Cyber Physical Systems

Opportunities and Challenges for Software, Services, Cloud and Data

NESSI White Paper

Networked European Software and Services Initiative

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Executive Summary

This white paper identifies relevant challenges and opportunities for Cyber-Physical Systems (CPS), focussing on the impact of CPS on the main areas of NESSI and vice versa. NESSI is the Horizon 2020 European Technology Platform (ETP) for software, services and data. This paper does not aim to look at CPS from all angles, but provides a complementary contribution from the NESSI point of view. In particular the paper assesses the impact of the increasing role of software in Cyber-Physical Systems. Pure hardware, mechanical or communication network concerns are not in the scope of this white paper.

The paper is structured into the following main sections:

- Software engineering for CPS – The intelligence, dynamics and flexibility of future CPS lies in the ability to be context-aware and produce software that is both dependable and adapts to real time change, which goes beyond today's software engineering state of the art and practices.
- Cloud for CPS – Cloud computing is a key element to obtain ubiquitous system deployment, execution and interaction, and provides key principles (such as adaptation and multi-tenancy) that may be leveraged for all kinds of devices.
- CPS and Big Data – CPS with its computational power on the devices (including edge computing) will be a major source, collector, processor and distributer of data, not only in volume, but also in velocity, variety and veracity.
- Software-based services on top of CPS – Software-based services constitute a key enabler for leveraging, packaging and delivering the core capabilities of a CPS infrastructure, realizing the potential that lies in creating value to business applications.

Note that the topics of security, privacy and trust are intentionally left out. These will be covered by a forthcoming NESSI white paper.

Contents

1. Introduction

1.1. Relevance and Differentiating Aspects of Cyber-Physical Systems (CPS)

Horizon 2020 (H2020) refers to CPS as “the next generation embedded ICT systems that are interconnected and collaborating providing citizens and businesses with a wide range of innovative applications and services”. The Commission's own Advisory Group - ISTAG[1] - considered CPS as “the evolution of embedded systems into smart objects that will be joined together to create highly distributed systems, bringing a wealth of opportunities and innovations in technology, applications and business models.” Finally, the ECSEL Joint Undertaking defines CPS as “embedded intelligent ICT systems that are interconnected, interdependent, collaborative, and autonomous. They provide computing and communication, monitoring/control of physical components/processes in various applications.” [1]

The ongoing integration of software-intensive embedded systems and global communication networks into CPS is considered to be the next revolution in ICT, leading to systems that are interconnected, collaborative and provide users and businesses with a wide range of *smart* services. CPS leverages the Internet of Things and the Internet of Services (Cloud) to deliver systems that dynamically federate and interact with other systems and their physical surroundings. CPS will be able to *sense* and *control* (through actuators) physical world objects even if such interactions have not been explicitly prescribed at design-time. Such dynamic actuation, and the potential non-roll-backable modifications of physical world objects it implies, will be a key differentiating aspect of CPS – making it more challenging to design, implement, test and certify them in an efficient and effective way.

Europe is well positioned, but strengthened research and innovation activities are needed to meet the challenges imposed by the specific nature of CPS. The grand vision of CPS goes far beyond existing systems thinking in terms that it breaks fundamentally with systems developed by the assumption of a closed world. We go from the predefined and prescribed construction of a system (or systems of systems) to a construction that is evolving at run-time without any visible master plan. This new system notion is not easily captured by existing engineering principles such as *separation of concerns* and *divide and conquer*. In other words, clear system boundaries will cease to exist and systems may be overlapping since a system is virtually defined and may be a transient notion defined temporarily for the purpose of executing a single function or business process.

1.2. White Paper Contributions

NESSI is the H2020 European Technology Platform (ETP) for software, services and data (see http://www.nessi-europe.eu/). NESSI aims to have an impact on the technological future by identifying strategic research directions and proposing corresponding actions in its scope, including software engineering, software-based services, cloud and Big Data.

This white paper identifies relevant **challenges** and **opportunities** for CPS, focussing on the impact of CPS on the **main areas of NESSI** and vice versa (see Fig. 1). Therefore, this paper does not cover CPS from all angles, but aims at providing complementary perspectives reflecting the NESSI point of view. In particular the paper assesses the impact of having more

[1] ISTAG was the Framework 7 IST Advisory Group. In H2020 ISTAG has been replaced by the CAF (CONNECT Advisory Forum for ICT Research and Innovation).

and more software-intensive 'elements' in the CPS field; pure hardware, mechanical or communication network concerns are not in the scope of this white paper.

