ARTEMIS
STRATEGIC
RESEARCH
AGENDA
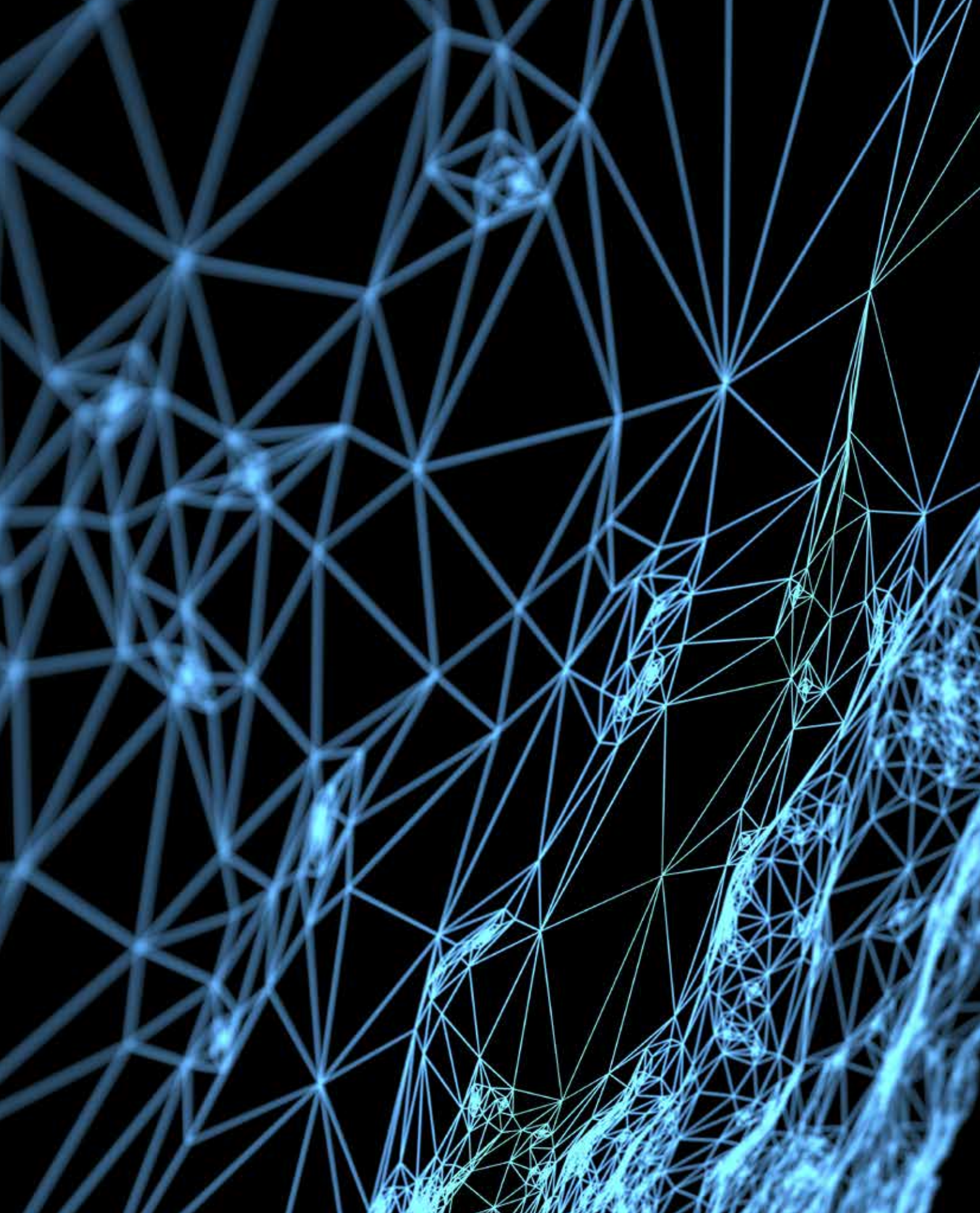# 2016

ARTEMIS
Industry Association

ARTEMIS STRATEGIC RESEARCH AGENDA 2016

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CONTENT

EXECUTIVE SUMMARY

THE PATHWAY TO THE DIGITAL TRANSFORMATION:
AN OPPORTUNITY FOR EUROPE

Cyber Physical Systems are "Embedded Intelligent ICT [1] Systems" that make products smarter, more interconnected, interdependent, collaborative and autonomous. They provide computing and communication, monitoring and control of physical components and processes in various applications. Harnessing these capabilities in time and across space creates applications with enormous and disruptive new functionalities with unprecedented societal impact and economic benefit for citizens and societies.

ARTEMIS Focus Areas are Key Drivers
in the Digital Transformation

The digital evolution, or digitisation, is a silent revolution that is transforming our way of living and of doing business. It is a tremendous opportunity for European stakeholders active in many sectors to benefit from this transformation as users and as suppliers. Indeed "Europe's Future is digital" – an excerpt from Commissioner Oettinger speech at Hannover Messe 2015.

As nowadays Cyber-Physical Systems technology is widely recognised as core enabling technology that forms the basis for the development of many innovative products and services in both developed and emerging economies, the digital transformation is considered as a great opportunity for their development and deployment, opening for every business in Europe and worldwide new markets for such innovative products and services.

In an industrial context Cyber-Physical Systems encompasses a wider class of systems than for Embedded Systems in their most strict definition. Therefore, ARTEMIS-IA distinguishes three focus areas that together create this wider industrial context:

- ▸ Embedded and Cyber-Physical Systems,
- ▸ Internet of Things,
- ▸ Digital Platforms.

These areas together will allow the emergence of new innovative businesses that support the opportunities for **value creation** in several sectors that **Embedded Intelligence** creates.

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[1]   *ICT : Information and Communication Technologies*

ARTEMIS VISION, AMBITION AND MAIN OBJECTIVES

ARTEMIS Vision and Ambition 2016

Cyber-Physical Systems technology, as a basis for embedded intelligence, is a major enabler of the Digital transformation and for the 'Digitisation of Industry' as well as for every business in Europe. It is increasing its innovation potential by boosting its ability to bring to the market a new and larger variety of smarter products and services that are reshaping their future and creating new unprecedented opportunities.

Powered by the new era of this Digital Transformation, **ARTEMIS will continue to support a vision where Europe remains among the world-class leaders in the area of Cyber-Physical Systems and Embedded Intelligence**. For ARTEMIS it is paramount to position itself as a digitisation leader for the benefit of the society and businesses in Europe and worldwide. ARTEMIS wants to play a major role in achieving a real Digital Single Market policy in Europe.

ARTEMIS Main Objectives

As mentioned above, ARTEMIS subscribes to achieving the 'Digital Single Market in Europe' by providing strong technological capability over the total value chain, and on both the supply side and the application side of Embedded Intelligence, thus closing the loop between market pull and technology push. Therefore, for the 2016 present Strategic Research Agenda ARTEMIS aims to fulfil a renewed set of main objectives:

- ‣ Consolidate the **pathway of the digital revolution,**
- ‣ Enable a **more agile and shorter development cycle through the adoption of design by composition and correct-by construction principles**,
- ‣ **Overcome fragmentation** in the European supply base for the components and tools of design and engineering,
- ‣ R**emove barriers between application contexts** to yield multi-domain, reusable components and systems,
- ‣ Extend the use of **digital platforms** to build stronger eco-systems needed for accelerating the innovation and the creation of new business models.

The Digital Transformation and the Applications Drivers

The ARTEMIS 2016 Strategic Research Agenda is derived within the perspective and highlights of a set of new drivers to orientate Cyber-Physical Systems research and development to be conducted in the highly competitive context of:

A. Digital Transformation Drivers such as:
- ‣ Leadership of vertically integrated companies,
- ‣ 'Always connected society',
- ‣ Platform concept and new 'hyper-scalability' of business models,
- ‣ Data value,
- ‣ Security,
- ‣ Software value,
- ‣ Vulnerability, trust and privacy.

B. Application context drivers in response to their predicted growth potential [2], such as:

‣ Smart Mobility,
‣ Sustainable Production,
‣ Smart Health and Wellbeing,
‣ Smart City.

The application drivers developed in the present SRA are just examples and do not cover all the potential applications such as smart energy, smart food, smart farming, smart wearables and many more.

ARTEMIS INNOVATION STRATEGY AND RESEARCH PRIORITIES

The hyper connected society requires revisiting the research strategic planning and its agenda to take account of the digitisation, and to maximise the impact of the technological solutions on value creation.

The research challenges depicted in the following chapters do not cover all topics needed; they represent the priorities that need to be addressed.

ARTEMIS SRA PRIORITIES

For the coming period (2017-2025), the following priority targets have been selected to guide the R&D programmes with the purpose of having greater impact and quick-to-markets results:

‣ Allowing the pace of product-family roll-out to be **governed by business needs** (rather than engineering limitations), such as increased connectivity, and gaining customer confidence, trust and acceptance by providing safe and secure products and protecting his privacy.
‣ **Getting faster to market by reducing the development cycle and development costs, and mastering the complexity**
‣ **Increased efficiency: easy user adoption and lower threshold of product introduction in the market.**
‣ **Improved sustainability:** by enhancing the products and systems ease of use, adopting multi-view system design (from conception to operation and services) as well as a reuse policy.

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[2]   *Refer to paragraph 4.3 below – IDC report IDC Press release 16 Oct 2014. And report # 252046 Oct 2014, and CyPhERS Project analysis on the economic potential of key technologies related to CPS*

ARTEMIS RESEARCH AND INNOVATION STRATEGY

In the SRA 2011, ARTEMIS innovation strategy was two-pronged: to **'Build on the leading positions where Europe is strong'**, particularly for the safety critical high reliability real-time applications such as the automotive, aeronautics, space and health sectors, and to **'Create new opportunities'** for Europe to be positioned at the forefront of **new or emerging markets with high potential growth rates.**

The new strategy will be more user-centric to better respond to the Digital Transformation by:
- **Taking account of the user's benefit and experience and empowering a business approach, over the whole value chain;**
- **Building better and more efficient European technological solutions for greater combined strength in the context of the global competition**.

Closer investigation of the societal challenges has highlighted the importance **a highly dynamic approach for better sustainability**, so that the **Innovation Strategy** is built into this 'bigger picture':
- To **change from static networked Cyber-Physical Systems to Systems-of-Systems** that are highly dynamic, evolving and never down.
- To consider the convergence of applications on open networks with safety, security and privacy requirements at all system levels.
- The **Cyber-Physical Systems technology should no longer be considered in isolated application contexts** but in relation to their contribution to the evolution of society and solving tomorrow's societal challenges.

STRATEGY IMPLEMENTATION

To overcome the plea of the silos effect between sectors, addressing research in a voluntary cross-domain perspective enables investment in research to be optimised and leads to wider cohesion and greater combined strength among application sectors.

This cross-domain approach is complemented by the development of **common building blocks** to make significant advances in design by composition. This will also accelerate the development cycle, maximise the reuse and the time to market, be more cost efficient in the adoption and deployment of technological solutions, master their growing complexity, ensure safety, security and privacy, allow flexibility and facilitate interoperability between the various systems.

The purpose of **Building Blocks** is to **increase development efficiency, enhance usability**, for better and easier adoption of engineering methods and tools, and to provide a holistic products/systems view covering the whole life cycle, also from a system of systems perspective. The following chapters provide a comprehensive description of **Strategic Research Challenges for the building blocks related to**:

A. CPS Architectures Principles (Reference Design and Architecture)
B. Design Methods, Tools , Virtual Engineering

C. Trust, Security, Robustness and Dependability

D. Autonomous and Robotic Systems

E. Seamless Connectivity and Interoperability

F. Cyber-Physical System of Systems

G. Computational Blocks

H. Digital Platforms (Cyber-Physical Systems creating smart services)

I. Basic Research, Fundamental Research.

ARTEMIS INNOVATION ENVIRONMENT - MAKE IT HAPPEN

ARTEMIS is an Innovation Initiative aimed at fostering the Digital transformation by supporting the development of innovative smart products, services and solutions in a large variety of activity sectors for the benefit of the users, citizens and businesses.

