of transport, transport routes, production systems, medical processes, logistic processes, coordination processes and management processes), which:

- directly records physical data using sensors and affect physical processes using actuators;
- evaluates and saves recorded data, and actively or reactively interacts both with the physical and digital world;
- is connected with other CPS and in global networks via digital communication facilities (wireless and/or wired, local and/or global);
- uses globally available data and services;
- has a series of dedicated, multi-modal human-machine interfaces.”

The above list of systems is not exhaustive, of course. One could add further application domains such as manufacturing, entertainment, consumer appliances, chemical processes, and civil infrastructure. Also the notion of “directly” recording maybe restrictive: indeed, a CPS should have the means, be these direct or indirect, not necessarily to record but to retrieve a sensed information, and to use one or more actuators to change the state of a controlled device. But adding to and refining further this definition may result in an overly detailed list of features and applications. In our opinion, a simple and yet general definition could be more effective to convey to the public and to the policy makers what CPS are all about. Consequently, we offer:

**Working Definition.** Cyber-Physical System A Cyber-Physical System (CPS) consists of computation, communication and control components tightly combined with physical processes of different nature, e.g., mechanical, electrical, and chemical.
Typically a CPS is defined and understood (evaluated) in a social and organisational context. Among the technical problems faced when designing and analyzing CPS, the core one is managing dynamics, time, and concurrency in networked, distributed computational and physical systems. Moreover and as is the case for systems of systems, independent CPS can dynamically interoperate in order to achieve a certain higher goal.

### 2.2 Evolution to Cyber-Physical Systems

There are two complementary though opposed forces that drive the evolution of technologies. On the one hand, new inventions are pushed through research and development, production and sales onto the market. On the other hand, innovations are developed in response to an identified market need. These two interacting forces in the case of CPS are presented in the next two sections. Afterwards, some sample CPS are illustrated.

#### 2.2.1 From networks and embedded systems to CPS

As already argued, CPS can be considered as an evolution of the research and the application to industry of embedded systems. A number of concepts emerged as control, communication and computation underwent a technology expansion that had not been seen before in part due to the rapid evolution of integrated circuit technology and design.

Embedded systems could not be confined to a single, albeit complex, device such as an engine controller, a braking device or a robotic arm. Cars, airplanes, trains and other transportation systems became increasingly a network of embedded systems that needed to communicate to perform their tasks. The advent of standards such as AUTOSAR [GbR06] decoupled the equation one device = one function. Functions could be shared among the networked components and a single component could host a number of functions. This evolution required designers to think of distributed systems where allocating functions and coordinating them became crucial.

This evolution yielded a research agenda with related funding about networked embedded systems where networking was not an afterthought but became integral part of the design process. Proprietary closed systems as embedded systems and devices increasingly become open; they are more networked and dynamically linked to other systems, provide more flexibility and more interactivity, and seamlessly connect the physical systems of actuator and sensor technology with virtual software systems.

Parallel to this evolution, a large class of sensors came to the market using MEMS technology that enabled system designers to base their artifacts on the measurements of a number of physical parameters that earlier were only estimated. In addition, wireless technology evolved from cellular phone to mobile internet and eventually to wireless sensor networks. The potential
of wireless technology is still to be fully deployed but it has already changed the technology roadmap of many companies. The important design parameters in wireless sensor networks are accuracy and reliability coupled with low cost and low energy consumption. This need resulted in the emergence of novel communication protocols such as Bluetooth and Zigbee.

The combination of networked embedded systems and wireless sensor networks has certainly characterized the research and industrial agenda for the past 10 years. The cross pollination of different industrial domains increased significantly: Ethernet technology typical of the computing world is making a foray into industrial automation and the transportation industry to bring performance to a level that allows more data to be exchanged faster. Smart phones and other entertainment devices are now an integral part of an automobile.

However, the complexity of designing these systems grew considerably since now the architectural choices increased exponentially and the functions that could be implemented grew to a point that bringing a working reliable artifact to the market became a real challenge. Very recent examples pointed to this criticality (e.g., in transportation, the problems arisen in the design of the Boeing 787 and in the infamous Toyota recall). In particular, unwanted unforeseen interactions among components are today a major concern.

Yet these problems have not stopped the continuous technical evolution of the field and its relevance for the world-wide industry. Indeed once wireless communication, sensing, computing and control are widely available at low cost, devices could be interconnected together without (or with limited) human interaction. Internet of Things (IoS) was born as a concept (albeit, at this time, it is still very much in its infancy). In addition, the Internet of Things, in some circles, links uniquely identifiable things to their virtual representations in the Internet containing or linking to additional information on their identity, status, location or any other business, social or privately relevant information with a financial or non-financial pay-off. This way, the Internet becomes real-world aware.

Coordination and collaboration among systems was of particular interest in the defense domain where the agenda for Systems of Systems (SoS) was of importance for battlefield management as well as fleet coordination. Now this concept has been exported an entire new world of applications including airport management, water distribution systems and the smart grid.

