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Road2CPS

Priorities and Recommendations for Research and Innovation in Cyber-Physical Systems

European Commission

ROAD2CPS

Meike Reimann, Carsten Rückriegel (Lead authors)
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Steinbeis-Edition

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Executive Summary

This document summarises the findings of the Road2CPS project, co-financed by the European Commission under the H2020 Research and Innovation Programme, to develop a roadmap and recommendations for strategic action required for future deployment of Cyber-Physical Systems (CPS).

The term ***Cyber-Physical System*** describes hardware-software systems, which tightly **couple the physical world and the virtual world.** They are established from networked embedded systems that are connected with the outside world through sensors and actuators and have the capability to collaborate, adapt, and evolve. In the ARTEMIS Strategic Research Agenda 2016, CPS are described as **'Embedded Intelligent ICT Systems'** that make products smarter, more interconnected, interdependent, collaborative, and autonomous. In the future world of CPS, a huge number of **devices connected to the physical world** will be able to **exchange data** with each other, access web services, and **interact with people.** Moreover, information systems will **sense, monitor and even control** the physical world via Cyber-Physical Systems and the Internet of Things (HiPEAC Vision 2015).

Cyber-Physical Systems find their application in many highly relevant areas to our society: **multi-modal transport, health, smart factories, smart grids and smart cities** amongst others. The deployment of Cyber-Physical Systems (CPS) is expected to increase substantially over the next decades, holding great **potential for novel applications and innovative product development.** Digital technologies have already pervaded day-to-day life massively, affecting all kinds of interactions between humans and their environment. However, the inherent complexity of CPSs, as well as the need to meet optimised performance and comply with essential requirements like safety, privacy, security, raises many questions that are currently being explored by the research community. Road2CPS aims at accelerating uptake and implementation of these efforts.

The **Road2CPS project** identifying and analysing the relevant **technology fields** and related **research priorities** to fuel the development of trustworthy CPS, as well as the specific technologies, needs and barriers for a successful implementation in different **application domains** and to derive recommendations for strategic action.

The document at hand was established through an interactive, community-based approach, involving over 300 experts from academia, industry and policy making through a series of workshops and consultations. **Visions and priorities** of recently produced **roadmaps** in the area of CPS, IoT (Internet of Things), SoS (System-of-Systems) and FoF (Factories of the Future) were discussed, complemented by sharing views and perspectives on CPS implementation in **application domains,** evolving multi-sided eco-systems as well as business and policy related **barriers, enablers and success factors.** From the workshops and accompanying activities **recommendations for future research and innovation activities** were derived and topics and timelines for their implementation proposed.

Amongst the **technological topics,** and related future research priorities **'integration, interoperability, standards'** ranged highest in all workshops. The topic is connected to digital platforms and reference architectures, which have already become a key priority theme for the EC and their Digitisation Strategy as well as the work on the right standards to help successful implementation of CPSs. Other themes of very high technology/research relevance revealed to be **'modelling and simulation', 'safety and dependability', 'security and privacy', 'big data and real-time analysis', 'ubiquitous autonomy and forecasting'** as well as **'HMI/human machine awareness'.** Next to this, themes emerged including 'decision making and support', 'CPS engineering (requirements, design)', 'CPS life-cycle management', 'System-of-Systems', 'distributed management', 'cognitive CPS', 'emergence, complexity, adaptability and flexibility' and work on the foundations of CPS and 'cross-disciplinary research / CPS Science'.

Non-technological priority themes, were particularly seen to be **CPS education, training and skills** and **business models** accompanied by recommendations to address the **'human in the loop',** and further invest in **community building and networks** and **collaboration** on a regional, national and global level as well as across domains and value chains. **Demonstrators and living labs** are essential to alleviate concerns and **regulatory and legal issues** to ensure a reliable framework. **Societal dialogue and awareness raising** as well as **ethics** are crucial elements of future CPS development, because of the pervasiveness of CPS into every-day life. Further recommendations include 'to focus EC incentives on open approaches such as **open data,** open platform building, supporting open innovations as well as open source solutions'.

Regarding the **application perspective,** five domains have been analysed for their specific needs, the advantages CPS can bring and barriers to be overcome for successful CPS deployment. Many similarities could be detected, especially for the underlying technologies, but also domain specific differences between **smart manufacturing, smart energy, smart transport, smart city, and smart health** could be observed.

Main **barriers** to be overcome, are missing **interoperability, integration and standards,** the **fragmentation** of initiatives and across application domains and missing **skills** (knowledge, competences, IT education, multidisciplinarity). Mastering **complexity,** and overcoming concerns regarding **safety and stability** will be crucial for the success of future CPSs. A major showstopper, next to **high implementation costs** and **missing demonstration** are concerns regarding **security, privacy and confidentiality.** Business related barriers include missing **business models,** missing **openness** (open data) and vendor lock, missing **legal frameworks, regulation, IPR** protection, **liability and** concerns regarding **multiple ownership. Conservatism** and **resistance** to change in some sectors and countries and missing **entrepreneurial** thinking are barriers together with difficult access especially for **SMEs.** Moreover, **social acceptance and awareness** needs to be ensured and **ethical concerns** need to be overcome.

In the concluding chapters, innovation opportunities with high potential impact on the adoption of CPS in different industrial sectors are discussed in more detail. Going beyond the pure technical compliance of the solutions, this includes, amongst other aspects, emerging business models.

In summary, progress in key technological and non-tech fields identified, will help to fuel the development of trustworthy CPS, broaden their applications and enable new business. A cross-disciplinary, multi-domain and inclusive approach should be followed, to best benefit economy and society as a whole.

1 Introduction

Digitisation is a term that has in recent decades become widespread. In general, digitisation is defined as conversion of analogue information into digital information. Digital technologies are all types of electronic tools, systems and devices that produce, store or process data. Digital technologies like mobile devices, sensor applications and interoperable systems are already part of our daily lives, and have affected the way humans interact with their environment. Further progress in areas like the Internet of Things (IoT), cloud computing, big data and data analytics, robotics and 3D printing will increase the presence of Cyber-Physical Systems (CPS), the digitally driven technological fusion of physical and digital spheres. In fact, CPS enable interconnectivity with different devices and systems. For European industries, there is large potential as the further integration of digital technologies into industrial processes can severely change the way business value is generated from products and services. Using large sets of data, digital technologies can be used to re-engineer business processes, e. g. creating sustainability by utilising available resources more efficiently and effectively. Recent studies estimate that digitisation of products and services can add more than €110 billion of annual revenue in Europe in the next five years (strategy and PwC, Boston Consulting Group, 2015).

Digital transformation and mainstreaming digital innovations across all sectors are now considered a necessity in order to stay ahead in the race for global advantage. The European Commission has expressed this need in its Digital Single Market (DSM) strategy and its succeeding initiative on Digitising European Industry. Digital is in fact a driver for economic growth, as stated in the European Commission's Communication on Digitising European Industry (COM (2016)180 final): "Embracing digital technologies will help companies to grow beyond the EU internal market and make the EU an even more attractive location for global investments". The EC Strategy towards digitisation includes:

- Facilitating the coordination of European, national and regional initiatives
- Mainstreaming digital innovation across all sectors by setting up a pan-European network of 'Digital Innovation Hubs'
- Strengthening leadership in key parts of the digital value chain e. g. platforms
- Supporting the development of standards and interoperability
- Providing a regulatory framework and eGovernment action plan
- Preparing people for the digital age by enhancing skills and training

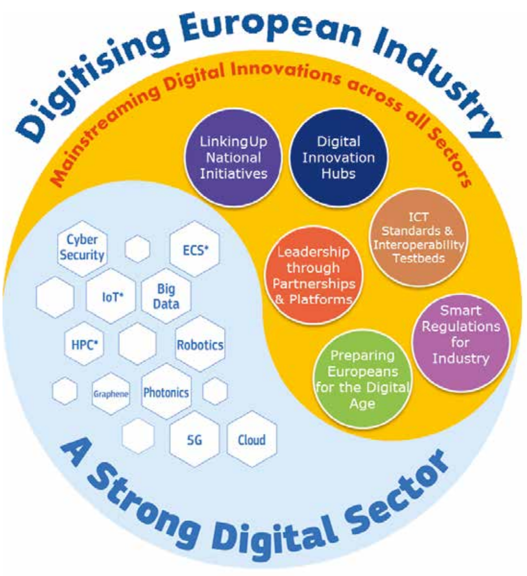


Figure 1: Digitisation Strategy of the European Commission (European Commission).

In order to seek full advantage of what digitisation offers, European governments have already initiated initiatives like 'Industry 4.0' in Germany, 'Smart Industry' in the Netherlands, 'L'industrie du Futur' in France or the 'High Value Manufacturing Catapult' in the UK. Nearly all Member States have meanwhile brought similar initiatives on the way. Under the umbrella of the 'Digitising European Industry' initiative, the European Commission foresees to complement these initiatives and stimulate coordination by involving public and private stakeholders at regional, national and EU-level. In order to mainstream digital innovation across all sectors the European Commission plans to invest about €500 million from its programme for research and innovation (Horizon2020) to be complemented by investments of the Member States.

For the areas of Cyber-Physical Systems, two elements of the 'Digitising European Industry' initiative are of particular importance: i) creation of a pan-European network of 'Digital Innovation Hubs' and ii) support of digital platforms.

The European Commission aims to set-up a pan-European network of 'Digital Innovation Hubs'. Digital competence centres such as technical universities and other research facilities that offer facilities for testing innovations prior to any investment by companies will be linked across the EU and turned into 'Digital Innovation Hubs' offering a one-stop shop for knowledge on latest digital technologies, testing facilities, access to finance, market intelligence, training and education, incubator services, innovation and other services. 'Digital Innovation Hubs' are an important step forward for mastering digital transformation, companies, particularly SMEs, can gain experience and insight on novel development of cutting edge technologies and have the chance to turn these developments into opportunities for their business. 'Digital Innovation Hubs' will provide for essential innovation eco-systems that help fostering the implementation of CPS across Member States.

Digital Platforms are digital gateways for various groups of a particular or more sectors creating value by enabling interaction between the different actors to achieve multiple business functions. Platforms can also bring together digital solutions for one specific sector. In the future, platforms will increasingly serve as a basis for business and economic growth. In order to accelerate the uptake of CPS implementation, platforms for CPS deployment will be a key feature and can be enabled by specialised 'Digital Innovation Hubs'.

2 Cyber-Physical Systems

The term Cyber-Physical System (CPS) describes hardware-software systems, which tightly couple the physical world and the virtual world. They are established from networked embedded systems that are connected with the outside world through sensors and actuators, acquiring data streams from the physical world, establishing and continuously updating a virtual twin of the physical world – and with the capability of interacting with the physical world, following instructions from the virtual sphere. (Geisberger, E., Broy, M., 2012). Furthermore, CPSs are not merely networked embedded systems but software-intensive, intelligent systems with the capability to collaborate, adapt, and evolve.

Digital components are increasingly integrated and embedded into products and services that are in everyday usage. In the future, CPS will become natural in managing complex systems (e. g. smart grids, transport and manufacturing) and will make everyday objects intelligent (e. g. homes, offices, cars, cities and clothes). The CPS community foresees large potential in creating a competitive edge for Europe, serving existing and new markets across different industries. CPS will bring a step change in the way industry designs, produces and generates value from products and related services.

CPS combine challenges from a variety of domains, including large distributed systems, sensor and actuators devices, critical infrastructures, Systems-of-Systems. Their pervasiveness in our environment makes some of these challenges tangible even for non-specialists. The advent of software intensive systems taking over a growing number of tasks (unmanned vehicles, high frequency trading, surveillance of field crops, etc.) is a source of both fascination and anxiety for a large part of society.

Traditional approaches of central control and superordinate management seem incapable of dealing with the vast eco-system of networked systems that today is only in its infancy. More flexible approaches are required to have the constituent systems of a CPS collaborate, negotiate, or organise themselves. Throughout the entire lifecycle of a CPS, novel approaches will be necessary, which an evolution of the systems engineering discipline will have to offer. Elaboration of technological challenges and steps forward in fields like ubiquitous autonomy, modelling and simulation, big data real time analysis, forecasting, human machine awareness, interoperability and standards and safety, security and privacy are needed to overcome the constraints successful implementation faces today.

Besides the technological challenges, the heterogeneous field of CPS also faces many non-technological challenges, which have to be overcome to enable a successful future implementation. A major problem is seen in the fragmentation of initiatives and efforts across domains and value chains, as well as in the alignment of research efforts with the requirements in the application domains. For an effective exploitation of emerging CPS-relevant technologies and approaches a clear picture of the field as well as a forward look to enable better planning are needed. Results from past and ongoing projects are still underexploited and constituencies are still not formed to an adequate level to reach a critical mass and cross-fertilisation across sectors and value chains.

3 Road2CPS Objectives and Approach

3.1 Objectives

The Road2CPS project has been conceived to accelerate the successful deployment of CPS by:

- Analysing the impact from past and ongoing projects, identifying the gaps and bridging efforts towards impact multiplication
- Developing technology, application and innovation strategy roadmaps for CPSs to serve as a catalyst for early adoption of CPS technologies
- Building a CPS constituency by bringing together the key players (from academia and industry) from a broad range of application domains, and across the value chain, to contribute to the Road2CPS action plan
- Enhancing CPS implementation and demonstrating business opportunities through case studies
- Developing recommendations for future research priorities and implementation strategies

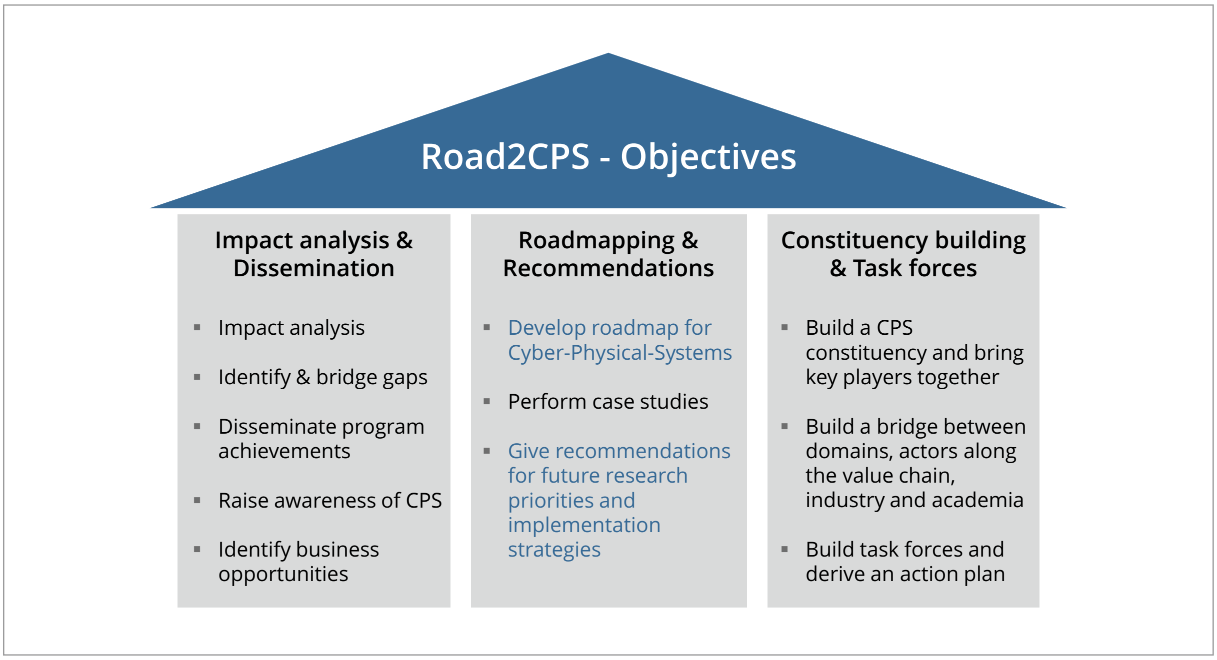


Figure 2: Road2CPS objectives (Road2CPS Project).