As, the term "innovation" is broadly used, the ARTEMIS "Research and Innovation" Strategic Agenda is intended to focus on a selected number of Innovation Accelerators to speed up research results to market.

One of its main objectives is to **inspire various Research Programmes (EU such as H2020, multinational such as EUREKA, or National or Regional),** ranging from fundamental and industrial research to experimental development of new products, processes and services to enable market introduction and highlight European added value.

ARTEMIS was among the first initiatives to set up Centres of Innovation and Excellence (CoIE), and label them (examples are EICOSE, PROTEMEO and ProcessIT). **ARTEMIS will continue to support these CoIEs and promote them to act as sustainable innovation hubs**, within easy and immediate reach of their eco-systems (often within working distance). The complementarity of the CoIEs and the Digital Platforms are mutually reinforcing as they both provide the right environments to bridge user needs with supplier offers. They provide the infrastructures for experiments and plug-play of use cases as well as create additional opportunities for SMEs to meet new clients, and be integrated in the eco-systems.

Standardisation awareness as the activities of various standardisation bodies related to Embedded Intelligence and Cyber-Physical Systems field has increased considerably in recent years. This responds to industry needs, having been identified as an industrial need, particularly in various critical application areas, as standardisation and standards are essential to ensure the market uptake for their smart products and related services.

The rapid evolution of the new global Digital Economy is generating needs and challenges with such a high growth rate that even the **human capital market** is not able to keep pace. So, **education and skill building will be a key pillar in the EU strategy** to have a relevant role (and thus relevant economic impact) in the Digital Transformation of society. Currently companies are struggling with what experts are calling the "largest human capital shortage in the world". ARTEMIS-IA will engage actions and recommendations to influence pan-European policies to better achieve long-term effects on the education and training in the curricula in the field of Embedded Intelligence and Cyber-Physical Systems and also make education and training a specific deliverable for all EU projects.

RELATIONSHIP WITH OTHER INITIATIVES

The figure below gives a global view of the positioning of the various European initiatives and the role of ARTEMIS-IA SRA as enabler. Each of these initiatives – PPPs – shows a high commitment in its respective area. But they also need to rely on each other's specificities and share a number of challenges and opportunities. The ARTEMIS SRA CPS focus area is transversal to the PPP's in the figure below. With the embedded software development, software-based services and the Cyber-Physical Systems technologies it constitutes an indispensable enabler.

ARTEMIS-IA will seek more openness and be open to the world through an improved **"International Collaboration'** plan that can encompass a wide range of activities, from the organisation of technical meetings, high-level meetings, conferences, schools (MOOCs and SPOCs) and, where possible, joint international projects". In particular, ARTEMIS-IA will foster the cooperation with the IEEE Industrial Electronics Society (IES) and "Industrial Cyber-Physical Systems" technical committee. Increasing international visibility will be implemented through its communication, the website and ARTEMIS-IA conferences (such as Co-Summit, Spring event, Summer Camp, Technology conference).
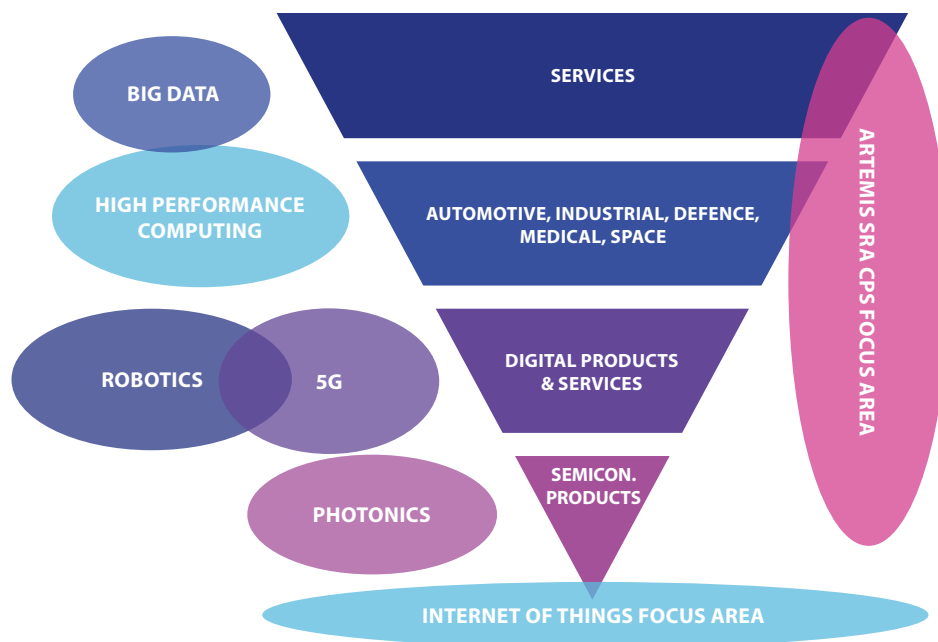
Figure 1 *ARTEMIS SRA focus with respect to other initiatives*

THE WAY AHEAD

*We need the right policy orientations and strategy
and increase investments*

Product diversification and added market value in products are created today by the pervasive use of Embedded Intelligence. This Embedded Intelligence in products and services is an important part of added value creation not only within the product or service but along the whole value chain, e.g. in engineering, production, logistics, maintenance, marketing, sales and after sales. Most often this added value of embedded software is not visible or tangible in the end product/service or its market offerings and thus its related value creation is indirect or implicit. The economic visibility of Embedded Intelligence is vital to the European Embedded Systems industry, whether large-scale business platforms or nano-transactions between IoT's. Software-driven transactions can be scaled very efficiently, which opens up interesting opportunities across many application markets. Embedded Intelligence adds value for each of these areas in various forms like increased functionalities, reduced engineering time, improved product quality, increased raw material efficiency and higher OEE market and sales platforms.

ARTEMIS has proven to be a unique programme that in just a few years succeeded in establishing the largest R&D&I projects ever in the area of Embedded Systems, particularly for safety-critical, high-reliability systems. Such projects addressed major societal challenges such as mobility, ageing society, manufacturing processes, healthcare systems, efficient buildings and energy management.

This renewed vision and strategy aims to follow this path in order to accomplish the ARTEMIS ambition and position it as a world-class initiative in the area of Cyber-Physical Systems and as a leading innovation environment that allows high value creation in new generations of smart products and services with the right economic visibility of embedded intelligence that is key to the European Embedded Systems industry for the Digital Future of Europe.

The emerging Digital evolution relies heavily on Embedded Intelligent Systems technologies in domains where it is paramount that Europe takes a leadership role.

This renewed Vision and Strategy aims to follow this path in order to accomplish the ARTEMIS ambition and become a world-class initiative in Embedded Intelligence and Cyber-Physical Systems.

We need increased investments to support our Research Agenda and to sustain our proposition of an Innovation Environment allowing high value creation in the new generations of smart products and services. Giving the right economic visibility of Embedded Intelligence is of utmost importance to the European Industry for the Digital Future of Europe.

INTRODUCTION

Cyber-Physical Systems are "Embedded Intelligent ICT [3] systems" that are making the products smarter, more interconnected, interdependent, collaborative and autonomous. They provide computing and communication, monitoring and control of physical components and processes in various applications.

Cyber-Physical Systems (CPS) refers to next generation embedded ICT systems that are interconnected and collaborative, also through the Internet of Things, and provide citizens and businesses with a wide range of innovative applications and services. These are the ICT systems that are increasingly embedded in all types of artefacts including our cars, our clothes and even our own body, making our personal devices, our homes, cars, transport systems, offices, factories and cities, etc. „smarter" and more comfortable.

Often endowed with control, monitoring and data gathering functions, CPS needs to comply with essential requirements like safety, security and near-zero power consumption as well as size, usability and adaptability constraints. To maximise impact and a return on investment in this field, the following challenges must be addressed:

- ▸ *De-verticalisation of technology solutions with CPS platforms that cut across the barriers between application sectors including mass consumer markets.*
- ▸ *Convergence of actors along the value chain from suppliers of components and customised computing systems to system integrators and end users.*
- ▸ *Creation of new CPS platforms for both vertical and core markets from automotive, health and energy to wireless communications and digital consumer products and services.*

With the fast development of control computers and communication systems, computing and communication capabilities are embedded in all types of objects and structures in their physical environment. Harnessing these capabilities in time and across space creates applications with enormous and disruptive new functionalities with unprecedented societal impact and economic benefit for citizens and societies. These applications allow the emergence of new innovative businesses that support the opportunities of value creation in several sectors, and nowadays leads to the **Digital Transformation**, i.e. the digitisation of societies and of industries.

Such systems bridge the cyber-world of computing and communications with the physical world, thus forming the Cyber-Physical Systems that integrate computation, networking, control and physical processes. Embedded computers and networks monitor and control the physical processes, with feedback loops where physical processes affect computations and vice versa. This intimate coupling between the cyber and physical is manifested also in a wide range of smart connected practical industrial systems, like connected cars, manufacturing plants, aircraft and integrated healthcare systems.

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[3]   *ICT : Information and Communication Technologies*

Product diversification and added market value in products are created today by the <u>pervasive use</u> of Embedded Intelligence. This Embedded Intelligence <u>in products</u> and services is an important part of added value creation not only within the product or service but along the whole value chain, e.g. in engineering, production, logistics, maintenance, marketing, sales and after sales. Most often this added value of embedded software is not visible or tangible in the end product/service or its market offerings and thus its related value creation is indirect or implicit. The economic visibility of Embedded Intelligence is vital to the European Embedded Systems industry, whether large-scale business platforms or nano-transactions between IoT's. Software-driven transactions can be scaled very efficiently, which opens up interesting opportunities across many application markets. Embedded Intelligence adds value for each of these areas in various forms like increased functionalities, reduced engineering time, improved product quality, increased raw material efficiency and higher OEE market and sales platforms.

These Embedded Intelligent Systems also referred to as Cyber-Physical Systems, will bring disruptive changes and a higher value creation.

The renewed vision and strategy of the present SRA includes the paradigm shift in the smart products where the emergence of highly distributed and large-scale Cyber-Physical Systems means that software has to live in an open and highly dynamic world, enabling these smart products to be remotely and continuously upgraded via their embedded software, thus generating a large variability of products and services, and making their production cycle and time on market **more economical, more environmentally friendly and responsible.**

Some examples:

Smarter Products using wireless sensors, ECS actuators and interconnections in a variety and numerous functionalities help save precious raw materials in their production.

On the road, vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication in combination with new vehicle control algorithms will also contribute significantly to energy savings and safety in road transportation.

CYBER PHYSICAL SYSTEMS (CPS) IN A FAST CHANGING WORLD

The world is changing fast, and although the vision, mission, strategy and research priorities published in ARTEMIS SRA first edition of 2006 and its update in 2011 are still valid, there is a legitimate need to bring them up to date in order to gear them towards a 2025 horizon and to adjust for a better fit with the fast changing world where the digital transformation era that has been accelerating recently disrupts societies, industries and innovates the ways of doing businesses.