As sensing and control technology grew stronger, the interaction between the physical systems that host the computing and communication components could not be ignored or minimized. In particular, mechanical devices that were actuated with man-activated hydraulic systems (for example, airplanes parts such as ailerons and flaps as well as braking systems and steering) evolved into a totally new architecture where electric motors were controlled automatically by electronic subsystems. This evolution was called electrification. In these domains, it became increasingly clear that a co-design approach was the only way to optimize the design and make it more reliable. This tight interaction was also observed in robotics and in health devices. We
could even envision a direct interaction between the brain and the environment! These systems so characterized were the embryos of \textit{Cyber-Physical Systems}. If indeed we regard (as we should) smart grids where system physics plays a fundamental role in concert with complex control and economic factors, they become as discussed in the next section an epitome of CPS. These complex, country-wide or even region-wide, systems are the natural future for CPS. Note that these concepts are not mutually exclusive: some are complementary with some overlap, some are almost inclusive of others. Indeed there has been a certain amount of confusion and useless turf battles when it comes to deciding which research to fund and what is more important for an industrial strategy. Given the particular characteristics of CPS whereby physics, computer science, communication, control and electronics are intertwined, it makes sense to consider them as the most general field among the ones we identified above. Fig. 2.1 is an attempt at showing how CPS encompass other fields and concepts.

![Figure 2.1: Dimensions of evolution (source: [Bro13])](image)

However, we need to pay attention to the temptation of making CPS the catch-all concept and in doing so, losing focus. The debate among ourselves and the experts is indeed to define the boundaries of the field.
### 2.2.2 Market opportunities

Of course, innovation in technology and the consequent technology push can only take place in close interplay with a corresponding demand pull. Only products and technologies that have been adapted to demand meet the acceptance of the market and end users because technological innovations are not only supply-side driven. Rather, demand-pull is quite influential: the more intense the demand, the more creative groups and individuals are drawn to work on unsolved problems; see [JS07].

The evolutions in the consumer market have been so fast that customers expect now new and improved features every few months in products they buy. In addition, transportation and healthcare markets are offering novel services and devices that improve user experience using extensively electronics and software. The extent to which customers demand features that were simply unthinkable a few years ago is frightening because of the implications on safety, security, privacy, cost and time-to-market. The market pull demands a new way of architecting and designing products and services that require holistic approaches and increased analysis and verification. The CPS agenda is indeed a fundamental part of the industrial and political campaigns that will characterize our immediate future.

By way of example, the use of renewable energy sources and the decentralisation of energy generation, which among others includes solar panels in individual households, electrical cars, and fast increase in the number of intelligent devices in the house, yielded a massive attention to a fairly new concept: the smart grid. Important actors in this domain are energy prosumers, i.e., end users that themselves generate energy,\(^1\) may demand energy from the supplying company when their consumption exceeds their production, or may alternatively feed the energy grid with their energy surplus; prosumers can buy as well as sell energy. This situation created the need to add intelligent components to the grid. The energy meters had to be upgraded in such a way that both directions of energy flow could be measured, as well as other relevant information such as date and time could be collected. The smart grid is an infrastructure to manage, control and optimize the flow of energy and balance demand and supply on a continuous basis. In particular, the Smart Grid requires embedded control with a stable provision of electrical energy, and net management as well as management of energy generation. The Smart Grid enables new capabilities such as prognosis regarding both energy production and energy consumption, distributed and decentralised energy generation (including renewable sources such as wind, sun, and water, whose availability depends on imperfectly predictable elements such as weather conditions), consumption-oriented pricing. Alas, the complex energy market where many players are active demands the tight integration between physical systems (the electrical distribution network, generators and load) with distributed intelligence (embedded controllers, distributed

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\(^1\)Prosumer = **producer and consumer**
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controllers, wireless and wired communication networks, sensors and optimization algorithms): Cyber Physical Systems are core for the development of the Smart Grid and its services. The Smart Grid is just one example of the market pull for a CPS agenda. Almost all areas of great public concern or economic value exhibit similar needs: for example, the transportation infrastructure, the healthcare system and the security infrastructure. Emergency services, fire brigades, environmental and security organizations would definitely benefit from a better cyber physical infrastructure, e.g., measuring and monitoring water level of rivers and lakes, and of the general conditions of forest areas. Transportation systems, which include any mode of transporting people and goods, e.g., rail, road, water and air, are undergoing a fundamental shift towards more controlled operation to improve pollution, energy consumption and efficiency. The control of a connected, cross-border traffic encompassing all the different (sub-)domains has dimensions that civil authorities and industry are still at odds with. The benefits are obviously great, a safe and secure way to reap these benefits is yet to be found. This is indeed a typical CPS problem: it involves measurement of the position, speed and trajectories of vehicles, congestion estimation, route optimization and ultimately issuing local control signals to self-driving vehicles. Transportation systems scenarios have been investigate in several studies funded by the European Community. In all these scenarios there is an angle that involves CPS. Automotive navigation systems can automatically detect traffic congestion and recalculate the route to the destination; in addition, users may require that during navigation, the system be aware of particular situations due to sport, political or entertainment events that cause roads to be closed and traffic diversions. This information could be provided by a traffic management system that gathers, combines and interprets, and puts aggregated information at the disposal of the system or end user. CPS may provide a way of bringing a reliable and trustworthy navigation system of this kind. In [BCG12], an example of even a larger scope for CPS is given: a number of heterogeneous CPS are to be coordinated and controlled, thus adding to the list of care-about for CPS typical Systems of Systems concerns. In this scenario, highways put a fee-based fast track for fully autonomous vehicles, that must be abandoned in case an ambulance is to be given way. This scenario links CPS specific for traffic management to CPS specific for healthcare systems or, more precisely, demands CPS dedicated to different domains to interact and coordinate. Similar CPS coordination problems arise (see, e.g., [AHK12]) when smart homes have to cooperate with CPS for both healthcare and ambient assisted living. Industrial production is based on the tight interaction among many players in the supply chain. The efficiency of the supply chain has constantly increased over the past years. Yet there is always room to improve. For example, the production schedule and the design of the manufacturing systems require solving coordination and optimization problems involving complex measurement, predictions based on historical data, communication infrastructure that should be
real-time and accurate, real-time scheduling and control of continuous time plants. Scalability, safety, security and sustainability are problems that need work; see [MFHMSR13]. We could continue with a long list of similar trends and expectations that can be observed in as dissimilar application areas as home entertainment, telephony, television, computer, Internet, medical care, automation, manufacturing, and logistics. In summary, a significant investment in the CPS domain is needed to respond to the needs of customers and civil organizations.
3 Vision, opportunities and challenges