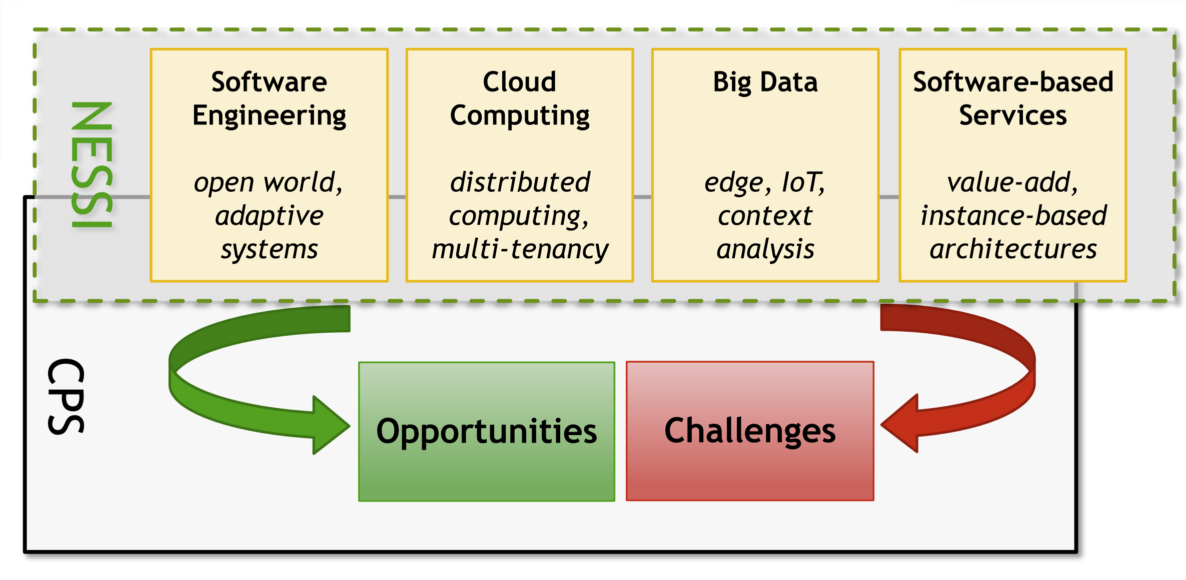

Figure 1. Challenges and Opportunities at the Intersection between NESSI areas and CPS

Additionally, the white paper strives to provide a view complementary to existing roadmaps and research agendas on CPS. While having a clear NESSI footprint, the white paper also reinforces many of the underlying technology requirements emerging from related roadmaps, such as the ones provided by ARTEMIS-IA and ECSEL-JU [1] [2].

The paper is structured into the following main sections:

- **Software engineering for CPS (Section 2)** – The intelligence, dynamics and flexibility of future CPS lies in the ability to be context-aware and to produce software that is both dependable and adapts to real time change, which goes beyond today's software engineering state of the art and practices.
- **Cloud for CPS (Section 3)** – Cloud computing is a key element to obtain ubiquitous system deployment, execution and interaction, and provides key principles (such as adaptation and multi-tenancy) that may be leveraged for all kinds of devices.
- **CPS and Big Data (Section 4)** – CPS with its computational power on the devices (including edge computing) will be a major source, collector, processor and distributer of data, not only in volume, but also in velocity, variety and veracity.
- **Software-based services on top of CPS (Section 5)** – Software-based services constitute a key enabler for leveraging, packaging and delivering the core capabilities of a CPS infrastructure, realizing the potential that lies in creating value to business applications.

2. Software Engineering for CPS

The emergence of highly distributed and large-scale CPS means that software has to live in an *open* and highly dynamic world. Traditionally, software development was based on the closed world assumption, which means that the boundary between the system and its environment is known during design-time and that the environment does not change while the system is executing. In contrast, CPS in general cannot be specified completely during design-time due to incomplete knowledge about, for instance, services and devices available during system operation [3]. CPS are required to support modifications that are not envisaged at design time, as these modifications are triggered by the actual system context at run-time. These context-aware modifications require that CPS are able to extend and modify their functionality without stopping and disturbing the rest of the system. The development of CPS therefore has inherently to live with uncertainty in the specifications [4]. During operation, such systems must frequently adapt to the executing environment changes faced at run-time and must be able to continue to behave in a controlled and safe way. This smart adaptation must be based on the system knowledge following a well-defined self-decision making process.