2005	2015	WHAT'S NEXT?
800 million mobile phones sold worldwide; 5% are smartphones.	1.4 billion Mobile phones sold worldwide; 80% are smartphones.	What will be the next driver to PC?
Android does not exist.	Android dominates the personal devices market (phones, tablets).	Android is for personal applications. What about an Android-like device for industrial applications?
Amazon launches the first cloud computing service.	Cloud storage is available from any smartphone.	How to distribute storage and computation in intermediate layers between local devices and cloud solutions?
Most general purpose processors are single core; Intel announces the Pentium Dual-Core.	Most general purpose processors are multi-core.	Advances in software design and tools to fully exploit the capability of multi-cores!
"Cyber Physical System" is a concept.	Anyone knows at least one example of Cyber Physical system: Automated metro.	Trust in highly automated systems still to be conquered.
Experts in Artificial Intelligence state "a computer program will not be able to beat a human champion of Go game before 2030."	A computer program beats the European Go champion and the former World Champion early 2016.	New disruptions to come based on innovative algorithms for embedding Embedded Intelligence.
The concept of Internet of Things does not exist.	Ecosystem structuring around key technologies: LoRa Alliance.	Towards a mature Internet Market.
Standalone entertainment devices in vehicles.	Integrated and Internet connected entertainment systems. Hackers claim to be able to take control of a car or aircraft through the entertainment system.	Better assessment and analysis of cyber-attack threats.

However, a number of key questions remains for the future:

- Is the vision of highly performing, environmental friendly and socially sustainable but yet competitive processes and products feasible?
- What is the potential of the Internet of Things?
- How will the developments of Cyber-Physical Systems within the Internet of Things environment drive the digital transformation?
- What are the research and innovation challenges for Cyber-Physical Systems?
- Is the Industrial Internet a sufficient concept for boosting competitiveness and securing Europe's leadership?
- How best can we build European platforms to accelerate the innovation cycle and the establishment of more dynamic ecosystems to support the digitisation of Europe?

Digital components are increasingly integrated and embedded into products and services of everyday usage. In the future, Cyber-Physical Systems (CPS) will become natural in managing complex systems (e.g. smart grids, transport or water management systems) and will make everyday objects intelligent (e.g. homes, offices, cars, trains, cities and clothes), the latter being connected to the Internet, leading to a network of physical objects – the Internet of Things (IoT). Both the CPS and IoT communities foresee great potential for creating a competitive edge for Europe, not only in existing markets, but also by creating new markets across industries and sectors.

ARTEMIS Focus Areas

As Embedded Intelligence in an industrial context encompasses a wider class of systems than Embedded Systems in their most strict definition, ARTEMIS-IA distinguishes three focus areas that together create this wider and industrial context setting:

- Embedded and Cyber-Physical Systems
- Internet of Things
- Digital Platforms

Embedded Systems are everywhere, built into roads, cars, trains, aircraft, medical devices, homes, offices and factories (industrial automation), payment systems, mobile phones and virtual reality glasses. Many high-tech industrial systems are classified as **Cyber-Physical Systems (CPS)** because of the close interaction between computation, communication and control elements (the cyber part), and physical processes such as motion and vibration (the physical part). Life in our society, along with security and safety, will increasingly depend on Cyber-Physical Systems linked to Internet.

The **Internet of Things (IoT)** is a collection of physical objects (Things) connected to the Internet— the things could be cars, buildings, pacemakers and other items which embed electronics, software, sensors and network connectivity. This enables these objects to collect and communicate data via the Internet. Although IoT and CPS share many technical and organisational concerns and challenges, research and development activities usually focus on different aspects: In IoT applications, the 'intelligence' – i.e. storage and computation capabilities used for data processing and decision making – is usually in 'the cloud' and the 'things' are mostly used for data collection and pre-processing. An example would be a traffic management system, which needs the location, speed and destination of each vehicle to compute best routes for each of them in order to minimise road congestion and maximise speed and comfort. Security, Big Data, Communication, IT architectures and other 'ICT topics' are typical R&D areas for IoT. On the other hand, in CPS the 'intelligence' is most often found in the 'Things' themselves, with the internet (or other networks) and 'the cloud' used for communication and external data gathering. Examples would include autonomously driving cars, in which, although they coordinate their activities with other cars and use data from roadside infrastructure or other external sources, the final decision about lateral and longitudinal movement is always taken within the car itself. Safety, computation with limited resources, real-time behaviour, cooperation and coordination strategies, human-centred design, and other 'Embedded Systems topics' are typical R&D areas here.

Digital Platforms[4], in the technical sense, are the supporting infrastructures to enable the digital economy to be built. Digital Platforms consist of hardware infrastructure with software services for which interoperability is well defined and understood. Cloud services, API architectures, open-source strategies, mobile development platforms and Internet of Things are some of the ingredients from which Digital Platforms are built. Companies that are born digital, such as Google, Amazon and Alibaba, have long understood the power of digital technologies. But many of these companies' most successful innovations are not products or services, but the digital platforms on which these products and services are built, and the business models that these platforms enable. Such platform-based business models fundamentally change how companies can do business, allowing them to create entire ecosystems that largely contribute to growing the company and driving strategies. So, a technical digital platform is the fundamental pillar for a business model that opens up entirely new paths to growth for companies. While digital-born companies have successfully mastered platform strategies, the opportunity is now opening up to every company in every industry. Digital Platforms are the enablers for the rapid digitisation of industry.

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4   *https://www.accenture.com/us-en/insight-digital-platform-economy*

THE PATHWAY TO THE DIGITAL EVOLUTION

The Digital Evolution is a silent revolution that is transforming our way of living and of doing business.

The on-going integration of software-intensive embedded systems into products, and their increased capabilities to communicate and interact with their surroundings and other smart products, provides users and businesses with a wide range of smart services and opportunities.
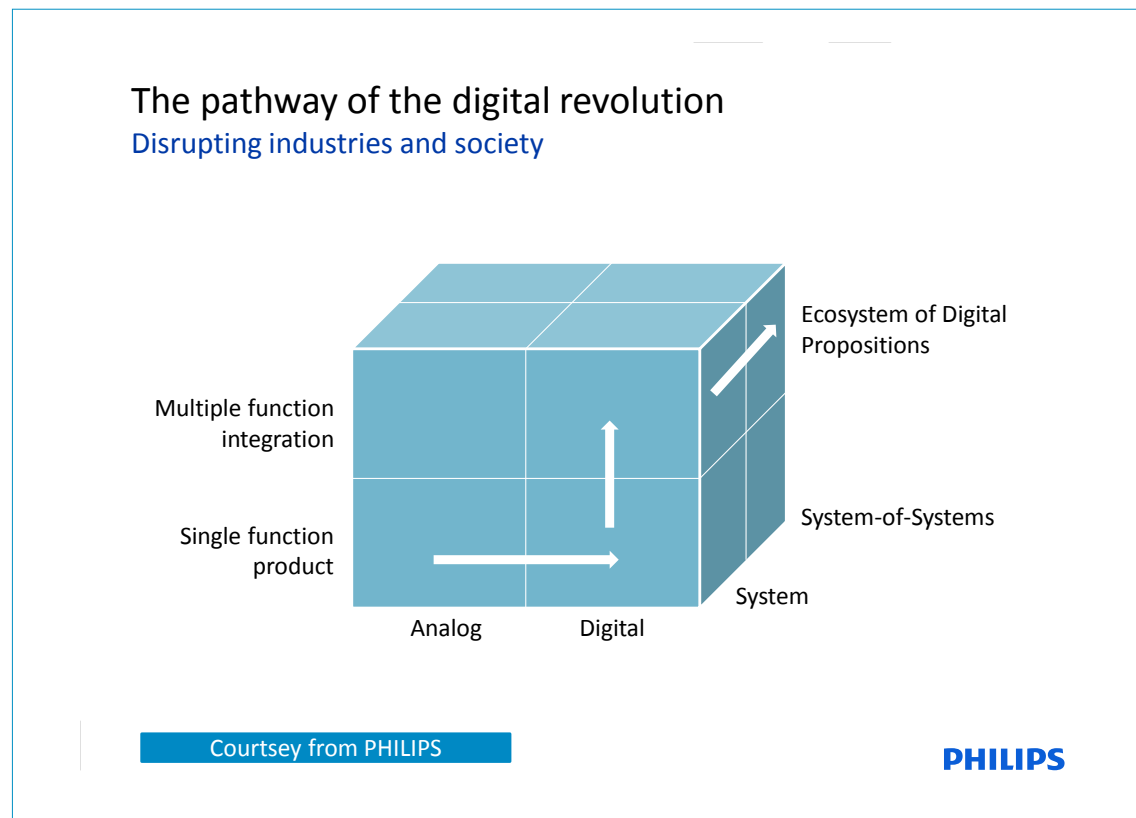
Figure 2 *The Pathway to Digital Revolution*

Numerous products have followed the evolutionary route as illustrated in Figure 2 above, evolving or disrupting, from mechanical and analogue single function products to digitised, multifunctional and integrated products, stand alone or in a system or as part of a System of Systems, with the result being a complete eco-system of digital propositions built around these products.

With this in mind, CPS is now considered as "the evolution of Embedded Intelligence" into smart objects that create highly distributed systems when interconnected, generating a wealth of opportunities and innovations in technology, applications and business models. Eventually these systems will evolve in a digital platform and ecosystem of digital propositions.

A future smarter world will require even smarter products, with greater autonomy and intelligence, enabling a variety of services in a multidisciplinary cooperation, and integrating both industrial and non-industrial processes.

The evolution of photography:
an example of evolution from a mechanised to a digitised eco-system

The first products existed in a mechanical or analogue (physical) form. These were then transformed into a digital form in an evolution from integrated electronic components to embedded software. The next step was integration into the digital mobile phone, and the photo and music players into one device.

The device became a smart phone, connected to the Internet, and consequently a system in a large system with cloud storage and computing; a further step from systems to System of Systems.

Figure 3 *The evolution of photography from mechanisation digitisation, integration and eco-systems.*

THE NEW RATIONALE: THE DIGITAL TRANSFORMATION

'Embedded Systems are everywhere, and they pervade all artefacts of life.'
This was the main rationale upon which the
ARTEMIS SRA 2006 was developed.

Since 2006, Embedded Systems have developed to connect the physical to the cyber world, becoming **Cyber-Physical Systems**, a connectivity feature that made them **Society's Neural System**.

Today, the ability to connect and be connected has grown unexpectedly faster than predicted, as evident in the smart connected products and devices that are transforming the global economy into the **'Digital Economy'** and leading to a deeper '**Digital Transformation'** of many sectors, resulting in a need for a reshaping of activities and business models to stay competitive and open up new markets. This ability to connect to all kind of networks, including the Internet, not only for communication but also for collecting data and computing, provides new opportunities and allows new businesses and trades to exploit the data value stored in the Cloud.

The availability of the digital information from the physical environment is a unique opportunity for the Cyber-Physical Systems industry. The information base for systems will be larger than ever before, resulting in more optimised, accurate and efficient realisation. Access to the knowledge of Internet-based information systems will utilise the smart products as sources of data and information that together constitute the Internet of Things. This eco-system will generate subsequent sales and revenues.

> *Networked Embedded Systems, i.e. Cyber Physical Systems, have, in effect become the neural system of society.*
> *Cyber-Physical Systems should, therefore, no longer be considered in isolated application contexts but in relation*
> *to their contribution to the evolution of society and, in particular, to their contribution in addressing today's and*
> *tomorrow's societal challenges and their digital transformation.*

CYBER-PHYSICAL SYSTEMS: A KEY DRIVER IN THE DIGITAL TRANSFORMATION

There is a need to exploit synergies across complete value chains and application areas at all levels considering embedded software, hardware and microelectronics with a global future vision of a "smarter anywhere and everywhere society".

In the world of tomorrow, a myriad of smart products and systems will be connected via all of kinds of networks, including the Internet, and will be able to exchange information freely. Until now, most of the research and development on the Internet of Things (IoT) has been focused on wireless sensors and on providing connectivity. In the near future using the information provided by the sensors and networks in a smart fashion and connecting sensing to actuation will be key to bringing value to users and society.

The connectivity provided by the Internet of Things will become an enabling technology **for Cyber-Physical Systems of Systems that close the loop from sensor information to actions performed by physical systems in transportation, energy systems, production plants, logistics, smart buildings, etc.**

Interoperability, particularly semantic interoperability, will be key, so that users of physical artefacts and their embedded intelligence may use the different languages of different domains but nevertheless still 'understand' each other. The emancipation of embedded information with semantics creates possibilities for completely new types of application that have not been possible to date.