A number of substantially improved systems and services, enabled by the novel capabilities of CPS, and their added value can be identified. In the first two sections below, these are summarily presented. The last section addresses the associated challenges both from the societal and the technical perspective.

3.1 Vision and added value

As mentioned above, CPS are open, ubiquitous systems of coordinated computing and physical elements. They are expected to interactively adapt to their context, be capable of learning, dynamically and automatically reconfigure themselves and cooperate with other CPS (resulting in a compound CPS), possess an adequate human-machine interface, and fulfil stringent safety, security and private data protection regulations. Further, ability to deal with incomplete data, data mining and data fusion, situation awareness, distributed knowledge and control, ability to handle short as well as long term goals and with local as well as global goals and information. Systems with these capabilities will putatively help in a series of challenges. In particular, CPS will be of great help in dealing with megacities, their sustainability as well as their survivability including dynamical and adaptable optimization of (better) integrated services (e.g., power grid and increased throughput of public transportation in an accident-free scenario).

With CPS, a 0-environmental-impact manufacturing scenario will come closer as well as some futuristic scenarios such as brain machine interfaces and cyborgs.¹

The CPS vision, in the end, is about a smarter planet instrumented by myriads of sensors, controllers and actuators that supports applications to make our life simpler, safer, and more enjoyable.

Summarizing, there is a number of added values associated with this vision, most notably new services/functionalities such as for example:

- easier access to information (albeit interoperability is a grand challenge, see below);

• monitoring, preventive maintenance;
• guidance and assistance, e.g., for informed decision making and optimization in transportation (delay/energy), use of electrical appliances at home for best cost, accident (with early warning, emergency call, hospital preparation, etc).

In addition, complexity management as well as optimized use of resources in production, administration, research, and any other labyrinthine organization, with associated improved robustness (e.g., through multiple data sources, decentralized control). It is expected that the advanced functionality in software can be achieved without additional hardware cost increment. In general, the systems will be more trustworthy and reliable, flexible and reusable, and moreover autonomous and able of self-repair (in general, self-x where x stands for organization, monitoring, etc.).

3.2 Opportunities

CPS enable a holistic view of a smarter planet, where increasing cooperativeness is taking place, allowing for multidimensional optimization and exchange. Thus, for instance, Europe could obtain solar energy from Africa and, in return, provide support for agricultural and industrial development. Under innovators without borders one can imagine, on the one hand, increasing education efficiency and knowledge sharing and, on the other, enabling and empowering innovations. Similarly, aeolian offshore along the coast can enable business collaborations among the countries. The challenge resides in existing export regulations and restrictions, which need be revised and updated.

Further opportunities open when social media and increased connectivity are considered. In a similar fashion, the reduction of costs takes place when a more direct (i.e., person to person) relationship is enabled, since this way the number of intermediaries is reduced and, at the same time, the efficiency is increased due to resources optimization (and to the choice of sustainable sources).

These opportunities seem to be only capable of arising if the innovation is human driven, also termed development with humans in the loop, and the thus resulting systems are called Human-Centric Cyber-Physical Systems (HC²PS). Necessarily, the requirements for human-centric systems must be elicited, the human-machine interaction (HMI) needs be carefully designed, and furthermore a deep assistance must be ensured. CPS have profound impact on human behavior, so acceptance issues like “which services do humans accept” and “what about privacy” must not be neglected. Monitoring health and emotional states, and a mediation of human/human interaction, can trigger human-social-mediator networks. But also highly trained technical staff are in need of integrated Socio-Cyber-Physical Systems, as it is the case for example in air traffic control.
Far reaching opportunities arise from broader information and knowledge availability. So, for instance,

- consumption awareness increases consciousness and, this way, resources can be handled more thoughtfully;
- labs can be remotely used and controlled by means of a research infrastructure (e.g., EIT, Horizon2020, national programmes);
- an increased dissemination and visibility of, e.g., research results can be achieved;
- corrupted behaviour can be uncovered (for example, sensors on pipelines);
- basic vs. premium (i.e., paid) services may be more sophisticated;
- the eReader can become a CPS, and thus have an immediate impact in education;
- social financing for innovation, for instance in film industry and publishing, can be triggered.

Moreover, various interactions exist between different domains. Generic and domain-specific functions can be automatically or manually combined with each other, enabling new functions to be added to systems or manual functions to be automated. As an example of cross-domain use of CPS, consider diseased people living in complex circumstances whose support is shared across several medical facilities, and the information about a patient’s medical condition used to provide appropriate services such as journey planning.

### 3.3 Challenges

The above sections present the advantages associated with CPS. These benefits carry certain challenges which we briefly address below.