From a software engineering point of view, dynamic composition of CPS poses a radically new situation. In contrast to 'traditional' embedded systems, hardwiring the system with its sensors/actuators at design-time is no longer feasible, because the concrete objects that the CPS will federate may be unknown at design-time. Also, individually and manually connecting the CPS with those objects at run-time will not scale once CPS consist of thousands or more collaborating objects.

2.1. CHALLENGES

- **Quality assurance of CPS in the presence of dynamic adaptation and discovery.** CPS solutions call for capabilities to monitor, control and manage the quality/performance constraints at provisioning time in open and dynamic executing environments, possibly via prioritised operations in response to growing distance from expected and allowed behaviour. How can we address stringent quality and performance requirements in software engineering methodologies and solutions for CPS? How can we handle situations when dealing with large-scale open environments such as smart cities, where sensing quality may be extremely differentiated and tasks to actuate are subject to many different sources of uncertainty? How can we extend testing and formal verification to deal with uncertainty and variability at the same time? Current quality assurance approaches are especially challenged in the presence of run-time adaptation. On the one hand, assurances of those adaptations during design-time is Infeasible due to uncertainty of actual adaptations at run-time as well as the uncertainty of which other entities a CPS will federate and interact with at run-time. On the other hand, verifying the 'whole' CPS during run-time is not feasible, as dynamic verification may be too expensive or slow, and severely challenged by the limited observability of CPS to serve as input for verification.
- **Middleware and platforms for dynamic evolution and composition of CPS.** Dynamic composition of CPS becomes a significant challenge for open CPS. How to deliver novel CPS-oriented support platforms with cross-layer visibility of both application requirements and low-layer context information? How can we engineer for run-time choreographies based on this visibility? How can we support the choreography of autonomous sub-systems and handle the large number of sub-systems in dynamic environments? How to balance the capabilities of the platforms with needs towards resource efficiency; e.g., using big and powerful frameworks ('bloat-ware') vs. using specific 'hand optimised' programs? Can we optimise or prune unused code and components? How dynamic evolution can be supported by self-decision-making processes based on system knowledge? How self-decision-making processes can be performed, making use of Big Data at run-time? Which mechanisms are necessary to inject new software code/services and integrate them with the rest of the running CPS? How can we manage uncertainty and probabilistic information?
- **Powerful abstractions for understanding and modelling CPS.** What are the right abstractions that are easy to understand and use, but at the same time sufficiently expressive to be mapped efficiently and ideally automatically to executable code? What would be

adequate abstractions (models) and information-hiding principles (interfaces)? How can we use those abstractions to address unexpected conditions and sensing/actuation component faults and to define safe operational areas? How can those abstractions be used to support deployment on heterogeneous devices and hardware configurations?

2.2. OPPORTUNITIES

Opportunities are closely related to challenges. However, as it is often the case with software engineering challenges, their solution typically lies at a quite technical level, and thus the importance of such solutions and their impact on humans may often be under-estimated.

- **H-CPS: Human-Operators-in-the-loop CPS.** In cockpits and control towers, human operators are involved to interpret data, to judge the criticality of a given situation and to decide on the adaption of an application during run-time as a reaction to foreseeable and unforeseeable changes and exceptions. Also, smart spaces often involve human actors, e.g. users who can perform actuation operations based on application suggestions (persuasive computing), thus dynamically modifying the execution environment and context with the uncertainties connected to human participation and involvement. Challenges in CPS integrating the physical elements, networks and the cyber elements are well understood and extensively researched - integration of human elements in CPS feedback loops is an open challenge. Understanding how humans interact with a decision support system combined with incentive mechanisms is needed for acceptance and efficiency of an H-CPS. How can we provide software system operators with dedicated adaptation mechanisms to leverage human decision making for adapting CPS to unforeseeable situations? How can we consider user characteristics and behaviour during the design of (adaptive) CPS? User incentives, 'punishments' and user-operated actuation may provide novel ways of adapting the environment of CPS. How can we leverage those for continuous observation-analysis-adaptation loops to significantly change the way CPS services and applications are designed and put into execution?
- **C-CPS: Crowds-in-the-loop.** Crowd behaviour may determine CPS operation and mis-operation in practice. While in the case of human operators the human-computer-interactions may be controlled to some extent, this is much more difficult if crowds are involved. However, the size and goals of CPS make the scenario of crowds and CPS interacting very plausible.
- **Software Innovation.** There is strong indication that software will in the future be the key enabling technology for businesses to innovate their products, services and organisations. For instance, 'Software-defined Anything' is among Gartner's top ten technology trends in 2014 [5], and the ITEA/ARTEMIS-IA high-level vision 2030 [6] highlights the impact of software innovation on revenue and jobs. We will see that software engineering will grow as a basic skill in most engineering professions. Since CPS will be a major system approach in the future for all kind of sectors, such as smart production, smart transportation and logistics, smart health, smart energy, smart housing, etc., software engineering will be a key competence for building these kinds of systems.