All these factors, combined with the data analytics to extract meaningful information means that we will be able **to create smarter environments everywhere and anywhere** resulting in increased intelligence, better services and enhanced productivity for all aspects of living and in industrial activities.

This current SRA therefore introduces not only the societal challenges as an overarching concept, but gives illustrative examples of the emancipation with four application drivers to show how CPS technologies are contributing to their growth and uptake, namely:

- ‣ Smart Mobility
- ‣ Sustainable Production
- ‣ Smart Health and Wellbeing
- ‣ Smart Cities

Opening new application contexts is also part of ARTEMIS Innovation Strategy to involve new actors. Smart Cities, Energy, Environment and Agriculture, Farming and Food, etc … are amongst these areas where the connected products powered by the **Cyber-Physical Systems** are decisive factors in their growth.

THE ARTEMIS VISION, AMBITION AND MAIN OBJECTIVES

Cyber-Physical Systems are a major actor to enable the Digital Transformation –

Establishing links from smart products to societal and new business models – development cycle acceleration-.

Innovation Acceleration: cost reduction /cost per function– ease of use - design by composition- better and efficient engineering

It is nowadays widely recognised that Cyber-Physical Systems technology is a core enabling technology that forms the basis for the development of many innovative products and services in both developed and emerging economies. It controls almost all products and systems from a dishwasher to a building, from electric drive to a production line, from a dashboard to a car and an aircraft. It enables new functionalities which differentiate these systems from earlier solutions and, thus, is a foundation of European industrial products saving and creating millions of jobs in a highly competitive international market.

'In a world in which all systems, machines and objects become smart, have a presence in cyber-physical space, exploit the digital information and services around them, communicate with each other, with the environment **and with people**, and manage their resources autonomously, the ubiquity of the Embedded Systems, with their present and forecasted evolution, will have more and more impact.'[5]

Most importantly, ten years after the first published Vision, the ARTEMIS projects portfolio demonstrate that **Cyber Physical Systems is a European success story and a lot has been achieved.**

ARTEMIS VISION AND AMBITION 2016

This digital transformation is not only of high industrial relevance for European growth, job creation, added value and the value chain but it also has a strong societal impact. Producing a valid market proposition to answer societal challenges such as ageing population, healthcare, energy, food and water supply, sustainable mobility and transport very much depends on large and open networks of Cyber-Physical Systems.

The connectivity provided by the Internet of Things will become an enabling technology **for Cyber-Physical Systems of Systems that close the loop from the sensor information to actions performed by physical systems in transportation, energy systems, production plants, logistics, smart buildings, etc…** These Cyber-Physical Systems networks are now forming an invisible *neural network of society* driving innovation on the level of society rather than that of a single industry.

In addition, everything that can be automated will be automated, and will embed a higher level of intelligence and acquire greater cognitive capabilities. The functionalities to be automated will be more complex due to increasing computational capabilities, decreasing cost of hardware and expanding availability of information. Increases in computational capabilities result from development in integration efficiency, e.g. multicore systems, and distributed computing; e.g. cloud and data centres.

Increasing complexity is due to the increasing amount of data generated and used, where the Internet of Things is among the main contributors. It is also due to the increasing complexity of functionalities to be automated. Traditionally automation has been applied in controlled or very predictable environments, but this is changing to a situation where **detection of context and account of human behaviour, for example, have become more important (deep learning).**

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[5]   *ARTEMIS SRA 2011*

Therefore, powered by the new era of this Digital Transformation, ARTEMIS will continue to support a vision where Europe remains among the world-class leaders in the area of Cyber-Physical Systems and Embedded Intelligence. For ARTEMIS it is paramount to position itself as a leader in digitisation for the benefit of the society and businesses in Europe and worldwide. ARTEMIS' ambition is to play a major role in implementing the European Digital Single Market in European policy.

The main trends that will define the new era of Cyber-Physical Systems are:

- ▸ *The integration of functions across application contexts on large and open platforms*, and
- ▸ The *combination with the Internet, its information and data, and computing resources*. An application will no longer be localised in a single device but distributed over a range of devices interconnected even on a large distributed geographical area.

From an Internet perspective, these trends led to the *Internet-of-Things*, where billions of Cyber-Physical Systems provide information about and interact with the physical world that, in turn, can be used in information systems and deliver a considerable amount of data. From this perspective, this opens new opportunities in collaboration and control with **access to Big Data in information systems**.

In the **new area of *Cyber-Physical Systems* (CPS)** the networked smart products with Embedded Intelligent Systems are considered an integral part of their physical surroundings. Two types of Cyber-Physical Systems (CPS) can be identified, (1) *control intensive CPS systems* utilising the new opportunities for innovations in control, such as in sensor networks, smart energy grids or traffic management, and (2) *software and communication intensive CPS*, which utilise the new opportunities for powerful software systems that enable new embedded system services by integration with services of the information systems infrastructure, such as to control complete airports.

Internet of Things, and consequently the Things of the Internet, and Cyber-Physical Systems are complementary directions which together will help to shape a society where humans and machines increasingly interact to provide services and solutions for the benefit of society that are inconceivable with the present state-of-the-art technology.

But, unlike the semiconductors field that is governed by Moore's law, research and innovation in the Software and Embedded Intelligence field follow an iterative cycle, responding to user needs, exploiting the ever-growing potential offered by miniaturisation, harnessing the complexity, matching the physical and cyber world, seeking the grail of greater and better performance, functional and non-functional, such as the ease of use expected by users, reduced time to market as well as energy consumption, autonomy, scalability, dependability, etc.

ARTEMIS MAIN OBJECTIVES

ARTEMIS subscribes to the 'Digital Single Market for Europe' by providing strong technological capability over the total value chain, on both the supply side and the application side of Cyber-Physical Systems. Therefore, the present Strategic Research Agenda, ARTEMIS main objectives are to:

- ▸ Consolidate the **pathway of the digital revolution**
- ▸ Enable a more agile and shorter development cycle through the **adoption of design by composition and correct-by construction principles**.
- ▸ **Overcome fragmentation** in the European supply base for the components and tools of design and engineering.
- ▸ **Remove barriers between application contexts** to yield multi-domain, reusable components and systems.
- ▸ Extend the use of **digital platforms** to build the eco-systems needed for accelerating the innovation and the creation of new business models.

The hyper connected society requires revisiting the research strategic planning and its agenda to take account of the digital transformation, and to maximise the impact of the technological solutions on value creation, businesses and market.

The research challenges depicted in the following chapters are not all-inclusive; they represent the priorities to be addressed.

CHAPTER 4

THE DIGITAL TRANSFORMATION IN ECONOMIC AND SOCIETAL CHALLENGES

4.1 DIGITAL TRANSFORMATION

From market perspectives, building the ARTEMIS vision and strategy takes into account the new economic context and its dynamics, i.e. its drivers, constraints, opportunities and challenges.

THE NEW INTERNET ECONOMY: DIGITAL TRANSFORMATION

In recent years we have witnessed a dramatic shift from "computers" to "mobile devices". Smart phones and tablets now dominate the consumer market, while desktop computer sales are decreasing, leading to a "post-PC world" with the key characteristic of pervasive connectivity. **The next move is just coming with the Cyber-Physical enabled world or 'Things of the Internet',** where billions of devices, sensors, actuators, will communicate together, to servers and to humans forming what some people call the **"Industrial Internet"** (from General Electrics) or "Embedded Internet" (from Intel) revolution. *"The real opportunity for change is still ahead of us, surpassing the magnitude of the development and adoption of the consumer Internet. It is what we call the "Industrial Internet," an open, global network that connects people, data and machines. The Industrial Internet is aimed at advancing the critical industries that power, move and treat the world…. Machines will have the analytical intelligence to self-diagnose and self-correct. They will be able to deliver the right information to the right people, all in real time. When machines can sense conditions and communicate, they become instruments of understanding. They create knowledge from which we can act quickly, saving money and producing better outcomes." (from http://gigaom.com/2012/11/28/the-future-of-the-internet-is-intelligent-machines/)".*

"We are now on the threshold of a fourth phase in the evolution of the Internet. Intel calls this the **"Embedded Internet",** *a network space where billions of intelligent embedded devices will connect with larger computing systems, and to each other, without human intervention. "(From Intel white paper "Rise of the Embedded Internet")*. *According to Cisco, "IoE Creates $14.4 Trillion of Value at Stake for Companies and Industries".* **This emerging revolution relies heavily on Embedded Systems technologies and on domains mastered by European technologies. It is paramount that Europe takes a leadership role in this domain.**

4.2 DIGITAL TRANSFORMATION DRIVERS

In addition to the societal challenges Europe is facing, arising from *'the inverted demographic curves, the constantly increased demands for non-renewable natural resources, the climate change and the constant expectations for improved quality of life, where the modern European social welfare model and its sustainability is one of the major challenges facing the European',* described in ARTEMIS SRA 2011, the ARTEMIS Strategic Research Agenda 2016 highlights a set of new drivers where Cyber-Physical Systems will play a major role in the implementation of the Digital Transformation and the growth of Application Contexts.

LEADERSHIP OF VERTICALLY INTEGRATED COMPANIES

In the domain of consumer electronics, companies that have gained control over the complete value chain (from hardware to end-user applications) have recently shown a high success rate and seem to be more resilient to the economic crisis. Google, Amazon and others tend to extend their range from smart products to devices, and even from silicon design to retail or Internet shops; while Samsung, Apple and IBM are moving into services. Both clusters are creating an ecosystem and a customer lock-in over the complete value chain.

In the past decade, European companies have generally become less vertical, and Europe is now full of horizontal specialisation, which makes it difficult to compete because companies are squeezed between the economic pressure of providers and customers. In a complete value chain, it is sometimes necessary to have less efficient parts to gain overall better efficiency.

The vision of 'virtual vertical integration' encourages market leaders to define the conditions for successful business innovation building on emerging technological developments, and vice versa, to coordinate technological platform developments (hardware and manufacturing to system design and software engineering). On an organisational level, the horizontally specialised European industry faces a critical competitive situation, unless vertical ecosystems emerge. Based on this assumption, the present SRA strategy highlights the importance of the contribution to standardisation activities and setting adequate new standards, as standards are essential enablers for scalability and interoperability functionalities.

THE "ALWAYS CONNECTED SOCIETY"

As highlighted in the ITEA/ARTEMIS 2030 Vision, the virtualisation of communities has changed our society and the way information and knowledge are exchanged, made available or shared: "Individuals are no longer individuals only, but they are part of social networks and entities. Web-based social and business networks serve as virtual communities in which individuals may even adopt a virtual identity" (RB). This trend will get even stronger as social media could also replace many of the traditional types of media. Its economic impact will shape the IT market in general and Cyber-Physical Systems in particular.

However, this prediction of the strong demand of the young generation to remain and stay connected to their communities (the Always Connected Society) in any circumstances could be not fully justified as economic crisis, as recently observed, may have a greater impact on the individuals' budget than predicted/expected and seek better spending power dedicated to communication.

THE PLATFORM CONCEPT AND NEW HYPER-SCALABILITY BUSINESS MODELS

The platform concept that is now quite common in the Internet economy is also a characteristic of the Digital transformation as explained in the ARTEMIS Focus Areas (see Introduction). For the embedded software development and in the Cyber-Physical Systems based application building this Platform concept is cost efficient, as it provides facilities to experiment and test innovative products and services. It helps companies to scale up their development activities with limited effort and minimal investment and funding to rapidly deliver such products and service to the market. Standardisation efforts in CPS technologies are required to fully exploit this concept and open the market to various industries.