#### 3.3.1 Societal challenges

A word of caution is warranted here: while it is certain that CPS will open new market opportunities, serious challenges are to be taken into account both in the social context and in the technical domain. Social concerns are about the possible resistance to these systems due to a fear of rising costs and/or loss of power by legacy structures, loss of security and privacy, or any form of resistance to change. During our workshop, a range of potentially negative impacts were identified including the following:
• Security. The increasing pervasiveness of CPS will clearly provide increasing risks when it comes to security issues, for example concerning confidentiality (avoiding disclosure of certain information), integrity (making sure data is not tampered with, or that this can be detected) and authenticity (making sure that data and users are “genuine”, i.e., who they claim to be). When making a large amount of embedded systems data potentially broadly available, what information do we want to keep private, what information should, for example, insurance companies to get hold of?

• Managing disruptive societal changes. CPS will change personal as well as societal behaviors. Such changes may be particularly challenging during transition periods, compare for example in the transition to autonomous vehicles. As we become surrounded by intelligent assistive or autonomous systems, will we suffer from digital dementia where our current competence weaken to a point that new risks emerge? An example that was raised during the workshop, was the case of intensive care equipment with improved (intuitive) HMI, with the unexpected effect that hospitals started to use less experienced personnel, leading to new risks.

• Unclear user acceptance and barriers to use and adoption of new technology. This topic relates closely to the previous bullet. It will be important to include end-users and relevant stakeholders in developing CPS. Customizability is likely to be very important - and also feasible with CPS.

• Increased complexity. CPS provide new functionalities, many of which were not feasible before. This comes at the prize of introducing rather complex systems. Larger scale CPS will involve an increased set of stakeholders, will be difficult to understand (information overload), may provide conflicting information, etc. The complexity may lead to unintended emerging behaviors, for example, autonomous systems combining data in unforeseen ways. Complexity management techniques will be important in the design of CPS; it is important to minimize the accidental complexity.

Open discussions, larger scale pilots and societal involvement will be important as well as the adoption of appropriate legislation, policies and strategies to mitigate these risks. Of course, some of these risks could also be seen as opportunities for further research and innovation!

### 3.3.2 Technical challenges

On the technical side, a range of challenges (that could be turned into opportunities though) may also delay or even prevent the evolutions presented above. First of all, cross-domain integration and interoperability. More precisely, these new applications across domains require integration
of data sources, new industrial partnerships and possibly new incentives ( economical, among others). This leads to business and legal frameworks that need be reassessed, for instance regarding data ownership and liability. In turn, the question raises about new risks, e.g., safety and security, where the methods used in traditional embedded systems become insufficient. The certification will continue to be highly costly, until new systematic techniques are developed that address dependencies and verification as part of CPS. CPS still lack an established engineering methodology. A particular challenge concerns the role of software. While software provides the means for the intelligence of CPS, managing the increasing complexity is becoming a challenge (and this complexity growth is largely due to software); here two specific challenges deserve mentioning: (a) analysis, validation and stability, and (b) distributed algorithms and shared control. In industry, software engineering is not receiving enough attention; cf. departments in automotive industry still referred to as “EE” (Electronic and Electrical). We believe that there is a corresponding lack of insight by decision makers and managers.

Finally, grasping the vast number of opportunities with CPS requires that existing application domains with little or no knowledge of CPS technologies (e.g., sensing, embedded systems, networking, and internet), be able to learn and interact with CPS specialists, for example in domains such as transportation systems and healthcare.

The engineering challenges posed by CPS are addressed in more depth by the next chapter.
4 Engineering

The design of CPS is characterized by specific engineering challenges which are related to the particular combination of physical elements and computational elements. In this section, we provide an assessment of the most important aspects that should be addressed from a methodology, architecture and tool support point of view to solve the design problems.

4.1 System engineering

The first aspect, and one that may be considered the most important given its overarching character, is the problem of system engineering. The main observation is that system engineering is today not sufficiently systematic. The system engineering activities should start well before the hardware/software partitioning and design, and should involve a precise formalization of the requirements. This can be accomplished by providing models.

Models Models should be available at different levels of abstraction, in order to be able to handle the system from a high level to a concrete perspective. In addition, for each level, complementary models should be developed to address different aspects of the design, or views, such as function, reliability and safety. The combination of the levels of abstraction and the views forms a matrix of models, which should be employed during the entire design process. In this sense, the traceability of requirements from design to implementation was considered of primary importance.

Languages The issue of modeling identified in system engineering brings up the question of whether the current design and verification languages are appropriate for CPS. An important question is whether the design would be better served by richer languages, able to support the description of all aspects of CPSs, or by simpler languages, focused on specialized tasks. It can be observed that simpler languages would be more convenient, but only if the tools supporting these languages are able to easily interface to each other. This introduces the next item.

Open CPS platforms The CPS community strongly feels the need for open design platforms, in the form of standards not only for the integration of the components, but also for the
integration of models and tools. One example of one such platform is the RTP developed in the Artemis CEASAR project. Similarly, the CPS community should strive to develop a reference architecture for CPS, which defines layers and interfaces that have potential for standardization and granularity appropriate for the downstream tools and methods. To complement the reference architecture, the community should also develop reference scenarios and use cases for CPS applications, in order to facilitate ad-hoc and deliberate System of Systems (SoS) integration and “intuition at scale”.

Regarding the system engineering challenge, it can be observed that CPS requires the adoption of different kinds of “physics” for the cyber and the physical parts, and that engineers of different specialization do not necessarily communicate effectively. Abstraction, discussed below, and the ability to handle heterogeneous design, is one possible way to address this challenge. The next step is addressing engineering challenges is the identification of the technologies that would be able to support the development of system engineering and reference platforms. The ones that appear as the most essential are the following.