Road2CPS was a 24-month coordination and support action (02 / 2015–01 / 2017), co-funded under the European Union's H2020 Research and Innovation Programme in the area of Smart Cyber-Physical Systems. The project aimed at carrying out strategic action for future CPS through roadmaps, impact multiplications and constituency building. Road2CPS was coordinated by Steinbeis-Europa-Zentrum, Germany and supported by six other partners from 4 European countries (Loughborough University, UK; Newcastle University, UK; CEA, France; Fraunhofer IPA, Germany; AnySolution, Spain and ATOS, Spain) pursuing the following objectives:

The document at hand focusses on the development of a **Roadmap for Cyber-Physical Systems** (pillar in the middle), building on outputs from the other pillars and the **Road2CPS Recommendation**s for future research priorities and innovation strategies. This document presents the vision, challenges, research and innovation priorities for a set of highly important **CPS technologies** as well as the impact and deployment of CPS in **five application domains.** The main aim of the roadmap is to highlight the benefits of using a CPS approach (related to the market needs) and provide users with the most relevant technical trends that will help to implement this CPS approach. The document aims at giving support to the European Commission in structuring the future CPS related Research Programme, as well as at giving researchers in the field and decision-makers from industry, academia, and policy making of the related domains a broad perspective on developments and implementations in the field of Cyber-Physical Systems.

3.2 Approach and Methodology

The roadmapping methodology initially follows a parallel technology-push and market-pull approach, combined into a strategic innovation roadmap:

1. A **technology-driven approach** identifies priority research results and research fields with a high potential for a technological breakthrough. A special focus was put on the following themes: i) integration, interoperability, and standards; platforms and reference architectures ii) modelling and simulation iii) safety, security and privacy iv) big data and real time analysis v) ubiquitous autonomy and forecasting vi) human and machine awareness.

2. A **market-driven approach** identifies socio-economical needs, barriers and important application domains for CPS with a special focus on the following application domains: smart manufacturing, smart energy, smart transport, smart city, and smart health.

3. A **strategy roadmap** combines technology push and market pull perspective to derive strategies for future research and innovation priorities and their implementation.

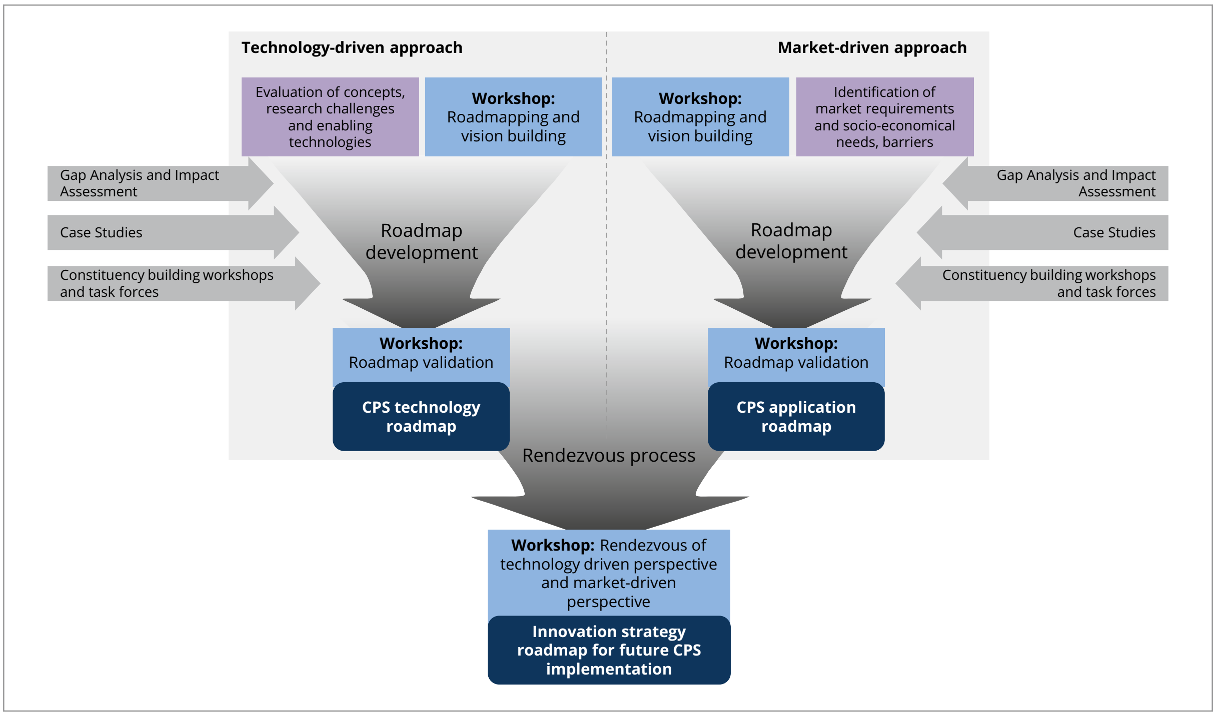


Figure 3: Overview of the Road2CPS approach (Road2CPS Project).

The generation of technology and application roadmaps started with an early roadmapping workshop to compare and validate existing roadmaps and to find consensus on priority themes to be further elaborated. The activities were accompanied by desk research and interviews adding relevant content during the roadmap building process, leading to 3 stand-alone deliverables (D2.1 Report on scientific and technological challenges and D2.2 Report on market requirements and socio-economical needs D2.3 Intermediate Technology and Application Roadmap). Moreover, results from other project activities fed into the roadmapping activities (gap and impact analysis, cases studies, constituency building workshops). The roadmaps were completed and validated within two further roadmapping workshops and final results were compiled into D2.3 Road2CPS Technology and Application Roadmap. The results and finding from the two perspectives were combined in a fourth roadmapping workshop on innovation strategies and recommendations for a successful implementation of CPS (D2.4 Strategy Roadmap).

Following a participative approach **over 300 experts** were involved in **4 roadmapping workshops** (Consensus Roadmapping WS, Paris June 2015; CPS Visionary Scenario WS, Stuttgart June 2016; CPS Technology and Application Roadmap WS, Newcastle October 2016; Strategy Roadmapping WS, Brussels November 2016) and **3 Constituency Building Workshop** (Future Platforms, Turin October 2015; ICT-1 Cluster Event, Vienna May 2016; Smart Destinations, Mallorca October 2016).

4 Technology Roadmap and Recommendations for Research Priorities

In the following sections, the technological priority themes identified by Road2CPS and the recommendations for future RD&I derived thereof, are presented. They include the following topics:

- Platforms, Reference Architectures, Interoperability and Standards
- Modelling and Simulation
- Safety, Security, and Privacy
- Big Data and Real Time Analysis
- Ubiquitous Autonomy and Forecasting
- Human and Machine Awareness / Human Maschine Interface

Progress in the described topics will not only lead to more efficient, safe, secure, reliable and trustworthy CPS but will also enable new applications and business opportunities in various domains, further described in chapter 5.

4.1 Platforms, Reference Architectures, Interoperability and Standards

4.1.1 Introduction

The use and interaction of CPSs requires an exchange of various formats via different communication networks. A large number of models, systems and concepts from an extremely wide range of domains play an important part in shaping the respective structure. A specific difficulty arises in terms of terminology and standardisation. In this context, standards create a secure basis for technical procurement, ensure interoperability in applications, provide uniform safety rules as well as a future-proof foundation for product development and assist in the communication between all those involved by means of standardised terms and definitions. In order to handle the complexity of this standardisation challenge, generic reference architectures as well as platforms are needed. A common understanding of the term 'reference architecture' is a generalisation of a set of solutions, for the depiction of one or more architecture structures. Furthermore, it shows how to compose different components in one solution, which is fundamental for the interaction of CPS.

In the short-term, it is expected that CPS will help companies facing challenges caused by globalisation. CPS can cover the need for responsive manufacturing and logistical processes and correspondingly lower communication barriers along current complex manufacturing value networks. The latter, in particular, have been caused by an ever growing trend for specialisation, which in turn increased the number of OEM (original equipment manufacturers) involved in the production of a specific product and decreased the vertical range of manufacture.

In order to meet the continuously raising demands of global markets, it is necessary to build up collaborative networks and to integrate Cyber-Physical Production Systems in the medium-term. To achieve this, it is necessary to reduce integration efforts as well as enable companies using services of multiple platforms at the same time. This means each company of the value chain is no longer bound to a specific software or service vendor, which will reduce the level of vendor lock-in.

In the long-term, this also enlarges opportunities for SMEs. Building on multi-sided platform approaches will enable them to participate in multiple value chains. Barriers for using one or more platforms at the same time will be reduced and it will be possible to enter different value chains with a minimum set of requirements. Furthermore, interoperability between different platforms is expected to evolve substantially and will eventually prevent predominance of platforms offered by large corporations part of the value stream.

Not only platforms but also CPS are evolving and are providing the basic infrastructure for lots of vital social, business and economic processes already. Even nowadays, many infrastructures would not function properly if their CPS systems would fail. Consequently, one of the important points is to guarantee a universal access to robust and secure infrastructure services. The two main pillars for this are standards and open interfaces, which build the basis for all upcoming evolutions.

Besides the technological aspect, the further evolution of platforms and CPS will also have a huge impact on society, like opportunities brought by communication infrastructure for business and work management and the increasing servitisation of complete sectors of the economy such as banking, transport, retail or government services. Barriers, which prevent overcoming interoperability problems, are mainly caused by the software architecture of components and integrated applications. Concerning the technical integration of platforms, it has to be considered that there are already various manufacturing IT solutions developed and applied on factory level as well as on manufacturing value network level. Each of these solutions brings its own data models, IT services and security measures.

4.1.2 Roadmap, Priorities and Recommendations

To overcome the barriers described in the previous section, a holistic multi-sided platform eco-system has to be developed. One of the major activities to reach this goal is the development of an integration framework, which supports the seamless exchange of data, information, and services.

The following steps should be taken to provide an integration framework, as well as to strengthen Europe's position as the industrial CPS provider.

Road2CPS recommends:

- Increase reliability of CPS systems – this opens the door to the certification of secure systems, the creation of validation methodologies and the impact of these activities into the different standardisation bodies
- Implementations of full CPS systems in different domains – currently there are very good solutions for individual parts of systems like smart grids, but there is a lack of a full deployment allowing the validation of the whole CPS subsystem. The provision of such facilities in this and other environments will strengthen the position of Europe and its technology providers.
- Sustaining the evolution of reference architectures and platforms – currently, much research and innovation has been carried out regarding interoperability; the focus for the near future should be to consolidate and integrate platforms and frameworks w.r.t data semantics and promote their access to a wide audience of companies
- To promote this current synergy in the long run, we need to integrate reference architectures and platforms in the curricula of engineers and technicians, and encourage a change of mind-set in traditional slow-paced industries towards more agility which one assigns generally to digital industries

- Improvements of standards are possible, incorporation of emerging standards and reference architectures should be considered, encouraging convergences initiated by standardisation bodies (like RAMI 4.0 or IIRA).[1]

In summary, the market is ready and waiting for innovative solutions based on CPS technology, but this will not be exploited in its full potential until existing concerns are addressed.

4.2 Modelling and Simulation

4.2.1 Introduction

When building an engineered system, computer-based models are usually created that describe the proposed system mathematically, with enough accuracy that predictions can be made about the final system behaviour. This allows designers to adjust the design before the first prototypes are built. In this way, modelling and simulation techniques are capable of improving design quality or reducing development costs, because models can detect design flaws at an early stage and are much cheaper for exploring design alternatives than physical prototyping. Therefore, widespread adoption of modelling and simulation techniques that support CPS design could potentially bring better and/or cheaper CPSs to many domains, in a shorter time-frame, whilst modelling used for verification and validation can improve reliability of CPSs, and could be incorporated into certification regimes.

Modelling and simulation tools are usually designed specifically for a particular domain and / or a particular discipline. Modelling notations and techniques from (at least) two disciplines are typically needed in order to design a CPS accurately (to reflect the contributions of the physical aspects and the cyber aspects). Unfortunately, it's difficult to integrate multiple modelling approaches, because of the difficulty of capturing and expressing identical information in separate notations which are not designed to support the same features. This makes it difficult to simulate global CPS behaviour using conventional modelling techniques (Branicky, M., and Mattsson, S., 1997; Fishwick, P., 2007; Sonntag, C., 2009).

There are a number of possible approaches to tackle the problem, including: aggregate modelling techniques, such as Dymola[2] or gPROMS (Oh, M., and Pantelidis, C., 1996), hybrid automata (Henzinger, T., 1996), hybrid Petri Nets (David, R., and Alla, H., 2001) and hybrid process theories (e. g., Cuijpers, P., and Reniers, M., 2005; van Beek et al., 2006). Automated model transformation is a possibility; this requires mapping between different formalisms. There are examples already available for platforms including Modelica, gPROMS and EcosimPro (Jorrín, A., et al., 2008). Common interchange formats have been created, including: DEVS (Discrete Event System Specification) (Zeigler , B., et al., 2000); SysML (Huang, E., et al., 2007); ModelCVS (Kappel, G., et al., 2006); and Modelica (Larsson 2006; Siemers, A., et al., 2009). Collaborative modelling ('co-modelling') and collaborative simulation ('co-simulation'), where models created in different tools can be used in joint simulations, are also a possible solution. Co-simulation frameworks include: Crescendo[3]; Simantics Open Simulation Platform[4]; TrueTime[5],Tronic Silver[6]; SKF[7]; and CAPE-OPEN[8].