The GAFA (Google, Apple, Facebook and Amazon) business model has shown an unprecedented and tremendous growth potential, with economic and financial impact, together as large as the economy of Denmark or South Africa, but realised with only one tenth of the people. GAFA models focus on getting customers to commit. Its innovative approach comes from earning money from the use of products, not from their production or products themselves. Such business models build open platform concepts and networks, leveraging connections and interactions as a source of knowledge and, therefore, performance. These platforms/infrastructures they create make a variety of actors in the Internet economy and other companies want to connect to participate and create value. And scaling is at almost zero marginal cost. The GAFA model proves that there is no future for closed systems in a Networked Economy. It should be adapted to the core areas of European markets that mainly address the Business to Business (B2B), Business to Machine (B2M), and Machine to Machine (M2M) segments.

A set of generic user-centric platforms can be used over several years and help developers boost their design capabilities, validating their options and offering creative and innovative products and services. The platform owner can run the platform as a lab, letting people create, innovate and compete, and can pick up the best product and have the opportunity to capture the highest value.

DATA VALUE

The big amount of data (data deluge) is generated by the increasingly connected smart 'Things' and exchanged in an open-ended relationship. After collecting, integrating, filtering and validating such data from all kinds of sensors and devices, model-based and data-driven analytics generates useful information and delivers analytics-rich applications with high value, sales and revenues. Data market evaluation estimates that the data sector is growing by 40% annually, seven times quicker than the overall ICT market. The Cyber-Physical Systems plays a key role in this data generation and flow by enabling their creation, sensing and processing.

SECURITY

Security and, consequently, the user's trust is an essential feature any smart product and related services for a successful, sustainable market acceptance and uptake. As Cyber-Physical Systems are open and used in a networked environment, security considerations are essential. They raise a number of technological challenges across all system components as well as the development stages of the system. Distributed computation, storage, data analytics and authentication services are increasingly deployed over so-called edge and fog computing devices. Safety-critical systems embed IP-based communication capabilities and enter fields of operation in fully open environments (e.g. automated driving). Established solutions ignoring security can no longer be trusted in this context.

THE SOFTWARE VALUE

The need for better software quality, higher productivity in software development and maintenance (updates and version releases), increases with growing system complexity, stricter operating requirements and expectations of continuous performance and functionality improvements. Mature, interoperable software tools are needed more than ever. Unfortunately, the lack of sustained investments in tools has been a recurrent weakness of our organisations. Tools are capital-intensive, high risk and often plagued with technical immaturity and unrealised hopes. The free and open source model has been effective in getting investment from companies and engaging with developer communities through mutual effort, but for Europe to take advantage of the disruptive technologies shaking the computing systems areas, and to realise the digitisation vision of European businesses, a stronger software ecosystem is needed to nurture sustainable, interoperable CPS software development. This is a major challenge for Europe within the global competition and availability of funding.

R&D Investment in KETS - detailed

Software
53,9%

Advanced materials
7,2%

Industrial white biotech
0.9%

Micro- & nanoelectronics
9,8%

Nanotechnology
0,1%

Photonics
0,8%

Advanced manufacturing
11,4%

Other biotech
2,9%

Environmental technologies
13,0%
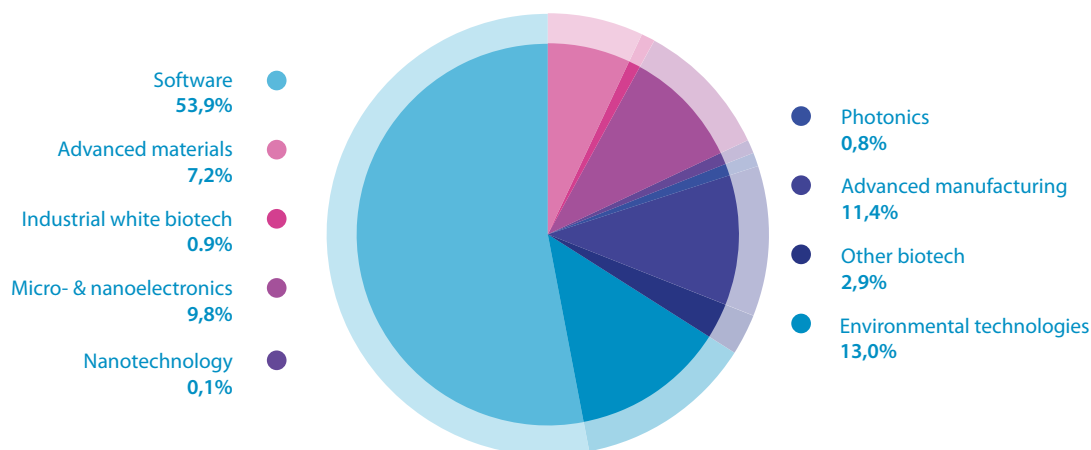
Note: The figure refers to 80 out of the 162 EU companies in the sample.
Source: European Commission JRC-IPTS (2015)

Figure 4 *R&D investments in key enabling technologies* [6]

VULNERABILITY, TRUST AND PRIVACY

The open nature of CPS means that they are both vulnerable to external attacks and internally less secure than expected. In addition, as they are used in numerous applications, their social acceptance is based on the way they are perceived and adopted by the users.

The ACATECH Study [7] describes the basic requirements that CPS security threats have to face, and the key factors that are essential for that acceptance, from their usability and usefulness to their ability to protect the privacy and inspire trust through their safety and security experience.

By reaching the right level of safety and security while protecting the user's privacy, CPS will therefore contribute to providing benefit to society in various application areas.

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[6]   *EU R&D Survey : the 2015 EU Survey on Industrial R&D investment trandsEUR 27541 EN*

[7]   *Acatech study (March 2015) : Living in a networked world –Integrated Research Agenda Cyber-Physical Systems : Eva Geisberger/Manfred Roy (Eds)*

4.3 APPLICATIONS DRIVERS

Markets trends/opportunity and growth potential for a
selected number of application drivers

According to IDC [8] report:

- "Intelligent Systems are to exceed $1 Trillion in 2019 as the Market continues to disrupt traditional industries including manufacturing, energy, and transportation".
- The market for intelligent systems — defined by microprocessors, connectivity, and high-level operating systems/UI in systems excluding PCs, phones, servers, and tablets — will grow from 1.4 billion units and $755 billion in revenue this year to over 2.2 billion units and over $1 trillion in revenue by 2019, according to the IDC report.

The CyPhERS project [9] made an analysis of the economic potential of some key technologies related to CPS:

- A 300% increase has been observed in connected machine-to-machine devices over the past five years with a 80-90% decrease of prices for MEMS sensors over the past 5 years. There exist 1 trillion things that could be connected to the internet across industries, with currently already 100 million M2M device connections across several sectors. The operating cost of the key affected industries is 36 trillion dollars.
- Server performance per dollar doubles every 18 months, where today renting a server in the cloud has one third of the cost of owning a server. Already 2 billion global users exist of cloud-based email services and 80% of North American institutions are hosting critical applications in the cloud. The GDP related to internet is estimated on 1.7 trillion dollar and the enterprise IT spent is about 3 trillion dollars.
- Sales of industrial robots grow by 170% every two years, with 12% of the global workforce of 320 million units in manufacturing being executed by robots. Robots could contribute to 250 million annual major surgeries and reduce the 2-3 trillion dollars spent on major surgery costs. Robots also might reduce 6 trillion dollars' worth of manufacturing worker costs, about 19% of global employment costs.
- From 10 kilometres driven in 2004, today 400,000+ kilometres have been driven by Google's autonomous cars. Potential market is 1 billion trucks and cars, globally, with 450,000 civilian, military and general aviation aircraft. The automobile industry revenue is about 4 trillion dollars with a 155 billion revenue from civilian, military and general aviation aircraft.

The application drivers developed can be found in the next chapters and are just examples and do not cover all the potential applications such as smart energy, smart food, smart farming and agricultural, smart wearables, and many more.

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[8] *IDC Press release 16 Oct 2014. And report # 252046 Oct 2014*
[9] *CyPhERS presentation by A. Sangiovanni Vencentelli at ARTEMIS Pre-Brokerage Event*
December 2014, Vienna

4.3.1 SMART MOBILITY

The mobility sector faces **crucial societal challenges**: **reducing CO_2 emissions, improving air quality**, and **eliminating congestion** for improved logistics and traffic efficiency using existing infrastructure wherever possible while advancing towards an accident-free and causality-free mobility scenario, which also addresses the needs of **vulnerable road users** such as children or an **ageing population**.

In this context, Europe will strive to **maintain global leadership** while serving the needs of society. The development and deployment of new capabilities provided by smart mobility components (consisting of electronics, sensors/actuator, CPS/embedded SW, communication, cloud based SW, system integration) as well as the introduction of the necessary new methods and tools for the design, verification and validation and production are key to achieving this.

Smart systems for mobility aim to provide vehicles, transportation systems and infrastructure with the required intelligence and flexibility by extending and reinforcing the well-established strengths of the European industry**. In this section "Smart Mobility" vehicle means cars, aircraft, vessels, trains, off-road vehicles, satellites, drones.**

Research, development and innovation in "Smart Mobility" will focus on capabilities in the domains of sensing, communication, navigation/positioning, computing and decision-making, control and actuation based on smart systems for mobility and the necessary development and validation tools and methods.
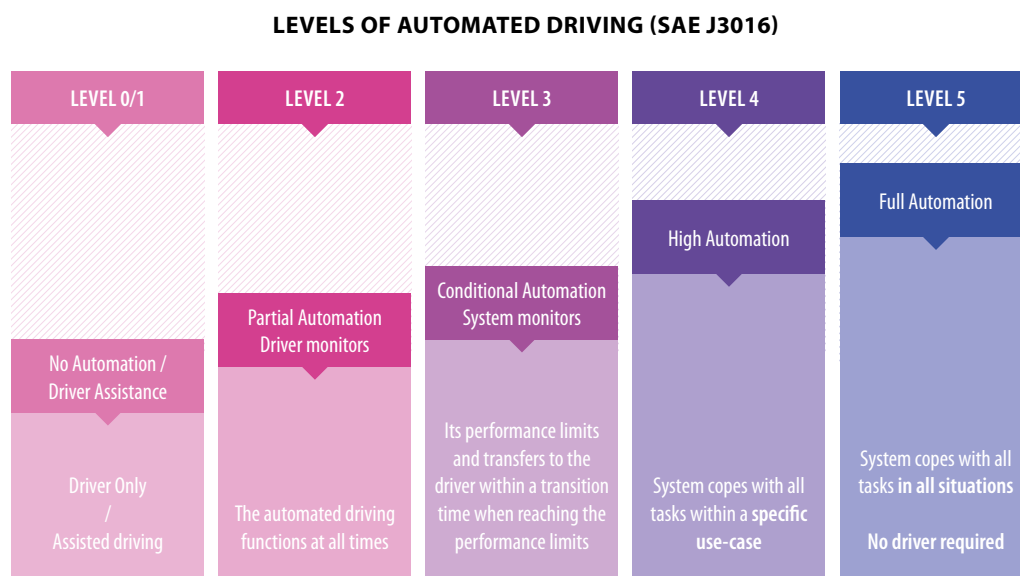
These functions will lead to **resource-efficient transportation** as they enable partly or fully electrified as well as advanced conventional vehicles that are clean, CO_2 optimised and smartly connected to renewable energy sources.

Smart mobility components will also enable different levels of **partial**, **conditional, highly and fully automated transportation** posing new challenges to traffic safety and security in mixed scenarios where vehicles with different automation levels coexist with non-automated vehicles. Additionally, the target will be to ensure flexibly coordinated logistics, mobility for the elderly, reduced congestion in cities, airspace, harbours, and further increased energy efficiency as it makes vehicles and traffic management systems smarter.