**Composability and Compositionality** These properties, which have to do with the ability to put together a system while retaining the characteristics of the sub-systems, can be considered essential for an efficient CPS design. An example that can illustrate the issue is the replacement of a component of an avionic systems with a new version, with presumably better performance. The design process should be structured in a way that this change would not require that the entire avionic system be re-certified in its entirety. In other words, composability and compositionality are essential properties to incentivate innovation, as new products could be more easily adopted.

**Abstraction** The ability to construct abstract models, able to cover the essential aspects a design, is also considered of primary importance. Besides automatic abstraction methods, which can provide substantial help to the designer, innovation is required in the way in which abstraction is taught in schools. The major point is that abstraction is a skill that has to be learned through experimentation, rather than taught.

**Affordable formal methods** Together with abstraction, the often critical character of CPS requires that its properties be checked formally, to ensure correctness. Affordability has to do with the ability to apply formal methods to chunks of design of sufficient size. The design should therefore be partitioned into parts whose granularity is appropriate for the application of formal methods. Compositionality would then be required to ensure the correctness of the entire system.

**Design space exploration** In addition to reference architectures, the complexity of CPS requires new ways to conduct early architecture exploration, given the heterogeneous nature
of the design. This activity must be supported by ways to extract relevant information from big data, such as simulation for performance evaluation, able to provide multisource integration and extraction. Of particular interest in the community is the development of correct architectures for autonomous CPS.

One challenge that can be identified in composability and compositionality is the difficulty in defining effective interfaces, required to apply the principles of decomposition and the method of divide and conquer to make the design effective. The development and use of systematic standards for the definition of interfaces is certainly one possible solution, leading also to the development of open architectures, as discussed previously. At the same time, a major challenge has to do with the difficulty in fitting innovation with the rigidity, the complexity and the multiplicity of standards.

Regarding design space exploration and architecture development, several aspects can be identified as critical. In the first place, validation requires the identification and prediction of emergent behaviors. In addition, given the often required activity of certification, one major challenge is the development of methods that are able to neuter the untrusted aspects of hardware, operating systems, input/output, etc., without damaging, or while maintaining, the utility and the quality of service of the system. Similarly, the issue of mixed critical systems can be put forward as a current challenge, which should be addressed with a combination of simulation and formal methods. The ability to develop flexible architectures can also be seen as one way to avoid obsolescence. In fact, another challenge that must be considered is the generalization of design and verification methods from individual products to product lines.

The final challenge, but one to which must be given primary importance, is the issue of education. Education is seen as essential to the preparation of engineers able to tackle the above engineering challenges, and who are able to master the diverse knowledge required in the development of CPS. Knowledge management, as well as the skill required for life-long learning, and the ability to collect the knowledge, are at the basis of developing a culture of CPS and the creation of a CPS engineer.

### 4.2 HW/SW evolution

The evolution of hardware and software is steadily continuing as manifested by the development of multicore processors and by mass-production of sensory systems such as accelerometers, gyroscopes and cameras in smartphones, opening up for even further applications. Multicore processors provide increasing computational power but at the same time raise the challenge of efficient parallel programming. At the same time, the improvements in size and capabilities of FPGAs leads to new opportunities for direct hardware synthesis of programmable logic, and cause the boarder
between hardware and software to become even more blurred. Drastic leaps, such as quantum and bio computing were perceived by workshop participants to not have an impact in the shorter term, and currently unknown impact longer term.

Software platforms are also evolving, from low level separation and protection schemes, such as hypervisors and virtualization, to middleware platforms, that enable flexible distribution of functionalities and various communication models.

A clear trend is towards an increased heterogeneity, encompassing hardware, networks and software. The embedded systems parts of a CPS are able to host a variety of functionality and capabilities; compare for example with a smart meter that apart from the basic functionality of measurement and display, also provide for remote status reports, reconfiguration and software upgrades. As another example, a car is hosting a wide variety of computational platforms and communication protocols. While separation of functionalities among different hardware units used to be the guiding principle, see Section 2.2.1, cost savings, opportunities to exploit interactions among functionalities, and cost-efficient networking, drive a tighter integration which leads to needs to deal with resource sharing among heterogeneous applications. Modular architectures and modular certification are perceived as important solutions to provide cost-efficient solutions for mixed criticality applications.

As heterogeneous networks integrate, their different assumptions surface and have to be dealt with; compare for example with Internet protocols, developed to provide high bandwidth, whereas many new CPS applications instead require real-time behavior (including small delays) and may be satisfied with smaller bandwidth. Given the increasing connectivity, larger distributed systems are forming (for example, vehicle convoying, also referred to as platooning), leading to increased efforts to standardize interfaces and protocols.

Product lines are evolving as a further means to enhance cost-efficiency, but reuse is challenging, and especially so in the context of the heterogeneity and environment assumptions that characterize CPS. Product lines require specific emphasis with respect to their design and verification. Another trend to enhance reuse and promote productivity, is through model-driven engineering (MDE), with a move from verifying the end product to verifying models; thus the need to ensure the appropriate fidelity of the models and means to transition as smooth as possible from models to implementation. Hardware/software codesign and design space exploration are promising directions for MDE as applied to CPS (note that the scope of codesign here refers to CPS, with broader concerns compared to classical HW/SW codesign). Multiple models (views and viewpoints) are required for CPS. Efficiently dealing with multiple models used for different aspects, their dependencies, consistency and configurations remains a challenge. It was noted that software engineering is craft based and slow at adopting MDE.