1 http://www.iiconsortium.org/vertical-markets/manufacturing.htm [Last visited November 2016]
2 http://www.3ds.com/products-services/catia/products/dymola/
3 http://crescendotool.org/
4 https://www.simantics.org/
5 http://www.control.lth.se/truetime/
6 http://www.qtronic.com/en/silver.html
7 http://www.skf.com/
8 http://www.colan.org/

4.2.2 Roadmap, Priorities and Recommendations

CPSs are required in many cases to offer reliable behaviour in challenging conditions, potentially constructed from multiple constituent systems, operating in different domains and engineering disciplines, developed by separate organisations. Systems level techniques should be capable of producing accurate system predictions and simulation. New approaches are required that build on the mature and well-understood techniques that are already used in these separate disciplines and fields, with mature, industry-ready tools capable of supporting traceability and model management. Techniques need to be as accessible and usable as possible, so that conclusions and analysis can be understood by engineers from varied disciplines.

Modelling and simulation technologies for CPSs should increase confidence in the safety and security of CPSs, increasingly offering support for model- / software- / hardware- / system-in-the loop simulation and testing, and enabling CPS certification (ARTEMIS, 2016). Open standards across the value chain will facilitate development of CPS, given the importance of interoperability for modelling and simulation tools and techniques. In the short- to medium-term, industry-led initiatives should continue development of open frameworks and standards for model interoperability, to support integration of heterogeneous models and datasets, including legacy components. Industry-academic coalitions can be leveraged in the same timescale to generate improved tool support for heterogeneous modelling techniques, including model management and traceability support, and the ability to consider models of different levels of granularity and abstraction in appropriate relationships to each other.

In the medium-term, industry-academic coalitions can contribute work on techniques to support incorporation of wider range of formalisms into CPS co-modelling techniques (e. g., agent-based models, probabilistic modelling, economic or human factors models), and incorporation of architectural features into models (for analysis of e. g., security or fault tolerance). In the long-term, this will allow the development of improved, systems-level analysis of global CPS behaviours, taking account of a wide range of environmental factors. Industry-academic coalitions could therefore be used in the long-term timeframe, to combine formal verification and simulation technology, and produce this system-wide simulation. This could help CPS designers to detect emergent behaviour and optimise CPS systems, particularly for systems that experience long-term evolution or short-term dynamic reconfiguration. There's a need to develop control strategies and methods for decision-making to facilitate reconfiguration and partial autonomy. Industry-led initiatives in the long-term could be leveraged examine this challenge, and also to evaluate model-based verification and validation techniques for CPS certification regimes (ARTEMIS, 2016).

There's a shortage of skilled technical staff in the marketplace with understanding of multiple disciplines. CPS curriculums for engineers and computer scientists are needed. Exchanges and training programmes can support this, and could be launched in the short-term.

Road2CPS recommends:

- Academic-industry collaborations should produce tool support for heterogeneous modelling techniques, including model management and traceability support, and the ability to consider models of different levels of granularity and abstraction in appropriate relationships to each other, in the medium-term. In the longer-term, as these techniques mature, they can be extended to support other useful types of modelling paradigm to capture, e. g. human behaviour.
- Also in the medium-term, academic-industry collaborations can also focus on combining formal verification and simulation technology, to produce system-wide simulation techniques that aid in detecting emergent behaviour and in system optimisation. In the longer-term, these can be extended to cater to systems that experience long-term evolution or short-term dynamic reconfiguration.

4.3 Safety, Security, and Privacy

4.3.1 Introduction

By definition, a CPS can affect the physical world, and in many cases will therefore need to be classed as a safety-critical systems. Meanwhile, security and privacy are important in CPS engineering because of the large amount of valuable data about persons and organisations, which is potentially collected. In general, the cross-disciplinary nature of many CPSs demands that approaches to safety, security and privacy take into account potential hybrid threats – such as security attacks, which exploit hardware vulnerabilities to reach software (or vice versa), or safety threats arising from unexpected hardware and software interactions.

In terms of safety: safety-critical system design aims to improve confidence that a system performs as expected. Safety assurance for CPSs is a challenge, in part because CPSs are generally required to be adaptable, easy to connect together and updatable (Trapp, M., et al., 2013). Assessing the safety of a system, checking its adherence to regulations or standards, and delivering certification, is a long and expensive process, so that the requirement for many CPSs to deliver adaptability is at odds with requirements for safety. Safety must be considered at the systems level, and, for CPSs, this implies considering aspects of hardware and software and how they interact. However, fault tolerance techniques employed in hardware and software design differ in some aspects, and there's a shortage of designers familiar with both disciplines. CPSs may need to support mixed-mode fault tolerance, since separate components may be employing different strategies to achieve dependable operation (Rubel, P., et al., 2007). The requirement to consider safety becomes more and more important as CPSs begin to acquire greater levels of autonomous decision-making, based on data collected about the environment. We need to be confident that a CPS imbued with full or partial autonomy makes decisions, which do not compromise safety.

In terms of security: there's also a need to look at 'end-to-end security' for CPSs (Sperling, E., 2016). The large numbers of wirelessly-connected devices which are found in some CPSs provide a greater number of access points than a traditional system, and there is a possibility of hybrid attacks, exploiting vulnerabilities in hardware in order to affect software or data (or vice versa). Techniques for delivering a secure system differ in hardware design and software design and there is a shortage of trained engineers familiar with the specialist security techniques employed for the two disciplines. Systems must be capable of changing over time, so that updates and patches can be deployed and functionality can be evolved. In order to maintain security, mechanisms for deploying updates, patches, etc., must be associated with security policies and technologies to avoid becoming a vulnerability that can be exploited when connected to a wider system (Sperling, E., 2016). Interfaces which have become obsolete must be blocked, so that they do not become forgotten entry points. Finally, if data is accessed by an intruder it's important to be able to detect this quickly so that mitigating action can be taken.

The ability to deliver safe and secure CPSs is tantamount to their widespread adoption. Both the public and the end-users (including industrial end-users) must be confident that information gathered by CPSs is reasonable and cannot be exploited; adoption of CPS technologies is unlikely to reach its full potential if this is not the case. An inability to design CPS which be have safely could result in injury or loss of life, since CPSs have an effect in the physical world.

4.3.2 Roadmap, Priorities and Recommendations

Approaches for managing security and safety need to be extended to cope with the characteristics of hardware and software.

In terms of safety: we need confidence that we can deliver systems which behave safely, even when they are fully or partially autonomous, dynamic, distributed, and surrounded by human users, operators or environments. Safety assurance of CPSs needs to be based on research results of a number of complimentary research communities (Mo, Y., et al., 2012). This requires improved modelling and simulation techniques in the face of systems that are reconfiguring dynamically, potentially experiencing connectivity issues and evolving in the long-term. Techniques should take into account many system aspects such as architecture, ergonomics and stochastic events, whilst integrating physical processes with complex computation can lead to unexpected side effects so techniques are needed to integrate planning and design across cyber and physical aspects. Advances in modelling and simulation techniques can be made in the short- to medium-term. Certification processes capable of coping with dynamicity would aid emerging markets and product development processes; this should be considered in the long-term. A culture change may be needed in many application domains to adapt to safety-oriented design; training and exchanges can help.

In terms of security: security techniques currently in use need to be extended to cover an entire CPS in its end-to-end operations, to ensure that the hybrid, distributed, systems-of-systems nature of a CPS cannot be exploited by attackers. This includes securing low-powered, low-resourced devices which may not be able to exploit conventional encryption, and ensuring that we can detect security breaches which exploit the hybrid nature of CPS systems. We can develop frameworks and tools that support reasoning about security at the systems level in the short-term. Also in the short-term, a new range of concepts may be needed to connect the different approaches employed hardware designers and by software developers, and a wider understanding of security concepts in CPS domains that traditionally have not concentrated on security. We also need a more advanced, detailed understanding of the role of the human in CPSs, since in many cases humans are part of the CPS architecture. This work can be initiated in the short- to medium-term.

Related to privacy: we need to ensure that both CPS operators, and end-users, fully understand the implications of connecting systems together. Education and frameworks could ensure that it's transparent to users what data is being collected from and about them.

Road2CPS recommends:

- Academic-industrial collaborations to build on existing modelling techniques for fault tolerance or security aspects of dynamic or evolving systems, and processes for achieving certification of such systems
- Encourage and support industry initiatives to extend or develop frameworks and tools that support reasoning about security at the systems level
- Industry-academic coalitions to study the role of the human operator in the CPS architecture
- Training schemes encourage efforts to develop shared concepts of security between cyber and physical sides, development of systems approaches, and training for engineers with different backgrounds and domains

4.4 Big Data and Real Time Analysis

4.4.1 Introduction

The current Big Data landscape is very heterogeneous, as multiple providers co-exist offering similar solutions at different layers. In theory, these should be interoperable, however, often this is not the case. Additionally, the regulatory framework is very diverse in terms of data handling, storage and management in the EU, thus most of the technology providers are based in the US. Nevertheless, European companies are embracing the development of full Big Data eco-systems aiming at overcoming some of the current barriers that prevent the development and deployment of Big Data.

Linked to this Real Time Data Analysis provides access to data with near-zero latency between data ingestion and processing, thus the results obtained can be directly applied to the processes that are influenced by the information considered. This technology will have huge impact on the evolution and adoption of CPS technologies in the different sectors.

The digitisation of infrastructures implies an exponential increase in the amount of data generated in the short-term, therefore the evolution of Big Data towards mature and complete solutions will transform industry worldwide, from preventing maintenance to optimisation of resource allocation covering multiple new services based on the data driven innovation. The graph presents expected contribution of Big Data to the different sectors.

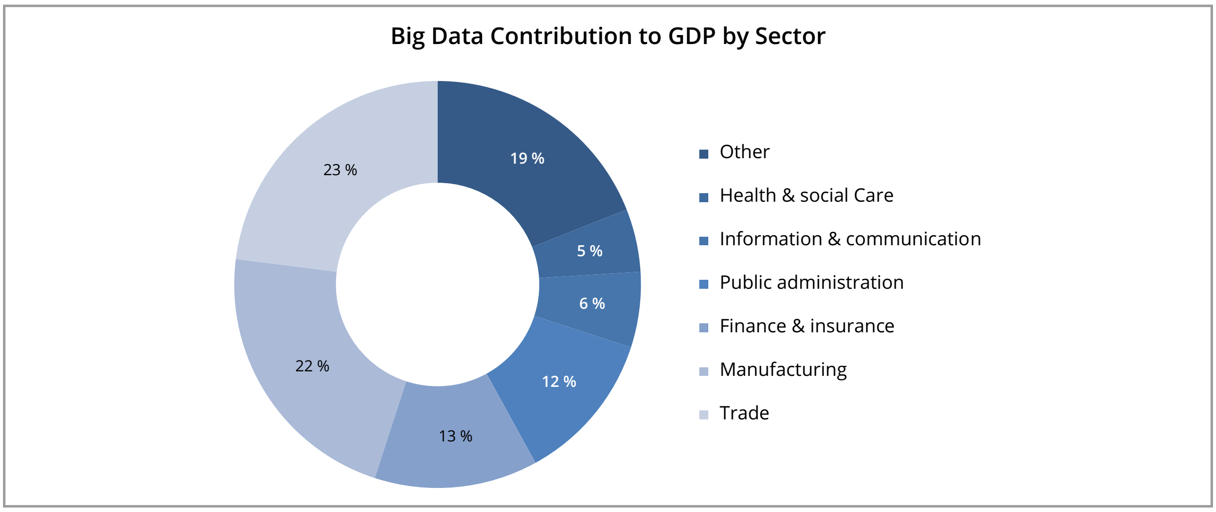


Figure 4: Expected contribution of Big Data to sectors (The information has been extracted from the report of Demos Europa and Warsaw Institute for Economic Studies – "Big & Open data in Europe. A growth engine or a missed opportunity?").

However, before reaching that optimal point several challenges remain to be tackled, urging solutions at different levels:

- The provision of stable and scalable solutions for the data '6cs'; clipping, classification, condensation, confusion, confounding and non-cancellation
- From a European perspective: decentralisation leads to disparate policies; a push is required to embrace innovation in some traditional sectors and to create stronger synergies between large companies and innovative SMEs
- From a market and business perspective, there is a lack of access to real Big Data infrastructures, and corresponding eco-systems are still in fledgling stages. Additionally, boost in Big Data is particularly hindered by issue of data sharing and access rights, IPR and regulations
- Technical challenges are caused by insufficient interoperability, lack of common standards for data and that no linked data are available for pre-processing
- Other factors determining the success and speedy adoption of Big Data solutions are the development of professional profiles, the capacity for changing users behaviour in the data driven society, and how to assure the safety and security of processes involving the use of data at all levels of the value chain[9, 10, 11]

9 ATOS-CODEX – https://atos.net/en/solutions/atos-codex-analytics
10 SAP HANA – http://go.sap.com/product/technology-platform/hana.html
11 SIEMENS – From Big Data to smart data http://www.siemens.com/innovation/en/home/pictures-of-the-future/digitalization-and-software/from-big-data-to-smart-data-why-big-data-has-to-become-smart-data.html

4.4.2 Roadmap, Priorities and Recommendations

In this scenario, there are several key aspects that will help to boost the adoption of Big Data solutions and that will strengthen the European position as technology provider. Currently the EC is funding two strategic projects that work on the demonstration of transformation capabilities of Big Data technologies in strategic sectors like Transport and Bio-Health under the ICT-15-2016 call. In addition to this there are also some smaller initiatives building smaller demonstrators and tools. These activities represent a great starting point, and cover some of the recommendations done by the BDVA in the Strategic Research and Innovation Agenda; however, more actions recommended to be taken.