Finally, smart systems for mobility will be fundamental for **integrated and multimodal mobility networks** based on smart vehicles and smart infrastructure (road, rail, airspace, waterways, stations, airports, hubs, etc.) and an increased level of information awareness (vehicle, route, weather conditions, etc.). Connecting cars to the Internet of Things (IoT) will lead to massive information exchange capabilities between mobile components and enable (entirely) new service possibilities, resulting in more comfortable and efficient travel and logistics. Thus, it also contributes to less congestion, increased safety and security, higher resource efficiency, faster point-to-point transfer, smooth intermodal shifts and less pollution by the transportation system as a whole. Smart systems for mobility are also essential for promoting and extending the use of sustainable modes among users, including public transport (bus, metro, light rail, "last mile" transport, etc.), and "soft" transportation for "last-mile" transportation (eBikes, bicycle, pedestrians, etc.).

The innovation provided by SMART SYSTEMS FOR MOBILITYEL in Smart Mobility will help to shape the convergence of the worlds of digital data and transportation that meet the needs and capabilities specific to Europe and provide

functionally safe and reliable products and related efficient processes. This will not only strengthen European leadership in electronics and smart embedded computer systems, but also support Europe's role as a frontrunner for innovation and engineering quality in the automotive and other transportation sectors, such as aerospace and railways. Hence, it will help to strengthen those industrial sectors that are most important for employment and economic growth in Europe.

LEVELS OF AUTOMATED DRIVING (SAE J3016)

LEVEL 0/1	LEVEL 2	LEVEL 3	LEVEL 4	LEVEL 5
				Full Automation
		Conditional Automation System monitors	High Automation	
	Partial Automation Driver monitors			
No Automation / Driver Assistance				System copes with all tasks **in all situations**
Driver Only / Assisted driving	The automated driving functions at all times	Its performance limits and transfers to the driver within a transition time when reaching the performance limits	System copes with all tasks within a **specific use-case**	**No driver required**

Figure 5   *The Five levels of Automated Driving*

Similar roadmaps exist for other domains of mobility like rail, aerospace, off-road vehicles, trucks etc.
The advances needed to achieve these milestones are expressed through specific targets in the domains of sensors and actuators, energy storage, drive trains, vehicle system integration, smart grid integration, safety, integration into infrastructure (e.g. parking, charging, billing systems …) and transport system integration. **All of these features are critically enabled by** smart mobility systems as such vehicles will demand **novel and increasingly powerful but more complex hardware, mixed-criticality embedded software and dependable vehicular networks**. Electrical and thermal architectures and interfaces supporting intelligent charging and refuelling technologies will be required separately. Overall, safety, security and transparent mobility services are a prerequisite for successful market penetration.

Parallel to the advancement of electric and plug-in hybrid passenger cars as well as light-duty vehicle technologies, electrified trucks and buses or fuel cell vehicles will be developed. However, the ramp-up of their deployment is expected to start later. Furthermore, resource efficiency is the driving force of research and innovation in other transport modes, e.g. air transport [10].

Significant breakthroughs have recently been made in advanced driver assistance systems by European vehicle manufacturers and suppliers. In order to swiftly proceed towards highly automated driving and flying, where the system relieves the driver of steering, accelerating and monitoring the vehicle environment, the following three steps can be foreseen in the automotive domain (see also [11] and [12] for similar steps in the other domains in the mobility sector):

- ▸ By 2020, conditional automated driving (SAE Level 3, see [13]) is expected to be available in low-speed and less complex driving environments, e.g. in parking lots and in traffic jam situations on one-way motorways.
- ▸ By 2025, conditional and highly automated driving (SAE Levels 3 and 4) is expected to be available at higher speeds in environments with limited complexity, e.g. on highways.
- ▸ By 2030, (conditional and highly) automated driving is expected to be available in most complex traffic situations, i.e. in cities.

Recently developed industrial roadmaps in Germany [14] and Austria [15] clearly point out what technical challenges have to be faced and what innovation steps are needed to sustainably introduce automated vehicles to the market. In closed and secured environments (e.g. factory floor, new city areas with dedicated infrastructure, precision farming, business and leisure parks, university campuses, etc.), a revolutionary scenario to introduce highly or fully automated vehicles without too many intermediate steps is likely to be proposed first.

While Embedded Cyber-Physical Systems therein will probably also be closed and carefully tailored, support for open environments will follow and impose much more critical demands:

- ▸ Embedded hardware and software will have to be regularly updated to follow e.g. legal requirements, respect the latest standards, introduce new security aspects, services and features, and ensure electromagnetic compatibility and to finally stay compatible with the latest vehicle technology.
- ▸ Eventually, vehicles with different levels of automation will be built on advanced driver assistance systems and cooperating components as well as on detailed driver status monitoring and environmental perception.

10   *Clean Sky 2 JTI Work Plan 2014-15*

11   *European Roadmap for Automated Driving, EPoSS, 2014*

12   *ERTRAC Roadmap for automated driving, 2015*

13   *Gereon Meyer, Sven Beiker (Editors); Road Vehicle Automation; page 11 ff; Springer 2014*

14   *S SafeTRANS, Gesellschaft für Informatik (GI), and Verband der Automobilindustrie (VDA), Eds., Einge-bettete Systeme in der Automobilindustrie – Roadmap 2015-2030, 2015 .*

15   *Austrian RDI Roadmap for Automated Vehicles, Austrian Ministry for Transport, Innovation and Technology, March 2016.*

To separate the development of sensors and actuators from control strategies and trajectory planning, a (de-facto) standardisation of object handling, object descriptions, scene interpretation, situation classification and management is essential. Therefore, the creation of industrial frameworks is recommended and an exchange of test procedures between OEMs and suppliers is encouraged.

As it seems impossible to define all the safety relevant scenarios up front, new "learning" concepts and adaptive lifecycle models are required, which continuously analyse real-world data for near incident scenarios, evaluate the potential impact, modify the control software or strategies, validate the improved systems and update all related vehicle components (maps, control software, information on road conditions etc.) in a highly dependable way, i.e., safe, secure, and in real-time.

Traffic and fleet management systems are crucial for highly and fully automated systems. Dependable communication networks (enabled by terrestrial and space systems) with wide coverage and high availability and data links among vehicles as well as between humans, vehicles and the infrastructure will be fundamental for traffic management systems. This will allow cooperative decision making in vehicle guidance and benefit from high-performance computing (HPC) systems.

Technology transfer to and from robotics and aeronautics and space is an essential part of the development process, and the creation of regulatory frameworks as well as in-vehicle and inter-vehicle standardisation has to go hand in hand with technology development. Similarly, the mandatory development of advanced and utilisation of existing traffic infrastructure will provide a framework for automated transportation systems.

4.3.2 SUSTAINABLE PRODUCTION

Currently, the world is undergoing a "Digital Industrial Revolution". This fourth industrial revolution is based on, and fuelled by, development and uptake of ICT, specifically architectures and services.

Already these are key innovation drivers for manufacturing companies. Creating suitable architectures and services as well as corresponding innovation strategies and new business models is modernising Europe's manufacturing capabilities and helping it compete against fierce global competition. It is expected that in the future, traditional factories will increasingly be transformed into smart digital manufacturing environments. Currently, however, the full potential for ICT in manufacturing is far from being fully exploited.

The production of goods and services is a well-known and critical part of our society. The production competitiveness depends on multiple factors ranging from design for production over production, environment and raw material efficiency to efficient market and business platforms and associated logistics. Automation and Embedded Intelligence play a vital role in all these steps to build the product and service value. Being the current world leader in production automation, Europe has the position and ambition to drive technology and business development in the field.

Top level needs for sustainable production identified by industry are:

- ‣ Circular economy
- ‣ Profitability management addressing OEE, product/service quality and business model accountability

Key to achieving this is Competence Management and Trust related to automation system security (operations and operations data), safety and privacy.
Identified critical automation competencies to achieve sustainable production are:

- ‣ Man and machine interaction, co-operation and co-existence
- ‣ Automation security and safety
- ‣ Human-machine interfaces and machine-to-machine communication
- ‣ Distributed production
- ‣ Sustainable operation
- ‣ Productivity platforms, products and services

The realisation of these competencies will be supported by technologies like Internet of Things (IoT), System of Systems (SoS), Local automation clouds, and Cyber-Physical Systems (CPS).

These technologies together have to address automation critical issues like:

- ‣ Real-time operation and communication latency
- ‣ ICT security and data integrity
- ‣ Engineering efficiency
- ‣ Run-time system evolution and scalability
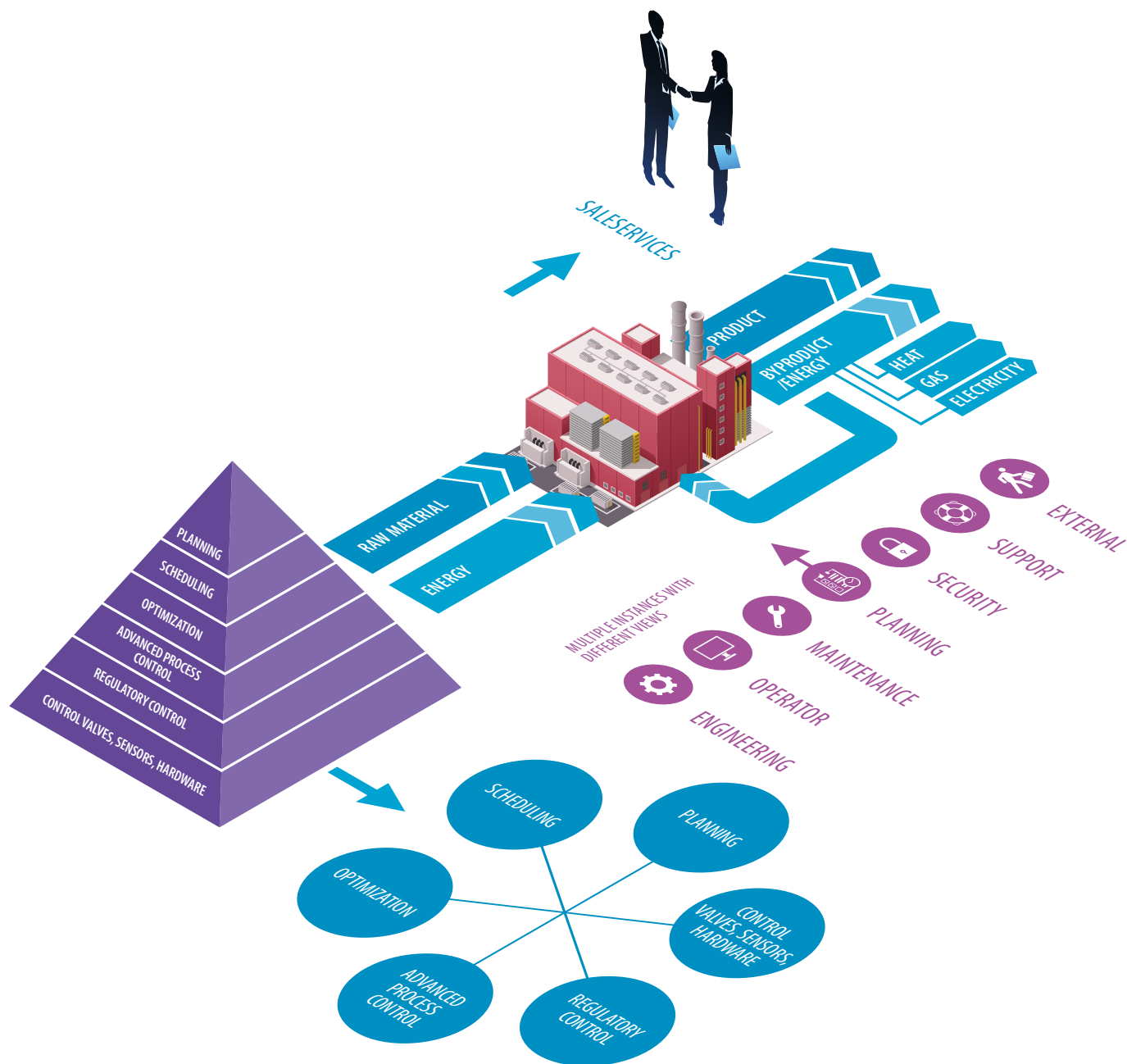
Figure 6 *The move to evolvable and scalable IoT and SoS based production automation with*
associated tools fosters sustainable production business

Each of the above technologies is built internally on embedded software that, in turn, requires tools and methodologies for engineering, design, operation and maintenance.