3. Cloud for CPS

Cloud computing is a model for enabling ubiquitous, convenient, on-demand, transparent access to a shared pool of configurable computing resources, such as networks, servers, storage, applications, and services that can be rapidly provisioned and released with minimal management effort or service provider interaction [7]. Originally, cloud computing was a way for the IT departments of big companies to mitigate costs and replace capital expenditures with operation expenditures. However, Cloud services have increasingly become a driver for agility, productivity and performance, impacting the processes and organisation of many companies, and – associated with broadband networks and smart devices – a digitalisation driver for mass market users [8].

Cloud computing is emerging as an interesting deployment option for CPS, to support and match the computing in CPS which is distributed amongst the compute continuum ranging from devices (including edge/fog computing) to the backend (server/data centre). Cloud computing therefore presents itself as a suitable computational model for the seamless integration of computational and physical components. In a complementary way, CPS 'elements' themselves may become resources in the cloud (analogous to virtual storage and virtual servers in the cloud).

3.1. CHALLENGES

- **Real-time data collection, analysis, and actuation.** For CPS to excel in their role, real-time collection of data has to be realised, and its subsequent analysis can help take the appropriate decisions and enforce them. Because of many CPS systems being time-critical, low-latency computation and actuation are required. This precludes physical centralization of analysis and decision making, and calls for a more robust distributed cloud architecture. How can we integrate CPS with Cloud infrastructures to this end? How can we bring the processing power closer to the point where processing needs to be done in order to properly and innovatively manage the flow of information? How can we model application and sensor profiles to reduce inefficient continuous interaction between CPS and server-side resources?
- **Multi-tenancy in CPS infrastructures.** How to deal with systems enabling different clients in the open world setting of a CPS? Using cloud resources as part of a highly dynamic CPS may require special care in client isolation, resource reservation, logging and billing. This goes way beyond server isolation and will require adopting advanced cloud paradigms to handle the isolation problem as container or cloud-enabled application-server isolation.
- **Dependable and predictable cloud SLAs for CPS.** Deploying critical CPS functionality to a cloud requires a high level of dependability, predictability and resilience of the cloud infrastructure. On the consumer and developer side of the cloud for CPS this implies obtaining explicit and pragmatic Service Level *Commitments*. Today's cloud SLAs are often only provided on a best-effort basis and can thus hardly serve as a reliable mechanism for risk prediction and mitigation. This requires understanding of the impacts of the CPS workloads on the infrastructure, careful planning of cloud capacity, careful risk management, auditability of the internal cloud management processes, and verifiable conformance to defined behaviour in terms of functional and non-functional requirements.
- **Cloud Services and Platforms for CPS construction and deployment.** The construction of CPS is not trivial: in addition to cloud infrastructures for their execution, infrastructures and services for their construction and deployment are necessary. Which kind of cloud services would be necessary for CPS construction and deployment? What would be the essential features of a cloud development framework for CPS in order to support the right development techniques and methodologies?

3.2. OPPORTUNITIES

- **Scalability, elasticity and availability.** Clouds can effectively scale up or down the resources, e.g. when load increases, when CPS indicate resource needs. CPS devices can be connected to the cloud quite easily (due to the standard API) and hence the construction of an entire CPS ecosystem should be relatively fast. Also differentiated quality of aggregated data, typically measured by multiple CPS observers, could be considered in order to achieve more cost-effective and scalable cloud solutions. Cloud platforms are based on replication and distribution of data on several cites, which could be spread around the globe. This should enhance the resilience and availability of the CPS ecosystems, especially in case of emergency.

- **Infrastructure costs reduction.** Maintenance of cloud computing applications is easier and more cost effective, because they do not need to be installed on each computer system, and can be accessed from different places. Multi-tenancy enables sharing of resources and costs across a large pool of users.