Road2CPS recommends:

- **Development of Innovation spaces,** cross-organisational and cross-sectorial environments that will allow addressing challenges in an interdisciplinary way
- Development of **policies and harmonisation of regulation** that support technological opportunities offered by Big Data and Real time analytics
- Promotion of **new educational programs** addressing the professional skills gap that emerging technologies are creating
- Promotion of programs that work on the **development of common data ontologies** that facilitates the integration of big data solutions and the replicability of the tools
- **Data Processing Architecture** represents a key challenge for the upcoming scenario of Big Data, on the one hand, it is required to **reduce the cost per bit;** on the other hand it is important to **identify valuable data to be stored** in the cloud and how **edge computing** modifies current approaches
- **Alignment of Real time analytics requirements** imposed demands improvement in algorithms **and processes** that must be demonstrated and assessed through different use cases and in different sectors and **exploiting computation capacity** currently available
- **Security is a major aspect** that has to be developed. Firstly, it is important to assure the integrity of the data collected, after that the architecture should be prepared for dealing with advanced communication scenarios implementing E2E encryption and robust architectures. Here the key aspects are reliability, security and safety
- Data based services and visualisation **moving from abstract processing algorithms towards services** exploiting the full potential of Big Data requires the development of visualization techniques that help to understand potential and value of solutions

In summary, the growing number of connected devices and sensors and the generation of huge amounts of data is a challenge and an opportunity that should be taken. The challenges of storage, preparation, analysis, usage and the seamless integration of new techniques like edge computing are enablers for future research areas and business opportunities. Interwoven with big data real time analysis in a digitised and data driven economy, data and information exchange processes will occur in near real-time – which means that Big Data analytic tools need to address this challenge, and the regulation should be harmonised and the expertise of companies complemented to be ready to seize this opportunity.

4.5 Ubiquitous Autonomy and Forecasting

4.5.1 Introduction

Autonomy in the context of Cyber-Physical Systems (CPS) is about who or what makes the decisions, and then executes them. The point of CPS is that many decisions will be made by non-human components using Artificial Intelligence, under the authority and responsibility of humans, partly to make use of human capabilities of wisdom and resilience, but also, importantly, to meet legal and safety requirements.

Progress in this technological area is very fast across the world, meaning that the state of the art is changing continuously, as can be seen in the arrival of multi-function robots, autonomous vehicles in driver assistance apps in automobiles and in control of facilities in the home, and this is just the start of the revolution. The impact is expected to be huge; a large market in billions of euros will be available in the 2020s. The promise of autonomy within CPS is immense; the potential for close control of processes with step changes in efficiency and effectiveness, enabling products and services to be tailored to the needs and desires of the individual for minimal cost and usage of resources. Not only will this promise change the lives of billions of people, it will make a significant move towards a sustainable world for our children.

But there are challenges; an old German proverb states: 'the devil is in the detail', and it is true that CPS has many challenges, especially for autonomy. Current progress is mainly in dealing with the physical world, where the laws of physics pertain. So autonomy applied to navigation and the control of machines is fairly well developed though many issues remain (Mosterman, P. J., and Zander, J., 2015); however, when CPS interoperate with humans in the delivery of services (e. g. robots for health care in the home), where considerations of ethical behaviour and cultural issues are of importance, progress is still slow, and much more cross-disciplinary research and innovation is required.

A second major challenge concern to jobs; it is widely expected that many jobs will disappear as embedded autonomy with CPS becomes widespread, disrupting social life and upsetting current economic models. This is somewhat outside the boundaries of CPS technology, but is a consequence that must be addressed.

The third major challenge arises result from the necessary interoperation of humans with CPS. Humans have numerous capabilities and talents, but coping with the massive floods of data within CPS systems is not one of them. Making sure that humans are able to exercise their authority and responsibilities wisely, effectively and with a minimum of unwanted consequences when faced with these floods is a technical problem still to be solved effectively; it is an area where modelling and simulation is of fundamental importance, and needs further work.

4.5.2 Roadmap, Priorities and Recommendations

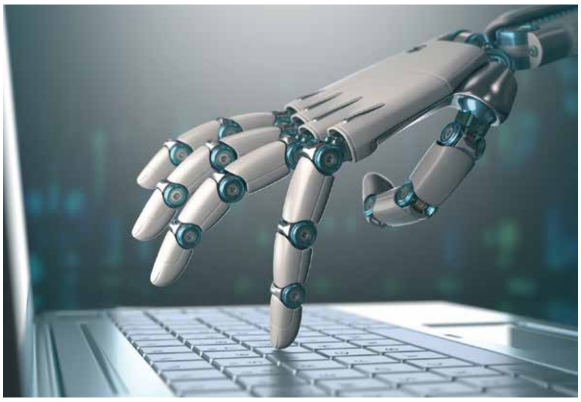
Progress in the development of autonomous applications and devices is proceeding at astonishing speed, driven by worldwide interest and accompanying financial commitment, both public and private. In general terms, the physical aspects of autonomy in terms of energy, mass, movement and perception of objects in the environment are near-market or deployed; autonomous vehicles demonstrate this. However, when control is more virtual than physical, progress at the present time is much closer to research and development stages. This is due to the combined issues of ethics, liability, consumer acceptance and the legal status of autonomous devices, all aspects of considerable importance. The more influence that an autonomous application has on human behaviour and societal life; the more difficult it is to develop, deploy and support the autonomous application.

In the short-term (2016–17), we expect to see a rapidly increasing number of applications involving autonomy, particularly in the domains of transport and manufacturing. These applications are likely to be in the form of real-world pilot projects, demonstrating both the potential for autonomous operations and also identifying and evaluating the societal adaptations necessary for these systems to be fully adopted, covering safety, availability, legal issues, human behavioural responses, etc.

In the medium-term (2018–19), CPS should be capable of supporting semi-autonomous systems at high TRLs, including virtual engineering and design space exploration of semi-autonomous CPS (ARTEMIS 2016). Multi-modelling tools such as INTO-CPS are expected to deliver pilot products in 2018. Support for the development of control strategies and methods for decision-making will facilitate reconfiguration and partial autonomy of system elements (Thompson, H., et al., 2015).

In the longer-term (2020–21), CPSs are expected to begin offering some features for fully autonomous capabilities, including initial, bio-inspired approaches for modelling self-configuring CPS with complex human interactions. Formal verification techniques will be a high priority area, given that many CPS will not have their configurations fully determined until run-time, thus placing great emphasis on modelling and simulation to provide assurance regarding safety, ethical behaviour, etc.

Road2CPS recommends:



- Develop the theoretical underpinnings of safe, legal and ethical behaviour by autonomous agents as a cross-disciplinary study
- Evolve a full understanding of the technologies and the support required in order to guarantee reliable, ethical, trustworthy behaviour by autonomous CPS
- Boost 'situation awareness' for CPS with autonomous components; for both the state of internal operations of the CPS and for the CPS operational environment
- Support techniques for run-time verification and validation to ensure that autonomous CPS are safe and reliable. This applies both to system components and to the whole CPS, given that the final configuration of the CPS may not be known until run time
- Develop standards, protocols and APIs for autonomous agents and their interconnections
- Enhance modelling and simulation tools for autonomous agents both for their design and operation, and for the agents to use

The main non-technical enabler for fast progress in autonomous operations is the generation of regulations, and business and insurance models to enable real-world testing of progress.

The main barrier to progress is the lack of a well-educated, skilled, widespread workforce to carry out the necessary R&D&I&M that this area needs.

4.6 HMI / Human and Machine Awareness

4.6.1 Introduction

In the practical CPS world it is now widely accepted that CPS necessarily must include and involve people. These people may be customers of the CPS, whose only interest in the CPS is that it helps them to achieve some personal goal or they may be co-workers within the CPS providing authority, resilience, agility, wisdom and skills; or they may be the systems engineers who design, instantiate, and upgrade CPS. Note that one individual can occupy all three of these roles at different times and in different places.

The goal is to ensure that individual can interoperate with the CPS easily, efficiently, effectively, safely and usefully to reach an objective, and feel at ease in doing so. Given that humans are legally expected to be in authority and to hold responsibility for what the CPS does or does not do, there is a strong requirement in CPS design and operations to be a safe and efficient interface between the people and the CPS hardware and software, especially when the CPS has autonomous components within, capable of making decisions that may have unintended consequences for people. Meeting this goal is fundamental for the legal and social acceptance of CPS, in turn allowing the promised benefits to communities and society arising from CPS individually and in networks to be realised.

However, there are many challenges; first as the non-human parts of the CPS become more capable, complex and autonomous in their behaviour, the more diffuse and complex are the transactions at the interfaces between the human and non-human agents. Secondly, there is an issue of trustworthy behaviour; this refers both to the behaviour of the non-human parts and of the humans; both sides of the interface need to trust the decisions and actions of the other side. Thirdly, because of the promise of efficiency, effectiveness and exactitude in the CPS paradigm, there is a requirement for minimum variability and maximum precision in human behaviour, especially when in authoritative mode. Fourthly, it is evident that modelling and simulation tools, techniques and knowledge will be fundamental not only for design, installation and configuration of the CPS but also for operations, for resilience and recovery, and for maintenance and upgrades. Finally, the world of CPS promises to be awash with tidal waves of data, which must be compressed to enable human understanding without loss of significant detail, in order that people may be 'situation aware' and therefore able to make good decisions.

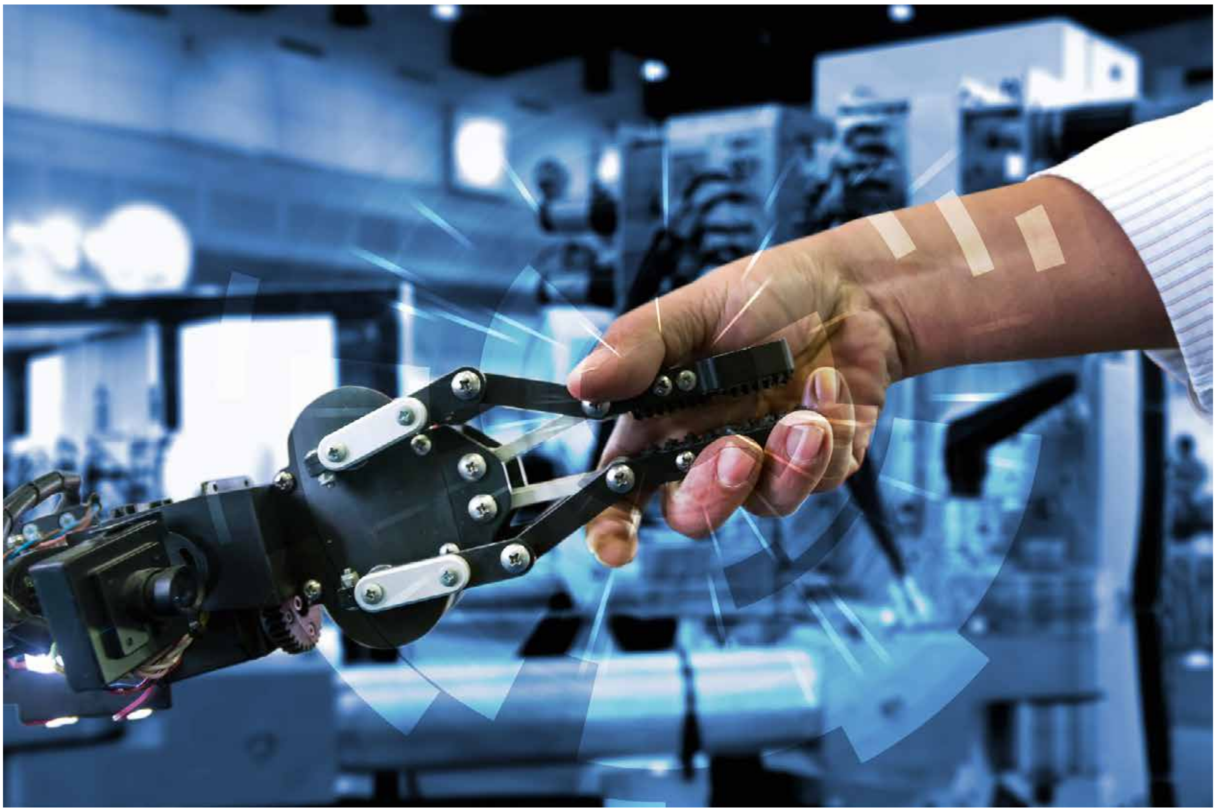
4.6.2 Roadmap, Priorities and Recommendations

In the short-term (2016–17), it is likely that attention will be focussed on physical interactions between CPS and people, rather than cognitive interaction (in other words, dealing with physical safety, avoidance of collisions, interpretations of human movements, etc.), necessary so that more complex cognitive interactions can be explored with less risk. In the medium-term (2018–19), CPS research is expected to focus much more on command and control, where issues of informed command and informed consent predominate. Necessarily, this includes situation awareness, both on the part of the CPS and of the humans with which these systems interact.

In the longer-term (2020–21), CPSs are expected to begin offering features for fully autonomous capabilities, in which the legal status of autonomous decisions are addressed, together with issues of ethics in CPS behaviour. We also expect that issues in the 'architecture and networking of trust' to be explored; how CPS can establish the trustworthiness of decisions made by their human co-workers as well as how CPS should behave to ensure their co-workers will trust them. Complicating these issues are the effects of contracts between businesses constraining how CPS components shall work, changing configurations of CPS, and many others, all collected together under the banner of ' new business models'.

Road2CPS recommends:

- Develop a platform for improved models for job design and trade space to minimise human variability, maximise performance and ensure safe, legal and ethical behaviour
- Support a full understanding of trustworthy behaviour for human-machine interaction, including the effects of cultures on trust and performance
- Improve interface technology for multi-channel, distributed interfaces for team performance, adaptable for different human skill levels and confidence
- Enhance modelling & simulation tools and techniques to enable verification and validation of human decisions and actions prior to execution
- Develop standards, protocols and interface specifications to extend human interaction with advanced, autonomous CPS
- Enhance modelling and simulation tools to make available human avatars for use in design and operations



The main non-technical enabler for fast progress in autonomous operations is a strong commitment to address the technology human-machine interaction. The main barrier is the lack of a well-educated, skilled, widespread workforce to carry out the RD&I&M in this area.

4.7 Conclusions – Technology and Research

The sections introduce and discuss many issues of importance to the benefit of the EU28 as a whole, to its communities and to its individual people. This is a common feature of each section; all the recommendations about the future and the RD&I needs affect all three levels. Furthermore, from a CPS perspective, the recommendations are complementary, necessary, and implementable.