Achieving the sustainable production of goods and services requires R&D to improve and integrate several technologies that address the required automation competencies and issues. To serve as inspiration for technology R&D, a number of integrated ideal concepts are proposed here:

▸ Instant access to virtual dynamic factory
▸ Increased information transparency between field and ERP
▸ Real-time sensing, networking and data-analysis
▸ Production industry as an agile part of the energy system
▸ Management of critical knowledge
▸ Automation system, service and function engineering
▸ Integrated multi simulator platform
▸ Automation system for flexible distributed manufacturing
▸ ICT Security

4.3.3 SMART HEALTH AND WELLBEING

Due to demographic changes the pressure on the cost of healthcare will continue to rise while economic growth in emerging countries is an opportunity to innovate. Health and Wellbeing will increasingly become digital and the care will be integrated over the whole continuum from prevention to early diagnoses based on home products up to highly integrated diagnoses and treatments in hospitals and rehabilitation in care centres and at home. Healthcare equipment will continue to evolve and grow in terms of functionality and performance. New non-invasive (image guided) therapies will disrupt the way of treating people in hospitals. New solutions, applications and services are required to support these changes. The digitisation of the Health and Wellbeing market will enable new solutions and services for the whole continuum of care. In the healthcare domain we see the following major trends:

▸ From Volume to Value: Move from reimbursing clinical activities to compliance with standards of care and the 'consumerisation' of healthcare
▸ From Response to Prevention: Move from treating illness to maintaining population wellbeing; resource allocation will shift to preventive care and reduction of complications and readmissions
▸ *From Episodic to Continuous: Digital platforms will connect information* across the health continuum to enable more definitive diagnosis, timely clinical intervention and decision-making
▸ *From Limited to Accessible: Expanding affordable access to care* for all will include solving challenges related to affordability, remote access and clinical talent

The challenges are to provide added value for all stakeholders in the healthcare domain. How can care provide meaningful information for the right decisions? How can hospitals manage their data in a business-like and meaningful way. How can I manage and access my healthcare information as a consumer. The goals are to better

leverage scarce resources improving access and quality of care, to reduce the overall cost of health management, to improve the accuracy of patient information and to support a healthier lifestyle.

The Health and Wellbeing market will become more and more digital enabling the aforementioned new solutions, applications and services. Devices will become more and more connected to digital platforms delivering their data in a secure, managed way. Individuals and patients will become more and more the owner of their data and will have to give consent for the use of their data. In order to become effective we need to create a more connected ecosystem of care for patients and providers. where data is collected from all kinds of devices and systems. In the ecosystem data is standardised and correlated for consistency, algorithms are applied for data to identify health patterns and trends. Information is only accessible in a secure, safe way.

These changes will require completely new kinds of products, both for the home market as well as for the professional market. 'Consumerisation' of healthcare will create a new market for devices in high volume and services enabled by digital platform ecosystems e.g. for the home market devices need to deliver medical relevant information to be used by healthcare professionals in hospitals. For the professional market increased integration of devices will enable new applications, e.g. multi-model Integration of equipment will enable new (image) guided interventions in a "Cathlab" where people are treated in a minimally invasive way.

The main Embedded Intelligence and Cyber-Physical Systems related challenges to be solved are:

‣ Increased functionality and performance of healthcare equipment,
‣ Interoperability of health equipment and devices,
‣ Certification of health devices,
‣ Digital Health Platform architecture and scalability,
‣ Secure IT/cloud solutions and services,
‣ IT interoperability in and outside hospital, between hospitals and health providers and at home,
‣ Design technologies incl. dependability, user-centric design.

4.3.4 SMART CITY

By 2050, 80% of the population will live in cities. City-wide challenges like accessibility, health and air quality, energy management, safety, climate neutrality and waste management are closely related. Therefore, integral solutions must be developed for major challenges like smart economy and smart governance develop.

A model and benchmark for smart cities is defined by TU Vienna[16]. This provides a preview into what parameters are relevant for smart cities. For example, smart mobility is based on the quality of local transport, international accessibility, ICT infrastructure and sustainability of the transport system. For smart environment, air quality, ecological awareness and sustainable resource management are the key indicators. Smart people build on indicators

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[16] *Smart City model and benchmark of TU Vienna: http://www.smart-cities.eu/index.php?cid=-1&ver=4*

for open-mindedness, ethnic plurality, lifelong learning and education. Smart living gathers all human centric topics like cultural and leisure facilities, health conditions, individual security, housing quality, social cohesion, education facilities, etc. Smart economy is derived from the city image, productivity, labour market, international integration, entrepreneurship and innovative spirit. Understanding, measuring, monitoring and controlling the state of a city by all these indicators requires complex city infrastructures.

Figure 7 *City of the Future and its large invisible Embedded Intelligent Systems.*

Cities of the future will rely heavily on large invisible networks of embedded intelligent systems. City infrastructures for energy and water supply, distributed energy generation and storage, waste management, smart mobility, healthcare or security systems will be efficiently controlled by seamlessly interacting large-scale service networks based on ubiquitous embedded intelligent systems. These smart city ICT infrastructure systems are networks that also will link to the individual networks of future homes with the networks of surrounding smart building and offices facilities, together forming systems-of-systems. In such (inter)networked systems, data security and privacy will have to be well-protected.

The climate-neutral city of the future will allow the inhabitants to live and work in energy neutral buildings, to efficiently travel, to do secure transactions and to enjoy their lives. This will pose new challenges to the supporting embedded intelligence. New business opportunities and especially services are likely to occur on the crossovers between existing and new infrastructures enabled by combinations of different embedded intelligent systems. And since Europe has the lead in many technology domains underlying novel applications in smart cities, Europe is in an excellent position to exploit these new business opportunities.

The application scope in this context includes the security of critical infrastructures, information exchange, access rights and authorisations, secure mobile computing, ticketing and payment as well as the security and privacy of personal data, and smart home/building related applications.

The ever growing numbers of communicating devices that run both open and confidential and private applications over internet require extensive understanding and research to support security and ensure privacy protection. Examples are mobile phones running e-banking, home-control and e-government apps, wireless sensors systems that monitor critical infrastructures such as streets, traffic lanes and smart energy. But also apps for smart metering for energy consumption control or control secure access to buildings and require both secure applications and tamper-proof hardware.

The sharp increase in numbers of embedded systems in daily life calls for a constant attention for energy efficiency, to keep the total energy consumption on this planet ecologically manageable.

Public spaces and places such as streets, parks, shopping centres, etc. is a big opportunity for smart spaces. The services in such places can only emerge if the their information is available and made open by embedded intelligent systems. Opening and especially making the information available requires investments in the infrastructure of these places in the form of embedded systems and connectivity, which is clearly not the case currently.

Probably the reason is that so far these have been more or less ad hoc systems built by smaller companies, if they even exist. European opportunity could be based on enabling innovative and collaborative digital platforms that are based on loosely coupled systems with standardised flexible interfaces. In order to make this happen the development and validation of open intelligent system architectures in real settings must be high on the innovation agenda.
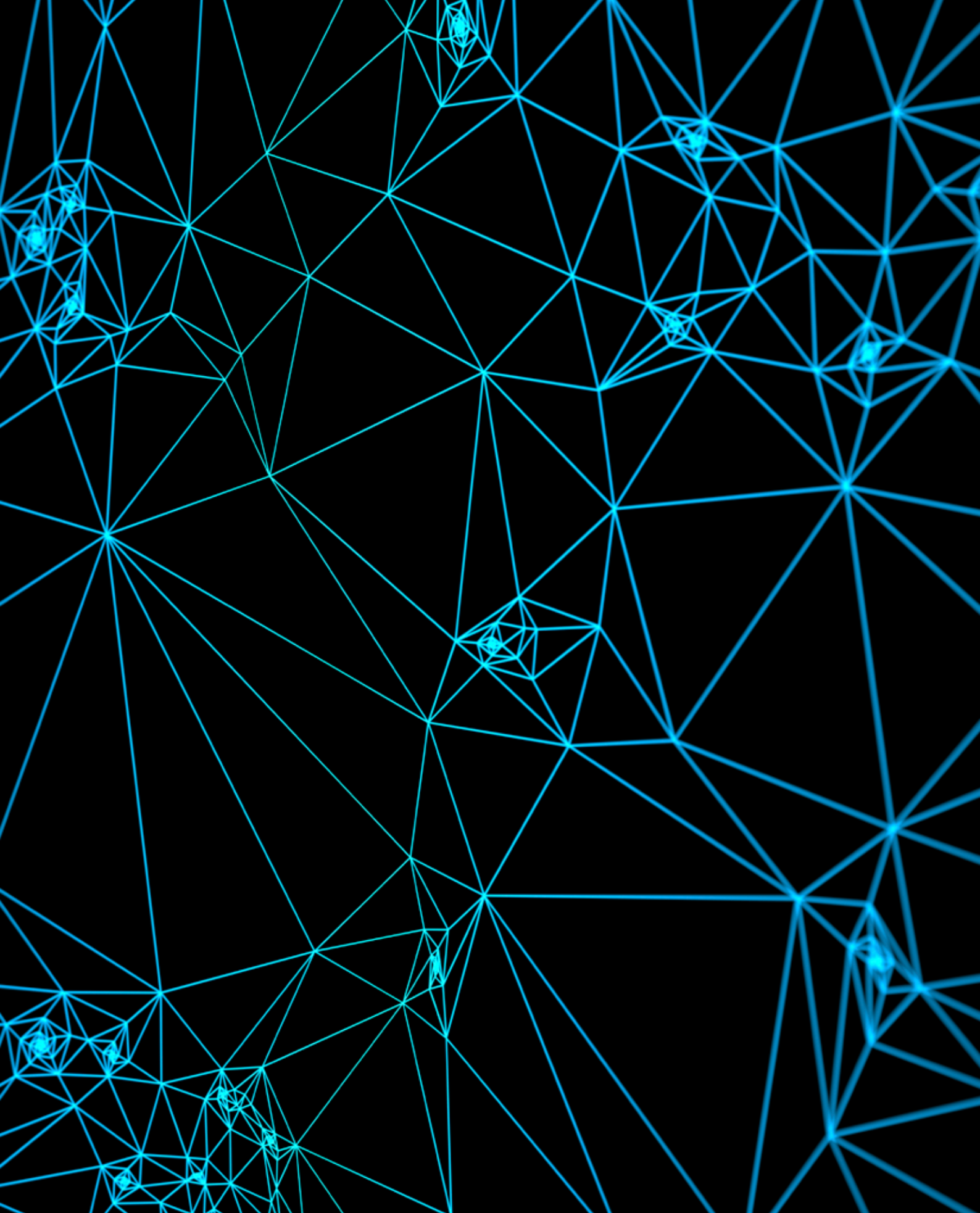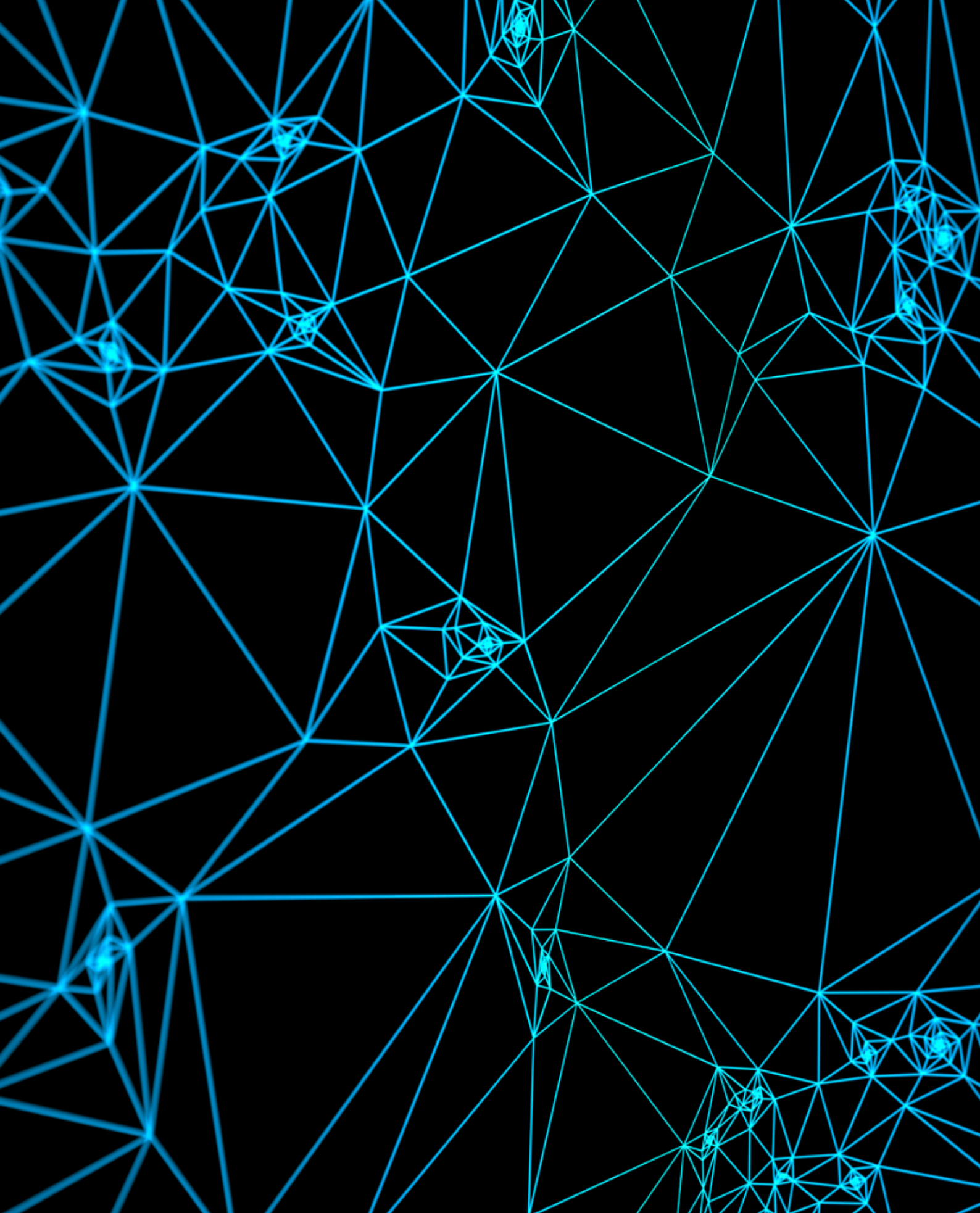
ARTEMIS INNOVATION STRATEGY AND RESEARCH PRIORITIES