Development of software is gradually shifting from in-house development to integration, use of open source software and also involving new forms of development (e.g., crowd-sourcing, com-
Workshop participants highlighted the lack of EU efforts that connect to European open source efforts, e.g., Linux. The importance of platform ownership or strong participation has been emphasized for driving innovation\(^1\).

The evolution of hardware and software to form part of larger scale systems, pinpoints needs and bottlenecks in developing CPS. Workshop participants expressed that many methodologies and technologies are not CPS yet ready. Improvements are required for example w.r.t. software engineering methodology, interoperability standards\(^2\), and how to deal with non-functional properties. Workshop participants as a consequence stated the following needs:

- requirements engineering and architecture approaches (modularization, interfaces, composability) need emphasize the importance of an adequate treatment of system of more and more complexity (and be mandatory for safety critical systems).
- new processes are required to deal with integrated hardware/software design in the context of CPS.
- education needs to address the broadened scope brought by CPS; multidisciplinary perspectives are required.

### 4.3 HMI and shared control

The integration of a high number of systems [BCG12] requires distributed, cooperative and interactive perception and evaluation of the situation and the distributed, cooperative and interactive determination of the steps to be carried out—depending on the evaluation of the situation, on the objectives of individual participants and the objectives of the community these participants belong to (local vs. global objectives). This cannot be done without subsequent coordinated assessment and negotiation of the decision taken, i.e., self and shared control and decision-making autonomy.

Such a level of autonomy requires decision-making on the basis of uncertain knowledge, cooperative learning and adaption to situations and requirements estimating the quality of own and external services and abilities.

A special goal is the coordinated processing of mass data as they are produced by billions of embedded systems.

The future does not lie so much in completely autonomous systems. Humans will interact with such systems in various ways. Thus, in general, CPS will offer several user interfaces. This

\(^1\)http://download.steinbeis-europa.de/2013-10-29-30_cps/29102013-cps-veugelers-university-leuven.pdf

\(^2\)With respect to interoperability, a workshop participant raised the question whether CPS learn from the telecom standardization efforts

Deliverable D2.1 – CPS Domain: Initial Synthesis
requires intuitive, multimodal, active and passive HMI support (with simplified control) and support of a broader (space, time) perception and capacity to act for individuals and groups. The system needs to be able to recognize and interpret the behavior including emotions, needs and intentions. For adaptive behavior acquisition and evaluation of data concerning state and context of human and system (extension of perception and evaluation skills) is required. A capability that is important, but difficult to achieve, is the integrated and interactive decisions and actions between systems and individuals or groups.

On the long run the ability to learn will lead to more flexible user interfaces, as they are required for mobile access to CPS.

The consultations with experts and roundtable activities led to the process control systems security problem and HMI vulnerabilities. These inputs are grouped into challenges.

**Challenges**

1. CPS include concepts from embedded systems, from engineering HMIs, and from global networks. Therefore it is necessary to unify and harmonize these foundations and to deal with additional effects and concepts that arise from the merger.

2. How to achieve the most predictable and reliable human-computer interaction (HMI), which is required by humans for integrated action.

3. Passive HMI, i.e., the conscious and unconscious observation and monitoring of humans or groups with the challenges of interpreting the observed behavior correctly or in the desired manner.

4. The conformance of CPS with international standards presents a new issue. For automation modules to properly work together, they must communicate with a standard protocol. Each individual automation module needs its own human-machine interfaces (HMI), but when they form a connected system, standard techniques are needed to build and operate a unified HMI that controls the entire system.

5. The connectivity of vehicles to infrastructure could greatly reduce traffic, which would reduce emissions and make commutes more convenient and efficient for travelers. But, this means that drivers are often unable to gain a clear picture of the systems or the situation. They are not able to accurately assess the systems’ behavior and capabilities because
   - their behavior is influenced by events and relationships that are not perceived by the user and do not form part of their understanding of the situation,
they do not demonstrate the 'normal', rule-based behavior that would be expected of social actors. Rather than obeying socially agreed, learned rules of interaction, the systems’ behavior conforms to the goals and functional rules established during their design and construction.

6. New issues relating to controllable human-computer interaction: The use of Cyber-Physical Systems not only raises issues concerning the controllability of technology and wider questions of safety and risk; there is also issues concerning the appropriate design of the systems and the relevant human-computer interactions and cooperation, particularly in terms of their impact on the direct or indirect actors.

7. Securing Cyber-Physical Energy Systems is a significant challenge [MSR+09]. The process control systems used to control Cyber-Physical Energy Systems were developed for a non-networked world and without a security requirement in mind. In recent years, these same systems have been connected to corporate networks, which are then connected to the Internet. This has led to the need of securing these process control systems. Some of this work involves bringing security techniques from the information technology domain to bear on the process control system security problem. However, process control systems have many unique features and functional criteria, which lead to a unique set of security related research challenges.

8. The development of Cyber-Physical medical devices requires new approaches to designing interfaces that satisfy a number of new requirements, such as the sharing of authority, the shared human and device understanding of the current state or agreement on the actions to be taken.
5 Acceptance, economic ecosystems and regulations

In this chapter, acceptance issues, economic ecosystems, and regulatory matters are addressed that may have an impact on the CPS agenda.