There are a few overarching conclusions that can be drawn from the text:

- There is a fundamental shortage of professional people in all flavours of engineering, especially electronics, hardware, IT and systems engineering to bring to fruition and deliver good services to the EU-society. But it is not just engineers that are needed; because CPS will pervade society very deeply, there is a need for other classes of professionals as well, including those from the social sciences
- Many of the sections allude to the need for more standards, particularly in connection with ontologies, to enable CPS to interoperate to form CPSoS, and to interoperate with human society. These ontologies should ensure coverage across all interoperability layers, from physical interconnection up to strategy and business. Absent these, and we may expect operational failures of steadily greater significance as the failures occur up the interoperability hierarchy
- The capability to carry out comprehensive modelling and simulation is a sine qua non for the lifecycles of CPS. There is a dearth of tools, architectures, languages, aggregated modelling techniques and capable people to carry out this work. A fundamental barrier in this area that is being addressed but not yet overcome is that the IT industry has worked with discrete time, whereas other engineers have worked with continuous time
- A particular area of concern for the future is the explosion of data that will be created continuously as CPS and their associated networks of sensors are instantiated in society. This flood may come to threaten the provision of communications, computing and storage capacity to utilise the data to create knowledge and value. This problem exists from the network technologies upwards to people who query the data and interpret the resulting visualisations
- Taking all these issues together, it seems evident that the near future, we may expect not just disruption to the external environment of business models, consumer habits, established procedures, and legal concepts; there will also be disruptions within the CPS that in theory will deliver a bright new world. With all the simultaneous development that will be happening in so many complementary areas, we may expect "failures to be the norm in CPS". It seems evident that resilience will become a much-sought-after capability within society in the near future
- Given the inter-related aspects of the points above, it may be beneficial for future funding of the expected developments to be oriented towards the Smart Community concept, since this embraces all of the points above. In other words, in future 'No Call stands alone'; any project must show some commitment to the Smart Community concept, and rather than looking inwards, should look outwards to co-operation with other projects. It will also ensure that each project will have to consider the humans who may be beneficiaries and victims of the project

5 CPS Deployment in Application Domains

CPSs find their application in many highly relevant areas to our society: **smart manufacturing, smart energy, smart transport, smart city, and smart health** among others. The inherent complexity of CPSs (and related complexity management), as well as the need to meet optimised performance and comply with essential requirements like safety, privacy, security, raises many questions that are already beginning to be explored by the research community.

Although major successes could already be achieved within specific areas, there is still a huge gap between theoretical concepts, technical developments and prototypes, and successful implementation and industrial application. Additionally, there are considerable differences with regard to the propagation and maturity of CPSs amongst the application domains, the actors along the value chain, academia and industry, and between the multiple disciplines contributing to this complex field. Strategic action is necessary to bring the relevant stakeholders together to: i) enable application domains to benefit from state-of-the-art technological developments; and ii) focus research efforts into those areas that will enable visions on future application scenarios to be realised. The following sections describe the vision and recommendations for different domains CPS has, or is expected to have, a vast impact on.

5.1 Smart Production

5.1.1 Domain Vision

Manufacturing is key for the EU economy and has a long successful tradition. At present the manufacturing domain is undergoing a fundamental change towards a more and more IT-related production – nevertheless the automation of the manufacturing processes is not a new phenomenon, but the level and the penetration of IT within this traditional sector is more accelerated than before. The term 'Industrie 4.0' proposed by the German government, indicates this paradigm shift and refers to past revolutions brought about by disruptive technological advancements: mechanisation (1st), electrisation (2nd), informatisation (3rd) and finally the 4th industrial revolution brought about by digitisation and interconnection of products, value chains and business models. The melting of mechanical and hardware-related aspects on the one hand and IT-related questions on the other hand is also known as IoT technology or, in case of the Road2CPS project, Cyber-Physical Systems.

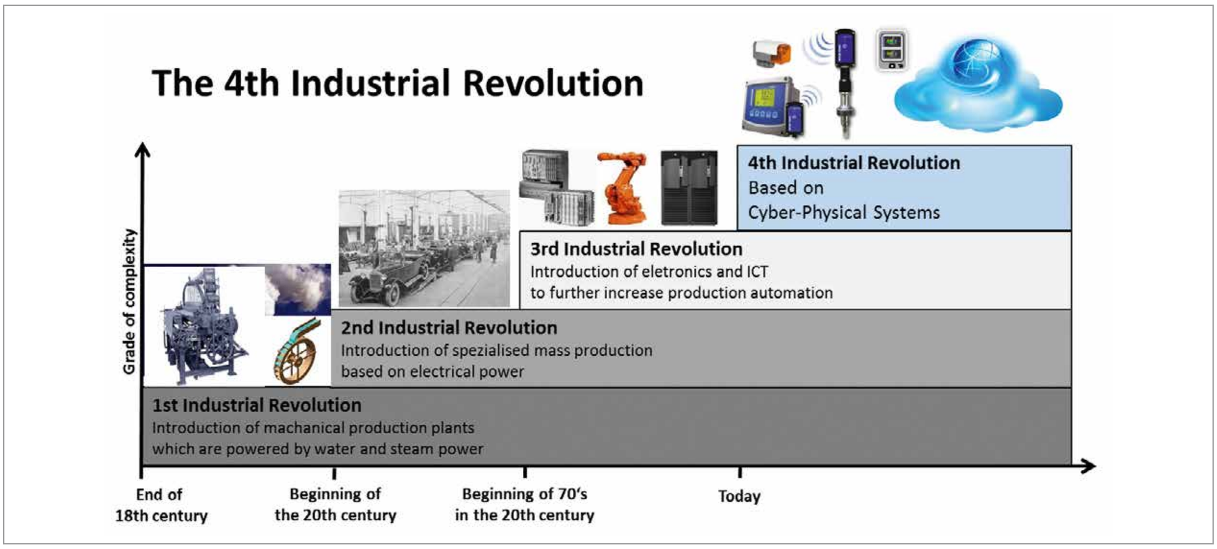


Figure 5: The different stages of the industrial revolution (Fraunhofer IPA).

Currently, there is a split between the different silos of 'physical world' and 'cyber world' – this needs to be overcome and shifted to the idea of industry 4.0. For instance, information is more provided by operators manually as well as through low automatised management processes between cooperation partners within the value chain and even more within different departments of one firm. This lack of standards and interoperability is a big issue in terms of creating a framework for a smart manufacturing sector. There is still need for awareness building, however some companies have already embraced CPS technologies to maintain competitive. There is also a will to integrate more IT in customer services. The vision for the smart manufacturing domain is to create an autonomous production system including aspects of servitisation, personalisation as well as transparency along the entire production process and supply chain.

5.1.2 Roadmap, Priorities and Recommendations

As the manufacturing sector is more traditional in terms of business models and application of radical innovations, good practise and success stories are necessary to convince the more sceptical decision-makers. Usually, they need to take the first step of experiencing the usability of the new solutions to be persuaded. The practical applicability of the new way as well as linkage with a successful business model could help to overcome this issue. Besides business cases, demonstrators and pilots could promote the transferability of the innovative solutions. Many SMEs, which are specialised in machine engineering are currently trying to develop digital services for their traditional mechanical or mechatronic products. Here they are confronted with a lack of standardisation in regard to security and communication standards. OPC UA is currently being viewed by many as an emerging de facto standard for Industry 4.0, but an actual decision still has not been made, which leads to insecurity on how to proceed. The German initiative Industrie 4.0 has also collected good business cases for large industry. However, the pilot studies should furthermore create an eco-system especially for SMEs.

The emergence of current IoT and IIoT platforms will most likely result in a number of domain specific platforms and not one or few large platforms, which cover all production needs. Since a common data model for interoperability spanning all domains is unlikely, an interdisciplinary approch of meta model development and semantic technology based on common standards needs to enable integration across platforms. This basic interoperability for various domain specific platforms by consolidating standards and reference architectures will enable the shift from the current purely service oriented focus to solution based business models which are based on combined services and collaboration from various platforms.

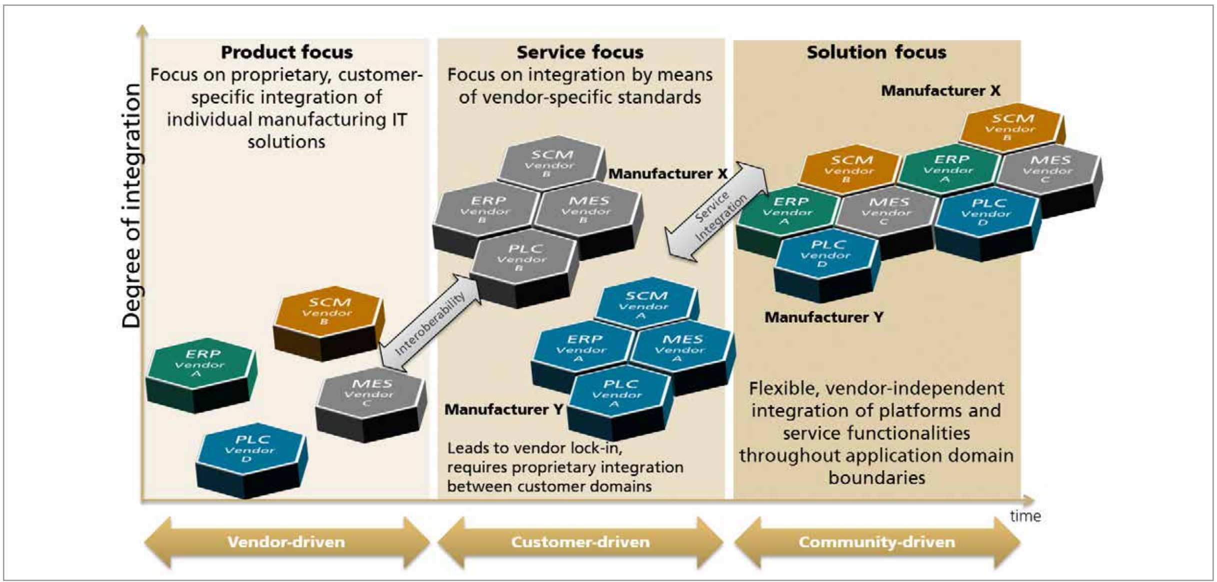


Figure 6: The shift from product focus to services and collaborative solutions in the future (Fraunhofer IPA).

Eco-systems supporting common test beds should enable faster and better exchange of experience and technology transfer of SMEs to drive innovation. Either by providing test suites for cross-domain equipment interoperability development or by creating eco-systems where participants can generate synergies. The integration of humans in digitised process chains is also an important topic, since the increased use of information and CPS technology will lead to changes in how current processes are executed and humans need to be integrated in an efficient, safe and meaningful way.

Regulation aspects and questions of legal frameworks are additionally a potential barrier for implementation of the Cyber-Pysical-Systems – solutions in this field need to be found by integrating different stakeholders such as decision-makers, academia, legislators, authorities, and industry.

5.2 Smart Energy

5.2.1 Domain Vision

The energy sector currently faces major challenges and upheavals, in order to continue meeting increasing demand for energy, adapting to changes in generation techniques and satisfying environmental targets. The sector's vision for future success centres on **smart grids**. A smart grid (Fang, X., et al., 2011; Hashmi, M., 2011; Giordano, V., and Bossart, S., 2012) is an energy-supplying infrastructure which is extensible, reliable, optimised, secure, resilient and flexible enough to cope with many small and large scale producers as well as with demand variations (Hashmi, M., 2011; Coll-Mayor, D., et al., 2007). It relies on much more and better-quality data about current and projected demands and usage against current and predicted power generation capacity. Smart grids are a vision and are not yet fully implemented; a variety of ICT technologies and engineering advances are necessary to enable this ability to store, manage and supply energy flexibly.

5.2.2 Roadmap, Priorities and Recommendations

Major challenges and drivers for the sector include:

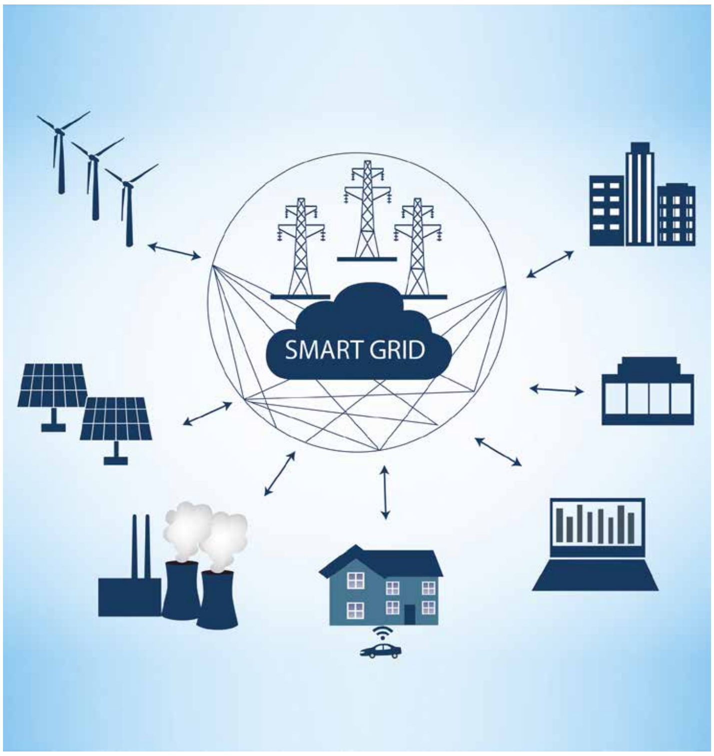
- Significant capital investment is required to increase the capacity, capability and efficiency of much of Europe's power transmission network (Hashmi, M., 2011)
- European Directive 2010 / 40 / EU commits Europe to decarbonised electricity production by 2050 (European Climate Foundation, 2009). However, the current energy infrastructure is optimised for carbon-based energy sources, which feature predictable generation from large powerstations. In contrast, renewable energy sources (RES) involve large numbers of distributed small generators (GRID+, 2013; acatech and EIT ICT Labs, 2012), and marked fluctuations in ability to generate (ROAD2SOS, 2013, acatech and EIT ICT Labs, 2012)
- Conventional techniques for managing load balancing have been based on large central generation and controllable industrial load (GRID+, 2013), which is not suitable for RES
- Energy demand is expected to continue increasing (European Climate Foundation, 2009). Predictions vary but some predict as much as 60 % increase by 2030 (Battaglini, A., et al., 2009), due to electric vehicles; rejection of carbonised heat; and increased numbers of small households (a separate household carries an energy overhead)
- As existing hydrocarbon extraction sites are drained, extraction will move to sites which smaller and less accessible, which will become economically feasible due to dwindling supply

The move away from carbon-based energy necessitates much more flexible grids, capable of adapting, monitoring and storing energy. At the current time, different stakeholders within the electricity markets have access to different types of information, and as a result it's very difficult to assemble an accurate, real-time picture of the current state of the global network, including current demand and capacity. CPS techologies are needed to close the gap so that a smart grid can collect this picture, analyse it and take decisions to ensure that current energy needs are correctly matched with available capacity. This principle of data gathering and network-wide monitoring is important for electricity distribution as well as oil and gas. **Big Data** is a major challenge here, since creating this type of picture will include data gathered potentially from millions of nodes (e. g., "smart" meters installed at consumer locations such as homes and offices) across national networks. **Modelling and simulation** tools will be needed for analysis and prediction. There is also a need for careful consideration of **privacy and security** issues when smart meters are widespread, to ensure that sensitive data is not "leaked".