4. CPS and Big Data

Data sets, both those in rest and those in motion, are tending to grow beyond the capability of traditional processing methodologies, and to differ from traditional data by being highly heterogeneous and having multiple sources (variety), not being completely trustable (veracity), being large and complex (volume) and arriving with high speed and non-periodically (velocity). This is known as Big Data [9] [10]. Big Data is about extracting valuable information from data in order to use it in intelligent ways such as to revolutionize decision-making in businesses, science and society. The continuous and tremendous growth of data volume and velocity combined with easier access to data and the availability of powerful IT systems have led to intensified activities around Big Data.

CPS will be a major source, collector and distributer of data, not only in volume, but also in velocity, variety and veracity. The importance of the intersection between Big Data and CPS will grow in the coming years due to the increased attention on data as important business assets. The combination of Big Data and CPS will be a *must* to remain competitive.

4.1. CHALLENGES

- **Handling massive data production.** New technologies will increase the already massive input of data, and in the case of CPS it will represent what has already been called a Data Tsunami. In addition to this ever increasing volume, the combination of heterogeneous data from various sources will require new applications for integration, query and analysis, along with high performance computing, and data reduction techniques [9]. The inputs will also be different from each other: Some will be numeric data, others will be graphical (photo, video streaming), and even others will be textual information. This variety can be faced by creating new types of data stores to support flexible data models.

- **Distributed data storage and processing.** In the technical arena, one of the issues to solve is related to remote storage of Big Data. Cloud-based models have helped make storing and processing big datasets much cheaper than before, providing data accessibility and IT power [8] [10]. However, this usually leads to a centralized data store at the cloud provider's data centre, which will not scale in the CPS setting. To enable decentralized data storage and processing a number of problems arise. Where and how must the data be stored? What replication, parallelism and requirements are there? In addition, due to the nature of CPS, the number of connected devices will increase quickly, leading to increasing amounts of data and increasing data traffic. Despite that increase in data volume and velocity, requirements towards real-time analysis of, and responsiveness to, that data will become increasingly important.

- **Monetizing Big Data stemming from CPS.** The combination of Big Data and CPS will lead to a daring movement from the management perspective: finding the best way to monetize this opportunity. New rationales and paradigm shifts will be plentiful, but market demands are too quick to be faced without approaching these new technologies to optimize a company's standing. The domains using huge datasets such as healthcare or scientific research have always been the traditional users of Big Data, but the current situation combining Big Data with CPS provides useful new areas, including such as in manufacturing or food production, where the new technologies can provide valuable context awareness.

- **Data visualization.** Due to the decentralized, distributed nature and mobility of data sources (such as sensors and smart devices), as well as the unprecedented volume and velocity of data itself, novel means for data visualization are required in order to leverage this information for human decision making. Traditional means for visualization as used in control centres and dashboard will not scale to this Big Data CPS setting.

4.2. OPPORTUNITIES

- **Leveraging Big Data analytics for CPS adaptation.** CPS will produce an unprecedented amount of data. Such real-time data offers novel opportunities for real-time planning and decision making and thus may be analysed in order to drive the dynamic adaptation of CPS. Using changes in user profiles, monitoring of context/environmental data through IoT, etc. Big Data techniques may deliver actionable insights on which concrete adaptation actions to perform by a CPS in order to respond to those changes.
- **Greater customization and smartification in the products and services:** European customers are demanding a greater customization and smartification in the products and services they consume, which is a chance to fill in with CPS and Big Data [10], which supposedly will generate a beneficial economic effect in Europe. McKinsey Global Institute states that very developed areas like Europe can profit most from Big Data [11], and the Centre for Economic and Business Research calculated the impact of Big Data in the United Kingdom alone from 2012 to 2017 to be 25.1 million pounds and 58,000 jobs. Europe is a leader in the introduction of embedded computing technology in several industries such as aerospace, automotive, health care, smart cities and transport, giving a great starting point.
- **Assuring CPS assets stay online**. To remain competitive, companies seek out new ways to get the most out of their assets, assure their assets stay online, and plan for unexpected failures. Companies must take full advantage of all available Big Data information resources by analysing data and applying insights to CPS. Early warnings on product quality and reliability issues help minimize disruption, waste and reputational damage. Smarter, just-in-time maintenance strategies based on predictive and prescriptive analysis may save money and boost operational efficiency. Predictive algorithms are useful to increase the performance in detecting unscheduled maintenance, aging assets, losses in processes, etc.