5.1 Acceptance and dropouts

The issue of acceptance has to do with the willingness of users to adopt or refuse a new technology. A “dropout” is an individual who, for various reasons, decides or is forced to avoid adoption or use of a device.

One key point about acceptance is to understand the reasons for dropouts. There are at least three issues to consider:

- There are people who do not like to conform to standards, and therefore decide not to follow the general trends, and willingly refuse to use a new technology.

- Some people may be unable to take advantage of or use a new device, for lack of understanding of the technology or difficulties in the usage. There is also an aspect of education involved.

- Finally, incentives in the adoption of a new technology may be missing or not be clear, or, worse, the incentive may be negative in the sense that the new technology is perceived as detrimental.

The issue of incentives is particularly interesting. For instance, one can easily find examples of a new technology with largely positive development, which might in fact show that certain previous approaches to a problem were not effective. Individuals who have a stake in the previous methods may therefore have little interest in the adoption of the new technology, and would rather preserve the status quo. The negative incentives may also arise if those who are supposed to adopt a new technology perceive that they may lose or have to give up control over the operations. All these effects give rise to conservatism. Another source of negative incentive is
mistrust. In particular, mistrust arises when it is unclear how far a technology can reach, or what its consequences may be.

At the opposite side of the spectrum, one must also carefully consider when acceptance actually takes place. Also in this case, we can identify various aspects:

- Acceptance is more likely when there is critical mass. Critical mass can be interpreted as the number of people adopting a certain technology, producing a “network externality” effect that increases the value for new adopters. Critical mass has also to do with the homogeneity of the system. For instance, a traffic system where all cars are self-driving would probably work more smoothly than a traffic system in which some of the cars are self-driving, and the others are not.

- Adoption is more likely when there is no legacy. Legacy, in fact, could make changing more expensive (infrastructure has to be replaced, investments may not be completely amortized yet, customs and habits have to be modified). For instance, it must be noted that the payment technology through the cell phone and near field communication (NFC) has found a much larger adoption in developing countries, where a reliable payment infrastructure is largely missing. In other words, acceptance is more likely when there is no alternative.

- Finally, usability is an important factor in acceptance. Increasingly, if new technology has to be used by the general public, who is not an expert in the development of the system, the system has to perform its functions using commands that the user finds natural, without the need to read manuals or spend time understanding the product.

There are several elements that can be identified as favoring acceptance. We have already discussed the issue of incentives and benefits, which have to be clear to the new users. A new technology must also be unobtrusive, and naturally blend and interface with other potential devices. Increasingly, users are becoming more demanding on the aspect of privacy and trust with respect to the provider of the service. Related to this, users have to be confident that the system cannot be tampered with, and expose private data to external third parties who may take advantage of the information. Adoption may also be favored or hampered by media coverage: often, the negative effects of a new technology resonate louder in the media, which may fail to highlight the benefits appropriately. An interesting aspect has to do with the potential liability brought about by the use of new technologies. For instance, instrumenting a physical infrastructure with sensors may provide a large amount of data. Those responsible for managing the infrastructure would then have an obligation to make good use of the data, which may require additional work and/or investment. Failing to follow up on danger signals may make them liable for the potential loss.
Of particular importance is the issue of usability. In general, one can identify two kinds of systems: those which are designed for people who are going to be trained on their use, and those who are designed to make life easier. These two classes of devices have different requirements in terms of usability. In addition, certain devices may have to be designed to interface differently to different categories of users: for instance, a medical device may have to be used by the patient, the nurse, the doctor and the relatives of the patience, all with different expectations on the functionality of the device. Usability has also effects on the perceived privacy and trust on the device: sometimes even simple technology may be hard to configure correctly, leaving a sense of mistrust in the user.

Another aspect which is particularly important in the area of acceptance is related to standards. Naturally, standards have the potential to significantly improve acceptance, as they increase the critical mass by providing compatibility between devices of different manufacturers. Standards are largely driven by the market, however standards also influence the market. The establishment of a new technology therefore takes place a lot more rapidly when a positive feedback reinforces the effects of both standards and markets. At the same time, we might deal with different kinds of standards, one for instance influencing the way devices are interfaced, another having more to do with the quality of a product, or how a process is performed.

It can be argued that achieving a higher degree of acceptance may be expensive. For instance, an infrastructure might have to be maintained. In addition, the aspects of privacy and security are expensive to guarantee, so the question is whether the users are ready to pay a premium for services that can provide a higher level of quality.

### 5.2 Economic ecosystems

The identified, far-reaching capabilities of CPS cause a rapid transformation of economic processes and relationships. As a result, traditional economic models shift accordingly. Indeed, the technological developments and their ubiquity trigger a change in products and services towards more openness and cooperativeness that moreover include interactive user involvement.

**General Considerations**

Regarding the market and its structure, CPS may turn out to be highly disruptive. Traditional business models may lose validity, and the competitive dynamics may undergo a radical change. A transition from conventional supply chains to so-called economic ecosystems is already happening. In CyPhERS we use the term “economic ecosystems” to mean a much more dynamic and networked “market” than the traditional linear or hierarchical supply chain. In view of the potential opportunities for economic growth and competitiveness represented by CPS, some
efforts need to be undertaken to explore the technology and measurement barriers in this important field. There are classical ways of analyzing markets, e.g., Porter’s five forces model [Por79], which consider the impact of competitors, new entrants to markets, etc., which it may be possible to extend to analysis of “economic ecosystems”.