CPS technologies can also be employed to improve efficiency and safety during industrial processes in the electricity, gas and oil sectors, by providing sensing capabilities, real-time monitoring and analysis and process automation. CPS technologies are important enablers for predictive maintenance planning, for example, and are also enablers for advanced monitoring and maintenance of remote infrastructure such as pipelines and power cables in inaccessible locations. At oil and gas extraction sites, CPS-enabled technologies enable automated processes, helpful for reducing costs and improving safety at remote and challenging extraction sites. Advances in **autonomous** systems that can increasingly tackle unpredictable environments – including underwater or underground – and make good decisions based on current conditions and environmental data will be useful. There's also a need for increased **interoperability** in the varied and diverse range of tools used to monitor energy grids and hydrocarbon processing; with a diverse range of tools on the marketplace, vendor lock-in and a lack of flexibility can be an obstacle that hinders adoption and exploitation of cutting edge technologies. There's a need for such systems to adhere to high standards of **safety**; modelling and simulation techinques to support rigorous engineering design will be needed to facilitate this, ensuring high quality designs whilst also reducing the cost of delivering safety. Smart grids which are genuinely flexible enough to cope with existing demand and less controllable generation methods are not yet a reality. Much research is required before these can be fully realised, including the topic suggested below. Investments in infrastructure for this sector are generally very large and long-term, and therefore expected implementation is also anticipated in the long-term.

Road2CPS recommends:

- Support efforts to reduce energy consumption e. g. through education, better building insulation, improving efficiency of existing devices, better power electronics, making better use of waste energy, etc. In many domains this requires excellent collaboration between engineering disciplines and computer scientists to exploit CPS techniques
- Install smart meters and upgrade infrastructure. Encourage and support appropriate open platforms and data exchange formats to enable smart grids in the electricity sector. Develop and install large-scale energy and heat storage solutions to support flexibility (this is in its infancy). Research and roll out real time market pricing & demand management incentives
- Consider carefully the evolution of market roles, particularly distributor roles, enabled by better ICT infrastructure
- Invest in big data techniques & improved sensing in order to enable effective smart grid management, and to improve the management and monitoring of other energy networks such as gas. Experience from other domains in predictive maintenance scheduling can also be deployed in oil, gas and electricity sectors
- Support increased automation to improve safety and efficiency at remote or inaccessible extraction and pipeline sites



5.3 Smart Transport

5.3.1 Domain Vision

The transport domain – aircraft, roads, rail, waterways, sea and, potentially, undersea are all in a rapid state of flux, with changes in the vehicles, their destinations, the physical infrastructure and the networks that link these and their customers together. At the same time, there have been changes to the business models, processes and procedures that make use of transport to deliver goods and people to their destinations. All of this has been driven by 'Artificial Intelligence' (AI) becoming embedded in software in these transport components, with the promise of faster, better, cheaper' delivery and, from a sustainability perspective, reductions in emissions and other waste. This rapid change in transport shows no sign of slowing, and affects all other domains as they utilise transport. For example, 3D printing of goods may result in great reductions in transport needs.

5.3.2 Roadmap, Priorities and Recommendations

There are four main drivers of change in the transport domain; firstly developments in 'Artificial Intelligence' enabling autonomous decision-making, better management of operations and reductions in cost; secondly improvements in computing power and enhanced networks (the IoT); thirdly, the move to alternative energy sources away from fossil fuels; and fourthly movements in manufacturing towards 'weightless distribution' such as 3D printing.

However, while these drivers are powerful, widespread and necessary, there are barriers, both technical and non-technical. Among the technical barriers are the current incomplete understanding of AI in the real world, the lack of standards and protocols for efficient operation of future transport networks, and the slow progress in restructuring renergy networks for transport and other needs.

Among the non-technical barriers are the need for a new regulatory environment that accommodates autonomous vehicles and networks, covering safety liability and insurance; the need for communities to accept the rate of this disruptive change to everyday life and to the environment as well as the major impacts on jobs, skills and employment; the need for businesses (especially SMEs) to change their ways of thinking, practices and patterns in this new world as well as meeting the challenges of new entrants into the domain from other fields who are keen to exploit the potential benefits.

Because the scale of change over the next decade is enormous, affecting inter-governmental regulations, ticketing and other networked office processes, in parallel with the introduction of technologies for driverless vehicles, all happening within the fixed architectures and infrastructures of cities and towns, there is an overwhelming requirement for planned, careful co-ordination to avoid wasted effort and needless disruption to communities and individuals. Chief among these co-ordination plans will be the development of large-scale information networks and Big Data applications that are safe and secure to enable the whole transport ensemble to operate effectively and efficiently, and to demonstrate resilience and fast recovery when circumstances demand this.

From a technology perspective, the development of autonomous vehicles in all transport modes as CPS devices that are safe, secure, and competent to fulfil user needs, as well as providing for human authority and responsibility over their operations is a paramount requirement. There will be an equivalent big requirement for standards and protocols for the interoperation of these vehicles and the information networks that will provide them with the instantaneous information necessary for smooth, safe operation.

All of this will require support; the networks, the vehicles, the information and knowledge both over the lifecycles of the individual components and of the whole Systems of Systems depicted below as change continually occurs. This is a demand on systems for education.

5.4 Smart Cities

5.4.1 Domain Vision

The SmartCities domain directly affects and is affected by other domains that are present in a city such as energy, transport and health above others, generating a complexity for the overall management of the city. Different technologies emerge (mainly IoT and CPS) that contribute to the efficient management of SmartCities. Interoperability is a key factor to combine the technologies used by the different domains. SmartCities call for more than just technological solutions; they must be human-centric and built for the sustained, optimal livelihoods of their inhabitants. CPS research and education communities will play a key role in SmartCities. A digital technology enhanced city is foreseen to improve performance and wellbeing, reduce costs and resource consumption, and engage more effectively and actively with its citizens.

5.4.2 Roadmap, Priorities and Recommendations

Three main drivers exist in the SmartCity domain:

- The development of local eco-systems capable of identifying everything a city needs and providing solutions at local level, the best way to solve problems citizens may encounter
- The development of cloud technologies (storage + processing) and big data applications, since decisions in cities could be taken based on data that has been gathered and analysed with the help of cloud technologies. Cities are direct producers of data, taking information both from citizens and from the great amount of different sensors and devices set-up in cities

- Providers of interoperability. Different devices, sensors, platforms, etc. coexist in cities and they interconnect with each other making cities a lot more efficient and therefore increase the communities' quality of life

These drivers are evolving very fast, but they need to overcome technical and non-technical barriers, the non-technical being more significant due to the fact that in the cities people are the focus. These barriers are security and privacy that deal with sensitive data, because not all data collected can be used directly and the privacy aspect must always prevail. It is a lot more difficult for citizens to accept security aspects that are more related to technological issues and especially convince them to share the data. The second barrier is linked with the existing digital divide and the difficulty of engaging citizens. The digital divide arises due to fast technological developments that make it difficult for older generations to adapt to them. This digital divide also exists in younger generations, which have problems in applying and understanding digital technology. Another barrier is related to different rules and regulations that exist throughout Europe concerning interoperability and standards applied to the main technologies applied in cities such as platforms, IoT, CPS.

The needs of cities are directly linked to the increase in the quality of life of its citizens, and this will be achieved by increasing the city's efficiency, promoting sustainable models and creating inclusive eco-systems. Linked to these needs are challenges that SmartCities have to face related to scarcity of both economic and human resources since skills and education. Collaboration within SmartCities is a big challenge taking into account the number of subsystems that coexist, share data and interoperate. The creation of innovative eco-systems where public and private entities can work together, including SMEs to promote bottom-up innovation is an opportunity that is being encouraged in different cities, but there is still a challenge to generate trust and joint collaboration.

CPS's challenge is to promote a new paradigm of SmartCities where the solution is not only technology and its interoperability, but also interaction with non-technology elements. Combining these elements will eventually create a city that is truly smart and capable of increasing the quality of life of its citizens. The technologies to be implemented are the combination of those that currently exists with those that will evolve over time. Interoperability between all of the devices in a city together with those implemented in other SmartCities will be the key to success.

SmartCites can be seen as large-scale Cyber-Physical Systems, with sensors that monitor cyber and physical indicators and with actuators that dynamically change the complex urban environment. Governments, organisations, and technology industries are confronted with the challenges of increased urbanisation, working to improve urban life by offering improved efficiencies with energy utilisations or services, for example.

The smart city approach is strongly dependent on non-technology elements like the acceptance of a CPS environment. Monitoring systems, autonomous controlling systems, and robots in fully automated automotive factories need to convince influential sceptics and of course have to be accepted by the population. As the SmartCity domain is a combination of different sectors such as transport, the building industry, energy, and infrastructure, the degree of complexity is even higher. Modelling and simulation solutions could help to reduce costs through a better overall planning.

5.5 Smart Health

5.5.1 Domain Vision

By 2025, the global population will have risen from six to around eight billion. In addition, the increasing average life expectancy of people in many regions of the world is creating a greater occurrence of chronic illnesses and a growing demand for high quality healthcare services. People's attitudes to healthcare are changing, too: instead of 'just' getting treatment for their illnesses, more and more people are placing value on targeted, preventive healthcare. Ambulant healthcare will increase in favour of clinical healthcare. In this context, a new model needs to be created, not only to solve new challenges in healthcare, but also taking into account the increasing costs of the systems.

CPS will be a key driver in this process. The rise of wearables and IoT technologies, the opportunities offered by Big Data for better analysis of medical data, the development of more complex and efficient platforms and training systems, and also the provision of innovative methodologies for performing traditional tasks in a more secure and effective way, all these factors are already "smartening" the health domain.

5.5.2 Roadmap, Priorities and Recommendations

The continuing financial pressure on health systems means that every year cost reductions need to be achieved. According to Ascent Look Out 2016+ research, digital means are foreseen to reduce European healthcare costs by 10 %, so the use of CPS could help to achieve this goal. The development of cloud technologies for storage and processing is also a driver for health sector; wearable will produce many data and information so future development in cloud technologies will improve the cost per bit (storage) and the cost for processing data. Commoditisation of Augmented and Virtual Reality will bring new benefits for patients and professionals in the health sector. Finally, the wide deployment of near field communication technology will facilitate the development of new services for medical professionals and patients.

However, there are also some barriers to be overcome, since Smart Health deals with sensible data **security and privacy** represent a big challenge both from the technical perspective but also from the user acceptance. **Patient acceptance of disruptive applications** is also a key factor to be solved that will require efforts in many directions from service design to user education. New uses of **telemedicine at home** require the deployment of sensors and devices at home that can be perceived as an intrusion. Moreover, the **heterogeneous health systems** and regulations across Europe are one of the main barriers in healthcare since developing universal solutions is very complicated.

Thus, there is a long list of aspects that will boost the deployment of CPS technologies in the Smart Health domain, increasing the accuracy of the diagnosis, simplifying monitoring and treatments going beyond personalised services based on data. The monitoring of stocks based on CPS technologies and the integration of the different solutions and platforms in a single suitable interoperable solution will pave the way to improve patient experience, re-invent businesses based on new opportunities, better delivery of a primary basic service, optimisation of the whole chain by introducing CPS technologies and develop IT architectures facilitating information among data exchange. Finally, new interfaces will bring innovative and more secure ways of interacting with systems preventing some of existing risks such as infections, time-consuming processes or stock monitoring.

CPS will be used increasingly in the health domain once key aspects are available. Increased application of CPS in the health domain can significantly reduce incidents of ill health through better preventive care, empower patients, reduce health costs, increase shared services, and provide tools assuring trust and compliance. Furthermore, promotion of collaborative interoperable eco-systems, should be increased and collaboration among private and public healthcare providers promoted.

Thus, new business opportunities appear for providers of technical enablers:

- **Platforms and Reference Architectures** – Through using platforms in health sector will be possible to integrate new IT solutions of different software vendors. SMEs in the health domain will be able to participate in several value chain avoiding high costs and efforts running two or more platforms in one company.
- **Interoperability and Standards** – Today, the health eco-system lacks any business model connecting all stakeholders, from patient to professional, so interaction between organisations within the eco-system must be straightforward.
- **Security and Privacy** – Privacy-enhancing technologies will help providers manage privacy risk by ensuring compliance with data protection legislation. Providers should be adapted to these privacy-enhancing technologies.
- **Safety and Dependability** – In order to reduce barriers to patients and professionals being able to access tools, services and data when they need, new security and safety solutions should be developed. Future business could be based on the development of these solutions that will be critical in healthcare.
- **Big Data and Real Time Analysis** – Nowadays hospitals collect vast amounts of insightful health data. New business could be developed in order to offer new services that make previously inaccessible data more available. Some examples might include offering anonymised patient data to pharmaceutical companies, and then these companies might use Big Data in order to improve treatments in healthcare.

CPS technologies are a key enabler in the Smart Health sector. Through using existing technologies such as cloud computing, social networks or Big Data, health care services will offer many potential benefits to patients, doctors and researchers. On the other hand, barriers, such as legislation and regulation disparity, have to be overcome, in order to encourage the collaboration between private and public providers. The expected evolution in the following years indicates that in the short-term the smart health sector will be evolved through CPS technologies providing new functionalities that optimise processes and patient information delivery.