5. Software-based Services on top of CPS

With the advent of CPS there are new opportunities for innovative ways to efficiently and effectively manage sourcing, development, production, logistics, and sales using software-based services and develop new business models for hybrid-serviced products. Beyond the physical flow of materials, e.g., in raw supply or end product form, the information provided by sensors, smart items, embedded systems and also end users opens up unprecedented opportunities in creating novel innovative software-based services.

The value to the end-user is created by the applications and software-based services making efficient use of the information from sensors directly or via systems of systems. Decisions may be taken in a much more informed way because CPS fosters access to an unprecedented amount of data about physical world objects with low latency. This substantially improves an organization's agility.

5.1. CHALLENGES

- **Instance-based architecture for a 'true' Business Network of Things.** CPS will allow to drastically simplifying handling of physical world objects (things) in software systems and services. As an example, instead of representing the physical items of a warehouse in a database (requiring scanning or monitoring of physical items), the physical items themselves may be directly queried. Such an instance-based architecture requires corresponding data standards, which can be processed by domain-independent and domain-specific services to do the following: (1) represent things such as products, batches, or designs; (2) software-based services on the business level to exploit and share seamless access to things; and (3) execute standardized software-based services, which trigger or reflect the movements between the participating organizations. Also, this architecture needs to handle aggregations of things (e.g. all packages of a contaminated batch), handle user authorizations and user access, and represent policies such as 'Minimum Stock Level' in Logistics. Such an instance-based architecture could naturally represent all relevant objects in a business network, facilitating companies to (1) become more agile in highly dynamic collaborations with ever more external parties; and (2) enable end-to-end visibility to track and trace the genealogy of things.
- **Service architecture for software-based services on top of CPS.** Future services on top of CPS will assist the business user rather than guiding him. Such software-based services need to have four characteristics which differentiate them from today's business applications: (1) be self-explanatory in a way that business users can design them to their needs without support from IT experts; (2) be adaptable/flexible, in a way that they are suitable for companies of any size, from a single freelancer to very large organizations; (3) be self-adapting and flexible processes, immediate integration of things into the network of business processes; and (4) be cross-organizational in nature. Setting up collaborations of services or including external data is currently time consuming and expensive, because users cannot implement this without deep IT expertise. The challenge is creating a CPS *architecture* making delivery of value-added, software-based services simple, allowing business users to setup collaborations on their own and within minutes. It should be as easy as setting up a connection on Facebook, allowing users to customize their system to their needs or include external data or Big Data on the fly, without involving IT experts. This also requires a unifying data model, which allows users to specialize generic objects and services according to their individual needs.

5.2. OPPORTUNITIES

- **Software-defined Industries.** Industry is shifting towards just-in-time processing, production and delivery of innovative products and services, often for a lot-size of only one. In manufacturing, for instance, programmable facilities produce customized products as opposed to large quantities of products. Highly optimized manufacturing plants and supply systems will be able to easily adjust to fluctuations or arising customer demands. Production in this model relies on the actual demand sensing and reconfiguration of the means of production in software through CPS rather than on the traditional long term prediction and prognostication. Variability in demand becomes a strategic advantage in the competition, if a company is able to take advantage of it. The days of static Lean Manufacturing are gone. Manufacturing companies have to become 'leagile' (lean + agile) or they risk becoming extinct. 'Leagile' implies (a) continuously monitoring and analysing huge volumes of data about production systems, supply chains and inventories, and systematically eliminating waste, and (b) elastically obtaining manufacturing capacity and capabilities on demand from the manufacturers at the edges, who wish to pool their capacity on the cloud to attract more orders from the ecosystem and thus increase utilization of their machines and resources, to cope with seasonality of demand [12].

6. Conclusions

Europe is well positioned, but strengthened research and innovation activities are needed to meet the challenges imposed by the specific nature of CPS. The grand vision of CPS goes far beyond existing systems thinking in that it breaks fundamentally with systems developed on the assumption of a closed world. We go from the predefined and prescribed construction of a system (or systems of systems) to a construction that is evolving at run-time without any visible master plan. In other words, clear system boundaries will cease to exist, and systems may be overlapping, since a system is virtually defined and may be a transient notion defined temporarily for the purpose of executing a single function or business process.

This white paper has identified four major areas of enabling technology with a strong impact on CPS: software, services, cloud, and Big Data. Traditionally, these enabling technologies are considered more from the business information perspective. The convergence of business information systems with embedded and cyber-physical systems will open up a range of novel opportunities, as well as future research and innovation challenges.

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