To an extent, the classical business school models of markets are relevant to CPS, but they tend not to be so effective at identifying “disruptors” and technologies which could induce radical changes in markets, e.g., because they cross domains. Thus, at the workshop, the focus was more on identifying some example disruptive trends and challenges, which could shape the CPS economic ecosystem. The results presented here were obtained from expert participants at the workshop and roundtable activities designed to gain real-time inputs on the critical measurement challenges and gaps that could impede development of future CPS.

The inputs from the World Cafe session start with some general observations; the other observations are grouped into disruptive shifts and challenges.

The disruptive shifts are rather speculative, and should be seen as indicating the major changes that CPS might bring about, not as fully worked-through examples. The examples cited here were prompted by discussions at the workshop, but have been expanded to try to indicate the level of change which CPS might be able to bring about. Arguably, the first two could be grouped together.

1. In a given domain, what can be viewed as commodities, and what has to be “special” to the domain, recognising that using only a fraction of the capability of a commodity item may be cost-effective if it is cheap and offers rapid entry into the market?

2. What electronic trade and contract frameworks need to be in place to enable markets, recognising that the current “click to accept licence” approach is already fairly meaningless, and is not realistic in a highly dynamic, electronically mediated market?

3. What legal frameworks need to be in place if CPS are to be used which are pan-European or even global in scope, to enable cross-border operation, but also to address liability (e.g., for safety and security)?

**Disruptive Shifts**

1. The potential for more dynamic and cost-effective distribution and logistics, with self-identifying products (an extension of RFID tags) capable of interacting with the transportation infrastructure to “self-route”.

2. The potential for highly-integrated transportation, with commodities being automatically routed and tracked through a variety of modes of transport, e.g., air, sea, exploiting knowl-
edge about the state of goods which are perishable, available carriage capacity, and road congestion. This might include, for example, using information from GPS (satellite navigation systems) in cars to enable an item to “piggy back” on a vehicle, which is going to (roughly) the right destination.

3. The potential for “smart fabrics” which currently mainly provide fashion opportunities to enable sensing and management of medical conditions, to interface with other devices, e.g., a smartphone, to issue reminders about medication, to be able to contact emergency services, should this be necessary (the fabrics might offer this capability, as nothing “special” has to be worn, thus it is easier to integrate into every-day life).

4. The potential to alter the “security ecosystem”, for example by enabling pervasive remote monitoring of property and assets, with the ability to direct “feeds” from such systems to law-enforcement agencies, in the event of a problem; this should facilitate law enforcement especially if there were integrating tracking systems, activated if assets were removed from their normal location.

Challenges

1. Where there are legacy systems which are hard to change, how can they be exploited and integrated into an effective CPS, noting that if they contain embedded sensors and actuators there may be no practical way to bypass them?

2. Where is the CPS support, or cross, multiple organizations and/or domains, who owns the data, how is it managed and protected so that owner rights are respected, but that benefit can be gained from the data?

Summary

These initial ideas from the World Café should be understood as such – the results of a first consideration of the issues, not a definitive statement on the issues. More specifically, this topic will be addressed in more detail in deliverable D3.1, building on some of the more classical management models, but also introducing some new perspectives on “market forces” which should help CyPhERS in understanding and mapping the economic ecosystems pertinent to CPS.
5.3 Regulations

The matter of regulations, in particular how the international landscape in Europe and beyond might be harmonised, on the one hand, and the need of modernization of existing instruments, on the other, in order to meet the challenges associated with the envisioned systems, was not a subject of the workshop. Nevertheless, a general concern in this respect was expressed. CPS will be broadly accepted and thus able to unfold their full potential if they can seamlessly adapt to different contexts of use and safely integrate in these contexts, thereby also addressing the needs of users and customers, who must experience the offered services as manageable and trustworthy. Existing regulations concerning liability and privacy protection need revision and possibly be updated to the new emerging facts and circumstances. Regarding liability, especially functional safety but also security, present regulations (including [IEC10]) do not cope with the integration capabilities demanded of CPS. Indeed, those regulations essentially limit design, implementation, commissioning, and maintenance of systems, i.e., dependability is often achieved by limiting access to the system. In their present form, therefore, they would contract essential properties of CPS.
6 Conclusions

In the previous chapters we tried to organize a collection of miscellaneous aspects associated with the envisioned CPS. This material will be further elaborated and become the basis on which a nominal-actual comparison will be drawn. Done this, recommendations for action will be proposed.

It is clear that, first of all, a common understanding about CPS, particularly a characterization including goals and boundaries of CPS, needs be elucidated. For this purpose, a authoritative glossary of terms and definitions can prove useful. The feasibility of CPS strongly depends on a solid theoretical foundation as well as an engineering discipline widely agreed upon. Due to the heterogeneous and interdisciplinary nature inherent to CPS, conventional methods of modelling and architecting systems seem insufficient if not partly inadequate. Evidently, foundational research and the development of techniques are of crucial importance; the question, in fact, is to specify and possibly prioritize which particular areas need special attention.

Besides the technical aspects, also other realms are affected by the materialization of CPS. The curriculum of the corresponding degree courses at the institutions of higher education need careful revision. Also for the operation and maintenance of CPS dedicated training courses need be devised. Interactive innovations are possible by means of economic ecosystems and platforms as well as regional and international innovation systems that integrate different life-cycles, business models and engineering cultures. In addition, advanced standards of development and of safety/security regulations, scalable security concepts and theories must be contrived.
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