5.6 Conclusions

The analysis of the domains revealed commonalities as well as domain specific drivers, needs, barriers and enablers. Some common requirements to be addressed for a better market adoption of CPS technologies are seen to be:

- Elaboration of regulatory frameworks for the different domains
- Train and educate labour force and traditional companies in IT and create strategies to attract talent to the EU
- Implementation of open solutions and standards to enhance interoperability and facilitate the integration of SMEs and innovators into the eco-system
- Adress security and privacy issues by providing technological tools as well as a legal framework that protects companies investing in innovative solutions
- Fostering new business models and a culture of innovation / entrepreneurship

Main Drivers and barriers are presented per domain below

Domain	Drivers	Barriers
Smart Production	▪ Reduction in cost ▪ Development of cloud technologies ▪ Deployment of new wireless communication technologies ▪ Increasing computing capability of embedded devices	▪ The manufacturing industry has a lot of legacy equipment which needs to be adapted ▪ Connected equipment increases need for trust and security concepts and solutions ▪ Increased interoperability requirements for connected equipment
Smart Energy	▪ Aging infrastructure ▪ Changes in energy demand, e.g. electric vehicles ▪ Less controllable, highly distributed renewable generation techniques ▪ Many small producers/consumers ▪ More flexible markets needed to support dynamic pricing, incentives	▪ “Smart” grids require major infrastructure upgrades, including real-time monitoring, smart meters, storage, big data ▪ Market structure must ensure stakeholders can benefit if they invest in infrastructure ▪ Market changes required to support flexible grids
Smart Transport	▪ CPS enabling autonomy in vehicles ▪ Sustainability agenda ▪ Potential benefits in information, quality, performance from CPS ▪ Adoption of ‘smart community’ measures to improve quality of life ▪ Willingness of governing bodies to create validation environments	▪ Safety, bureaucracy and regulatory issues ▪ Slow change of alternative power infrastructure away from oil ▪ Resistance to disruption of established business models and relationships ▪ Emergent, disruptive effects because of sensitivity of transport to changes in other sectors
Smart City	▪ Development of city eco-systems ▪ Development of cloud technologies and big data application ▪ Interoperability providers	▪ Security and privacy for dealing with sensible data ▪ Digital divide + citizen engagement ▪ Heterogeneous regulations across Europe
Smart Health	▪ Reduction in cost ▪ Development of cloud technologies ▪ Commoditisation of AR and VR ▪ NFC technology deployment	▪ Security and privacy for sensible data ▪ Patient acceptance of disruptive applications ▪ Heterogeneous health systems and regulations across Europe

Key messages extracted from the domain analyses are presented below:

Sector	Main message
Smart Production	▪ ICT modernisation in manufacturing industry needed to achieve Industry 4.0 paradigm ▪ Collaborative environments between the actors and engineering solutions can be provided by a number or platforms like Virtual Fort Knox, FIWARE, FITMAN and the Industrial Data Space ▪ RAMI 4.0 and IIRA are the two largest undertakings to provide a CPS or IoT based reference architecture and common framework for manufacturing ▪ The development of common framework and standards will boost the massive roll-out of CPS in industrial environments ▪ CPS systems present major concerns related to safety, security and confidentiality in the traditional sector. Moreover, a specific barrier is trust in cloud solutions (which will require a huge effort in education activities and building awareness) ▪ Entrepreneurship and innovation should be fostered in to a more conservative domain dominated by a risk avoiding innovation culture that is less open to new business models ▪ It is mandatory to involve SMEs in the production value chain ▪ Labour force is not skilled in IT; it is mandatory to perform training and talent attraction ▪ It is necessary to create a legal framework that protects EU companies and promotes the use of CPS technologies
Smart Energy	▪ CPS technologies such as big data, advanced modelling and analysis techniques are currently being developed in order to improve the industry's flexibility and efficiency in a few years ▪ Predicted timelines for main changes in the energy sector are expected to be delivered over decades rather than years ▪ Europe holds a leading position in smart metering, but is not the case in smart grids ▪ Current grids must be upgraded to address the new challenges derived from the new RES ▪ The energy market is heterogeneous and fragmented across EU and it is required to create a common market place and its supporting tools that increase competitiveness ▪ Some key technologies (i.e. energy storage) are still not mature and once they reached it the real-time monitoring and trading will be driving forces in energy market
Smart Transport	▪ Technology is ready to be deployed but it is necessary to create a legal and societal framework that help accepting the innovations ▪ Non-technological requirements are a key factor in Smart Transport, so it is issues of standards, laws, regulations, and the acceptance of change by populations that are the constraints on progress ▪ Smart communities will benefit of introducing CPS in transport and pilots must link both ▪ The commercial barriers should be removed by EU countries for boosting CPS adoption ▪ The competitive and heterogeneous environment with large companies and SMEs coexisting could raise the fear of future ▪ Training is mandatory for minimising this risk
Smart Cities	▪ CPS's challenge is to promote a new paradigm of SmartCities where the solution is not only technology and its interoperability, but also the interaction with non-technology elements ▪ Interoperability among current technologies and with those implemented in other SmartCities will be the key to success ▪ CPS deployment is driving the modernisation of many aspects of cities daily activities improving efficiency and resource consumption ▪ Digital divide must be considered in the provision of services to citizens for maximising the number of citizens with access to them ▪ Collaboration of horizontal and vertical platforms is critical for maximising the benefits ▪ Open platforms and standards must be adopted to enable the access to third parties in the smart city eco-system and to create new business models helping overall sustainability ▪ Current waves of Smart City initiatives have to collaborate for sharing experience and lessons learned
Smart Health	▪ The expected evolution in the following years indicates that in the short-term smart health sector will evolved through CPS technologies providing new functionalities that optimise processes and patient information delivery ▪ CPS technologies are a key factor in the Smart Health Sector ▪ The possibilities of CPS go beyond patient monitoring and can improve all procedures in healthcare ▪ Remote management enabled by CPS improves patient monitoring and treatment control ▪ The awareness regarding a healthy lifestyle has increased ▪ Through using existing technologies such as cloud computing, social networks or big data, health care services will offer many potential benefits to patients and doctors ▪ It is necessary to overcome barriers, such as legislation and regulation disparity, in order to encourage the collaboration between private and public providers ▪ There are major concerns related to security and privacy, the sensible data managed and the regulatory framework must be clear on how to handle it

6 Recommendations for Research and Innovation Strategies

The transition from FP7 to Horizon 2020 has been characterised by a greater focus on innovation. A real change in the way of doing things demands a critical thought on what innovation really means. Some definitions found in literature are 'Innovation is an invention that has a socio-economic effect' (Madelin, R., and Ringrose, D., 2016), or 'Innovation is anything new that changes the society adopting it'. From them we extract that innovation happens when there is a direct impact – either of economic or societal nature – from the adoption of a result. After a careful analysis of many projects (with a special focus on CPS) we see that major investments have been made on the supply side but very **low effort has been devoted to the engagement of the demand side.** Even though this seems obvious, in practice we realise that a myriad of platforms, technical frameworks and developments were built following research-oriented requirements, therefore resulting in outcomes that are far from real industrial needs. Furthermore, we see that potential customers of such results are not even involved in the conception, deployment and validation loop. In addition, lack of real life or quasi-real life conditions for trials and validation gives as a result a technology, application or system that is not integrated in a credible value chain or as we prefer to call it, it reflects the **lack of a business eco-system.**

As a consequence of this, main recommendations from Road2CPS to enhance innovation capabilities include a) improvement of the business eco-system (meaning that needs are driven by industry and pilots are implemented at large scale and in close-to-real life conditions so that validation of technologies is realistic; this also implies the involvement – in a direct or indirect way – of players and stakeholders that are part of such eco-systems in real production environments) and b) investment on actions (not necessarily technical ones) that help to bridge the gap between the prototype phase and the market (i. e. assuming that the TRL is high enough, we encourage investments in those activities that may have a direct impact on the adoption of the results, such as it could be the case of skills development).

Following that approach, Road2CPS revisits in more detail three particular angles that follow the aforementioned blocks, where main recommendations are summarised and depicted here:

How to create business eco-systems that lead to adoption of research results

- **Investment should not only be devoted to the supply side, but should be aligned and balanced with respect to the demand side.** Past experiences have shown that it is very difficult to push for a technology where the customer is not at all involved. This could slightly vary from one sector to another, but lack of real requirements and needs (that can only be brought by such potential customers) lead inevitably to poor interest by future adopters. It is therefore of utmost importance that users / adopters of the solution are in the loop from the very beginning. **This does not mean involving just one potential customer, but a representative sample of companies that drive a specific market**. Adoption of a technology, for example, does not only depend on the functional requirements specified by a use case; it also relates to non-functional aspects such as scalability, which can only be tested when a large-scale deployment takes place. As a matter of example, in Road2CPS, interviews with experts have continuously brought elements like interoperability to the high-priority list. In most cases, the use of open standards appears as a means to address that challenge. So, when fostering adoption of CPS solutions that entail interoperability issues, global consensus among major players in the target market is needed (sometimes creating conditions for de-facto standards can be a good solution to avoid long processes associated to formal standard definition). This, once again, means that a business eco-system is needed, bringing together supply and demand, and in both cases, ensuring that major actors are involved in the process (not necessarily as partners of a particular project).

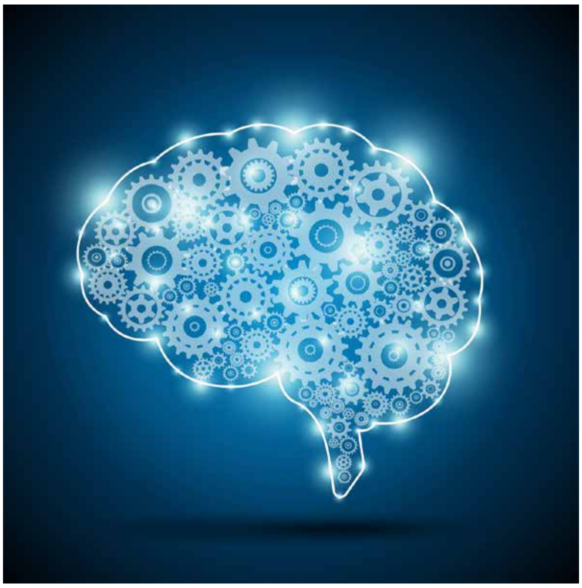
- The discussion of setting up business eco-systems and innovation environments adds an important point to our recommendations, which is the **geographical dimension** of the players involved (as well as the size of players: e. g. SME involvement). Looking at past projects we see a focus on stakeholders that are organised in a top-down approach. Insufficient or no attention has been paid to scaling results through coordination and involvement of local actors. **Coordination and synergies with local innovation eco-systems should therefore be enforced.** Here we see many opportunities. For example, cascading funds and open calls provide a good way to involve local SMEs and start-ups that could either contribute to technology developments or to technology adoption in an agile way; new growth through **smart specialisation** (European Commisson, Research and Innovation) focused on cross-region piloting on innovation could be enhanced (good references already exist, such as the Vanguard Initiative); this could be expanded to pre-commercial procurement and scaling. In advanced manufacturing technology, for example, EU suffers an uptake gap between large firms (75 % using best-in-class kit) and medium firms (65 % not using the kit). **Digital Innovation Hubs** under the Digital Single Market can help with this under-performance.
  - Finally, and even though mentioned above, **fostering adoption is not exclusively related to the private sector.** Additional measures in line with pre-commercial procurement or **public procurement of innovative solutions** by local, national and EU public institutions would have a direct impact on the credibility of the innovation eco-system.

Innovation Governance

In the context of Road2CPS, Innovation Governance refers to the policy and regulatory environment associated to innovation. Hence, it also includes the preparation of research and innovation programmes. For the purpose of simplicity, we highlight here some of the most relevant points:

- **Adaption of regulatory environment to research experimentation:** we acknowledge that changing regulations is a long process in the EU; however, simpler mechanisms should be applied at least in the context of research activities; allowing innovators to test in real life conditions would create a favourable innovation framework. This would also enable a valuable learning experience because it would increase our understanding of where regulatory changes are needed. Some examples already exist such as ***Innovation Havens,*** a framework for the real-life testing and demonstration of innovative solutions even if not all existing procedures and requirements of legislation are fully complied.
- **Research for Innovation:** Research is not the only driver of innovation; some studies point out at least 10 key factors, being research just one of those. That is why Road2CPS encourages **investments in different activities to the usual ones in previous programmes,** which could help to bridge the gap between research results and markets. Innovation in terms of **instruments** should also be an important topic. Improvements have been made thanks to open calls, SME instrument, setting up parge scale pilots but more agility should be achieved, ensuring that critical stakeholders of innovation eco-systems that are currently out of the game of Horizon 2020 – because it is not worth for them – get attracted by a new framework. Measures to increase the speed of the whole process would also benefit the performance of the system. For example, having good testing facilities for companies would help to validate solutions and correct actions where needed. The pressure of competing regions worldwide should alert European stakeholders about the ‘urgency' of accelerating innovation (which could be compatible with other longer-term instruments for basic research). New measures in terms of policies and instruments should be accompanied by a clear understanding of where the challenges are and should be assessed over the time for a critical evaluation of their performance (Innovation Growth Lab, Horizon 2020 programme are already working in the domain of innovation policy assessment).

Skills development adapted to changing needs



Development of skills is one of the areas where the EU should increasingly invest. Even though education is not a direct objective of the research and development framework, concrete measures need to be integrated in some topics. Technologies evolve very quickly, and the work force should be aligned with such rhythm if we want that those solutions are widely adopted by the market. The concept of Innovation Hubs, where SMEs are supposed to get access to new skills is a positive step in that direction; projects like EDSA (European Data Science Academy), focused on the design of curricula for data science training and data science education across the European Union (EU) are also a valuable contribution. This kind of actions should be reinforced and new (more focused) instruments may be defined to accelerate this path.

The current Digitising EU Industry Policy provides a very suitable framework to test new instruments and changes in the existing framework programme. Activities under development in the areas of Digital platforms and Digital Innovation Hubs go in that direction, but are not sufficient to face the challenges in terms of competitiveness and innovation that we, Europeans, have ahead of us.

7 Recommendations for Business Opportunities

The goal of this section is to bring to the discussion potential areas of work that may have an impact on the adoption of CPS in different industrial sectors going beyond the pure technical compliance of the solutions, since this aspect has been widely addressed by our sectorial roadmap. This includes, among other aspects, **emerging business models**.

New technologies are dramatically changing the way to do business and remain competitive in a global playground. This implies threats, but also opportunities that can result in stronger industries if these opportunities are adequately leveraged. Traditional actors in value chains are evolving towards more **dynamic and open business eco-systems** where other – new – stakeholders play a role, in some cases throwing out the well established organisations. This transformation driven by new technologies has already transformed industries like media (press, music, video consumption), tourism or banking. But such **transformation will affect most economic sectors**. Some of them make intensive use of CPS, such as the automotive industry, where autonomous cars will bring companies like Google and Apple as direct competitors to traditional manufacturers. This sector will be highly based on data and therefore reliability and security of such data will become essential, changing the **center of gravity of value creation**. The phenomenon of digital transformation is not stoppable, and those that are unable to adapt will simply dissapear. It is not by chance that one of the most relevant policies pushed forward by Commissioner Oettinger is precisely the so called **DEI (Digitising European Industry)**, aiming at facilitating the adoption of digital technologies (and the associated transformation) by companies operating in more traditional sectors or by smaller players for whom access to these resources is a barrier. In this context, **further support to the creation of digital platforms as well as the set-up of Digital Innovation Hubs** is encouraged as a way to speed up the digital transformation.

One of the effects of applying new technologies has to do with the **"servisitation" of many industries.** Availability of massive amounts of data enables the creation of very innovative services around the product that sometimes generate more benefits than the core product. As example is a mobile phone. Many operators distribute devices for free as a way to charge users for other added-value services. Coming back to the very understandable case of cars, forecasts say that in the future we will not pay for the car, but we will pay for the time we use it, or the number of kms driven; all this is possible thanks to the inherent intelligence of the systems and the capacity to control parameters almost in real-time. Pay per use was precisely one of the business models that created more disruption with the advent of the internet and it is nowadays highly exploited by emerging organisations that use the virtual world (digital platforms) to commercialise both products and services in the real word. That is the case of Uber in the personal transport / taxi domain or Airb&b in the accomodation segment. The novelty here is that none of these companies own those assets, but technologies help them to exploit the community effect, creating emerging business models. Disruption introduced in the respective markets is so huge that it has led regulators to intervene to protect traditional players. What should be the EU position in this regard? Should **markets be kept open** ("contestable" as a key enabler of innovation), so that i. e. innovating firms should be able to gain profitable sales in competition with established firms by providing better or cheaper products or services to customers using new business models (such as the cases previously described) provided competition is fair. Our recommendation is **not to over-regulate and adapt to the evolution of the markets in an agile way after testing different models.** In that sense, a **pro-innovation regulatory environment for experimentation and testing** was already recommended in the previous section of this document.

The effect of new business models in transforming industries does not only have to do with the distribution channel (for example, listening to music in Youtube instead of buying a CD); in this particular case Youtube gives you access to music without paying money. This is what google has been doing from the very beginning and this has also been the norm on the web. **Monetisation happens through different means and not anymore as a consequence of the basic transaction.** Publicity models with freemium versions are enabled by data. **Data is the engine for many other changes** in completely different business areas.

Another phenomenon related to the **exploitation of network effects,** is the one of **multi-sided market**s and enabling platforms. In those ones partners, customers and suppliers share data asset platforms to be used by the participating players. The economy of data behind gives all players access to a larger market, where the different sides are (within limits) mutually reinforcing i. e. growth in one side of the market can drive additional insights that enable growth in the other. Increased profitability is enabled by market operating costs being shared between the participating members (not necessarily equitably) and the potential to command higher prices because of perceived increased value of services enriched by the shared data insights. Eco-systems like Android or Apple benefit from the same concept. The higher the number of applications is, the more attractive it will be for the user that will buy an iPhone or a mobile device with android OS respectively. At the same time, an application developer will work just for the platforms that have a massive amount of potential customers behind. So, this mutual reinforcing effect is clearly visible here. How does it translate into concrete recommendations?

- The first element is that platforms will become commercially viable if they maximise network effects and benefit from economies of scale. This requires reaching a critical mass of users, and that is why **we encourage the support of platforms that enable multi-sided markets.** Nevertheless, there are many strategies to create the critical mass. One of them is granting access to the platform at very low or zero cost to drive adoption. That is the model that many EU-funded projects focused on platforms are following, such as FIWARE.[12] The main challenge is that it has to keep the benefits for all parties involved and requires a solid sustainability plan to raise business margins.
- The second element where recommendations can be derived has to do with the fact that **more attention should be paid to challenges associated to new data-driven businesses.** The following list describes some of them:
  - Cost: There are close to zero marginal costs associated with creating, storing and distributing data; whereas producing goods and services can be very expensive
  - Rights over ownership: It is much more difficult to identify and preserve digital rights, meaning that once a data set has been sold to a customer, it can very easily be sold on to multiple third parties
  - Privacy: There are huge grey areas to contend with over data security legislation, not least because countries have different rules and regulations over how information is governed, stored and accessed. This issue has recently come to light again, after the European Court of Justice ruled that the transatlantic Safe Harbour agreement is invalid. The agreement lets American tech companies, such as Facebook and Twitter, use a single standard for consumer privacy and data storage in both the US and Europe. The repercussions could be huge, forcing US organisations to transfer their European user data to Europe and follow 20 or more different sets of national data-privacy regulations
  - Growth: Data businesses have the tendency to develop much faster than traditional goods or services organisations, expanding into monopoly or oligopoly structures
  - Access to data: incentives need to be created so that organisations are willing to share data under certain conditions with players that can generate value on top of them. This requres secured environments and a suitable legal environment that favors trusted relationships between data providers and data owners.[13]
  - (Free) flow to data: a schengen of data is needed to allow data flows in Europe as a means to scale businesses
  - Data integration: breaking data silos means cultural / mindset change, but also the need to work on common, harmonised, standard, and shared data models

Cyber-Phsyical Systems are at the core of this revolution, since they enable many of the emerging business models and eco-systems previous described. And in the same way that technologies enable new business models, it is also

12 https://www.fiware.org/
13 Some interesting experiences can be seen through the SDIL (Smart Data Innovation Lab), a German initiative focused on data-driven innovation

true that emerging business models bring back **additional research areas** that require further attention in coming programmes, such as end-to-end security by design. Plenty of them have been pointed out along this document.

8 Summary and Conclusions

The key outcomes and conclusions derived from the Road2CPS activities are summarised below:

- As CPS combine a huge variety of technical, industrial and business domains, many different **standards** within and between different industries as well as along the value chain and at different vertical levels exist that inhibit **interoperability** between different systems and between components within a given system. In future, a variety of redundant **reference architectures and platforms** should be avoided and the access to these should be easy for a huge number of organisations and companies. Approaches that support open standards and reduce vendor lock-in should be in focus. Furthermore, interoperability between platforms and between devices should be promoted.
- **Modelling and simulation** solutions have become an important element in the area of engineering, and will be essential for CPS, particularly for those CPS that cannot be switched off, because they are safety-critical, and for those that are not fully configured until run-time. The advantage of M&S is the potential reduction of effort in terms of costs and time and the potential for improved performance or better quality designs. However, adoption of modelling and simulation solution in SMEs is still not fully exploited. Modelling and simulation face further challenges such as heterogeneity in modelling notations and high requirements from CPS-side for fault tolerance, resilience, and dynamics. The increasing role of human aspects as well as consideration of autonomous systems is also an aspect of M&S, which are not sufficiently considered currently. Multi-domain, multi-dimensional, and multi-objective approaches of modelling and simulation should be more in the focus of future work.
- **Safety, security, and privacy** aspects that are considered as hot topics for many domains should be addressed by CPS solutions – the development of security algorithms is one module of many others. Cyber-Physical Systems as a key enabling technology for many application fields such as infrastructure requires key properties like safety, security, and privacy of systems. Without addressing these aspects the establishment of CPS in many sectors will be delayed significantly – especially in traditional sectors like manufacturing. Approaches for ensuring either security or safety in a CPS need to consider challenges from the hardware or the software of a CPS, evolving into holistic techniques that consider the properties of the complete system end-to-end. Certification, regulation, and standards are valuable concepts for dealing with safety-critical issues.
- Through the significantly growing number of connected devices and sensors, the generation of huge amounts of data is a challenge and a great opportunity at the same time. Not only the generation of **big data,** but also storage, preparation, analysis, usage and the seamless integration of new techniques like edge computing are important fields for future research and enable novel business opportunities. To cope with big data real time analysis in a digitised and data driven economy, data and information exchange processes will occur in near real-time – which means that big data analytic tools need to address this challenge. Besides velocity, volume, variety, veracity, and value are further properties that are highly relevant and thus form quality criteria for the big data value chain as a whole.
- **Autonomous systems** are becoming more and more omnipresent; autonomous transport systems like the DLR in London or the google car are two examples of Cyber-Physical Systems that support humans and help in terms of decision-making processes. Ubiquitous autonomy could lead to finer control over manufacturing, transport and logistic processes and will help to monitor and track unique elements as well as complex products. In an ideal autonomous environment, CPS take on jobs that are repetitive, dirty, dangerous or boring and which are currently done by humans. While this is a clear benefit, there are social challenges that must be addressed, such as job loss, job displacement, continuous retraining, and the provision of a living wage for all.

- The topics **human machine awareness** and human-in-the-loop are becoming increasingly important in all respects – e.g. controlling of machines by humans is more complex in a cyber-physical world. CPS can have, depending on the type and adjustment, a certain level of autonomy that requires suitable solutions considering complex human behaviour. The emergence of cobots, as an example for machines working together with humans, show the challenges that arise in the field of human and machine awareness aspects. Furthermore, ethical questions such as how a CPS should behave in a complex, critical situation that include humans are still not ultimately answered.
- The degree of automation within the **manufacturing industry** is already at a high level – nevertheless the step towards a mainly digitised sector still needs to be done. Some demands from the industry for technologies are already met, but a broad variety of different standards at different levels of the value chains hamper the interoperability and lead to a fragmented domain. Platforms are one instrument to overcome this and the most important approaches that foster the development of a common framework are the RAMI 4.0 and IIRA reference architecture models. RAMI 4.0 is linked to the Industrie 4.0 initiative and IIRA to the US-based Industrial Internet Consortium. A challenge in manufacturing is to convince the more conservative decision-makers concerning IT-based products such as cloud solutions. Recognising that change is endemic to society and that errors will always occur, the assurance of resilience in systems is intertwined with automation.
- The **transport domain,** more than the manufacturing and compared to the energy sector, is to a higher degree connected to human-specific aspects. The human-in-the-loop topic is more central, which means that not only safety, security, and privacy aspects are of prime importance, but also non-technological questions that are not easy to measure nor to calculate. Awareness building and acceptance for CPS by the society are necessary to overcome current barriers.
- The **energy sector** is evolving from a marketplace oriented around small numbers of large providers into a domain with many smaller stakeholders with flexible roles. This includes more and different stakeholders such as policy-makers, energy aggregators, advanced energy distributors with increasingly flexible roles, application developers and IT and telecommunications providers, in large and small companies newly entering the market as well as end users who are better informed than ever before about their energy usage requirements, thanks to smart meters. CPSs enable this trend, which also leads to generation of more data than before. A higher degree of interconnections and communication processes result in a higher degree of complexity – aspects of self-healing infrastructure, integration of diverse renewable and fossils sources as well as decision support mechanisms based on real-time information will gain importance in the future.
- Similar to the transport domain, the **smart city** approach, is to a higher degree dependent on non-technology elements like acceptance of a CPS environment. Monitoring systems, autonomous controlling systems, and robots in fully automated automotive factories need to convince influential sceptics and of course have to be be accepted by the population. As the smart city domain is a combination of different sectors such as transport, building industry, energy, and infrastructure for instance the degree of complexity is even higher. Modelling and simulation solutions, as in other domains, could help to reduce costs in the long run.
- Cyber-Physical Systems are valuable to support the different stakeholders in the **health domain**. As safety, security, and privacy are always of crucial importance, these issues need to be guaranteed in particular in the context of healthcare and different states of health of patients. In addition, the legislative and regulatory framework has to be adapted to CPS-based healthcare systems considering not only the already existing technologies, but also the new and future cyber-physical solutions.
- **All domains** have in common that a lack of skills is observed that has to be overcome by promoting education and skills in relation to CPS. Education programmes need to address these challenges and measures to train the labour force in traditional sectors and firms in terms of IT skills supported by awareness building processes involving the broader society. Additionally, talented professionals outside the EU should be attracted by targeted policy and by industry and research institutions.

- New **business models** will arise in the wake of the paradigm shift towards a CPS-based economy and society, but support is needed to foster entrepreneurship and mentality to generate radical and disruptive innovations. Further promotion of SMEs and start-ups through targeted incentive programmes as well as knowledge and technology transfer measures will be necessary to cope with competitors.
- In summary, progress in the key technological fields identified, will help to fuel the development of modular, secure and trustworthy Cyber-Physical Systems of the future. As many similar challenges and opportunities exist in different application domains, a cross-disciplinary, multi-domain approach should be pursued. The involvement of and dialogue with the society is seen as key to make CPS a success and to best benefit economy and society as a whole.

As an overall conclusion, it is clear that the funding that has been provided for the development of CPS technologies has delivered useful and significant results from a technological perspective. However, there are many technical extensions still required, justifying funding. There is also evidence that there should be a shift in focus towards the many industrial, business and community issues involved in the adoption of CPS technology. The latter are now becoming urgent as barriers to the adoption of CPS within the EU community.

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Picture: Road2CPS Consortium meeting Mallorca October, 10th 2016.

Digital components are increasingly integrated and embedded into products and services that are in everyday usage. The term Cyber-Physical System (CPS) describes hardware-software systems, which tightly couple the physical world and the virtual world. They are established from networked embedded systems that are connected with the outside world through sensors and actuators and have the capability to collaborate, adapt, and evolve.

Cyber-Physical Systems find their application in many highly relevant areas to our society: multi-modal transport, health, smart factories, smart grids and smart cities among others. The deployment of Cyber-Physical Systems (CPS) is expected to increase substantially over the next decades, holding great potential for novel applications and innovative product development. The CPS community foresees large potential in creating a competitive edge for Europe, serving existing and new markets across different industries and sectors. Digital technologies have already pervaded day-to-day life massively, affecting all kinds of interactions between humans and their environment. However, the inherent complexity of CPSs, as well as the need to meet optimised performance and comply with essential requirements like safety, privacy, security, raises many questions that are currently being explored by the research community.

This handbook was developed within the framework of the European project Road2CPS, coordinated by the Steinbeis-Europa-Zentrum, Germany in collaboration with six partners from four European countries (Loughborough University, UK; Newcastle University, UK; CEA, France; Fraunhofer IPA, Germany; AnySolution, and ATOS, Spain).

It presents the vision, challenges, research and innovation priorities for a set of highly important CPS technologies, as well as the impact and deployment of CPS in five application domains. The document aims at giving support to the European Commission in structuring the future CPS related Research Programme, as well as at giving researchers in the field and decision-makers from industry, academia, and policy making of the related domains a broad perspective on developments and implementations in the field of Cyber-Physical Systems.

The Road2CPS recommendations for research priorities and innovation strategies serve as a strategic guide for further investment into Cyber-Physical Systems and align future CPS research with needs, trends and demands of European businesses.

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