5.1 ARTEMIS PRIORITY TARGETS

For the coming period (2017-2025), the following priority targets are selected to guide the R&D programmes with the purpose of having greater impact and quick-to-markets results:

▸ Allowing the pace of product-family roll-out to be **governed by business needs** (rather than engineering limitations),

- *increased connectivity of the networked Embedded Intelligence (i.e. Cyber-Physical systems) – as the neural system of society*, should no longer be considered in isolated application contexts but holistically to address today's and tomorrow's societal challenges

- *Exploiting the ubiquity of the Cyber-Physical Systems*, which goes far beyond that anticipated, where embedded applications are surfacing (emerging). Embedded intelligence now links the cyber world to the physical world (Cyber-Physical Systems) and shares all kind of networks (including Internet) and components in configurations whose conceptual structure have to map to their physical structure, with increased quality of services.

- *Increasing customer confidence*, trust and acceptance by providing safe and secure products and solutions.

▸ Faster to market: **reduce the development cycle and development costs** by:

- *Optimising the factor Technology Time to Market/Technology Time on Market*, which is continuously increasing and affecting new markets and products. Indeed, development cycle optimisation and 'cooperation speed' in transfer from basic research (academia) to applied research (academia and public research institutes) and industrial research (large industry, OEM's and supply chains and SMEs) is a great challenge

- *Shorten the time to market:* improve the development cycle and technology maturation

- *Mastering the complexity* while reducing the cost and increasing the performance is a key challenge: Complexity is induced by increased functionality, but must guarantee safety and security. The exponential potential increase brought about by semiconductor miniaturisation is creating great opportunities, and necessitating equivalent investment in the Cyber Physical Systems in order to leverage the exploitation of the new potentials. Ensuring correct and secure collective and autonomous behaviour of the heterogeneous interconnected elements will be at the core of the challenge. It will encompass a multi-disciplinary approach, <u>various levels of tooling and methodologies</u>.

▸ *Increased efficiency: easy adoption by the users and lowering the threshold of product introduction in face of rapidly changing market needs better pervasive/ adoption (OS, standards, ..),* life cycle management *(e.g. upgrades)*

▸ *Improved sustainability:* by enhancing product and system ease of use, adopting multi-view system design (from conception to operation and services) as well as a reuse policy.

5.2 INNOVATION STRATEGY

The cross-domain approach: reducing the fragmentation,
better leverage on investment, cross-fertilisation

ARTEMIS innovation strategy is two-pronged: one is to **'Build on the leading positions where Europe is strong'**, in specific technologies and in various application domains, particularly for the safety-critical, high-reliability, real-time applications in the field of automotive, aeronautics, space and health sectors. And the other to **'Create new opportunities'** for Europe to be positioned at the forefront of **new or emerging markets with high potential growth rates** to become among the world leaders in these domains and particularly target Process Industries, Smart Cities and Energy Efficient Buildings, Environment, Food and Agriculture.

To position itself in the on-going Digital Transformation of a large variety and numerous activity sectors are undergoing**, the adopted ARTEMIS Innovation Strategy will be inclusive of the market and market needs, of society and of technology, in a flexible, open and dynamic approach to continuously adapt to the evolving challenges in the areas of major changes**.

The new strategy will be more user-centric:

- ▸ **To take into account the user's benefit and experience, over the whole value chain** from deeply Embedded Intelligence to operation and services in order to enable the Digital Transformation, value creation and the emergence of innovative business models;
- ▸ **By building better and more efficient technological solutions** to be stronger together in the context of global competition. This new approach aims to complement the cross-domain approach to provide components or subsystems as building blocks, in a Model Driven xxx. The purpose is to **increase development efficiency, enhance usability**, to achieve better and easier adoption of engineering methods and tools, and to provide a holistic product/system view covering the whole life cycle and from a system-of-systems perspective.
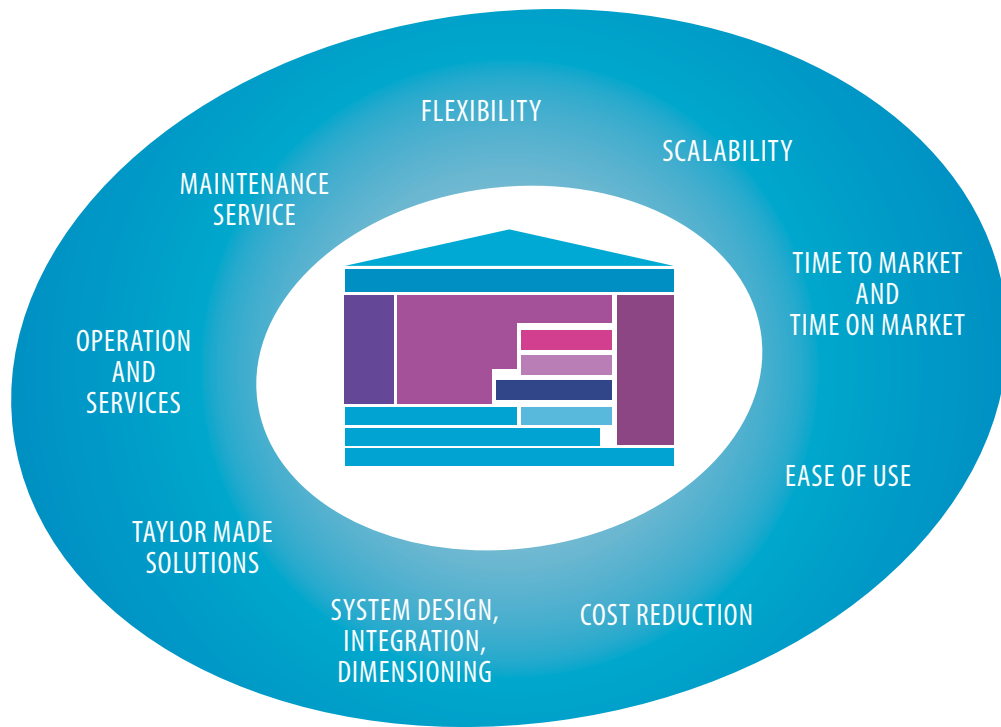
Figure 8 *Digital Transformation: a highly dynamic approach for better sustainability*

Closer investigation of the societal challenges has highlighted the importance of interoperability, system autonomy, networking - including use of the Internet - and consideration of mixed criticality for more dependable systems. This 'bigger picture' for Cyber-Physical Systems implies change from local networks to open and interoperable networks. This leads, in turn, to a change from single-system ownership to multiple-design processes and responsibilities involving many parties, multi-views, with conflicting objectives.

- ▸ There is a **change from static networked Cyber-Physical Systems to Systems-of-Systems** which are highly dynamic, evolving and never down. The convergence of applications on open networks introduces safety, security and privacy requirements for components and network, as well as availability and real-time behaviour in areas where such requirements have not been an issue so far (such as in home networks and car-to-infrastructure communication, …).
- ▸ **Cyber-Physical Systems technology should no longer be considered in isolated application contexts** but should be seen in relation to their contribution to the evolution of society and, in particular, to their contribution in addressing today's and tomorrow's societal challenges.

5.3 STRATEGY IMPLEMENTATION

The cross-domain sharing of research and technologies to embed intelligence into products and services is one of the main innovative strategies ARTEMIS developed in the SRA 2006. This cross-domain approach is not only valid to address the 'Digital Transformation' challenge that most economic and business sectors are heading for, but it becomes **of greater importance for sharing solutions between the various application sectors.**

Indeed, to overcome the silos effect plea, addressing research in a voluntary cross-domain perspective enables the optimisation of investment in research and increases communalities of functional and non-functional properties. This should lead to wider cohesion between application sectors, joint strength and more cost-efficient adoption and deployment of technological solutions, and facilitate interoperability between systems.

The **Matrix Approach** developed in the previous versions of the SRA to cut barriers **between market sectors** and facilitate **cross-domain sharing of technologies and research** has now to be complemented by a novel approach based on model development to improve the overall industrial competitiveness, to allow fast and agile development, to reduce the development cycle and reduce the development risk.

This change in the paradigm will improve the design by composition, by using more models that are based on a top-down strategic road mapping while setting an ambitious set of high-level objectives.

5.3.1 THE CROSS-DOMAIN APPROACH

The successive ARTEMIS Strategic Research Agendas identified three main areas of research where the application contexts/domains should share communalities and synergies to overcome the fragmentation and create critical mass for the investments and to embrace the technology challenges, such as:

- ‣ Architectural models and principles allowing new functionalities and performance
- ‣ Safe and secure by design, based on interoperability standards for systems and design tools
- ‣ Situation awareness for distributed real-time and highly certified operations
- ‣ Interconnection, to enable the development of new and smart applications and to create solutions to the areas of major change
- ‣ Dynamic, autonomous, adaptive and self-organised ES
- ‣ Seamless interaction of the ES with their environment
- ‣ Optimised and consistent processes and tools.
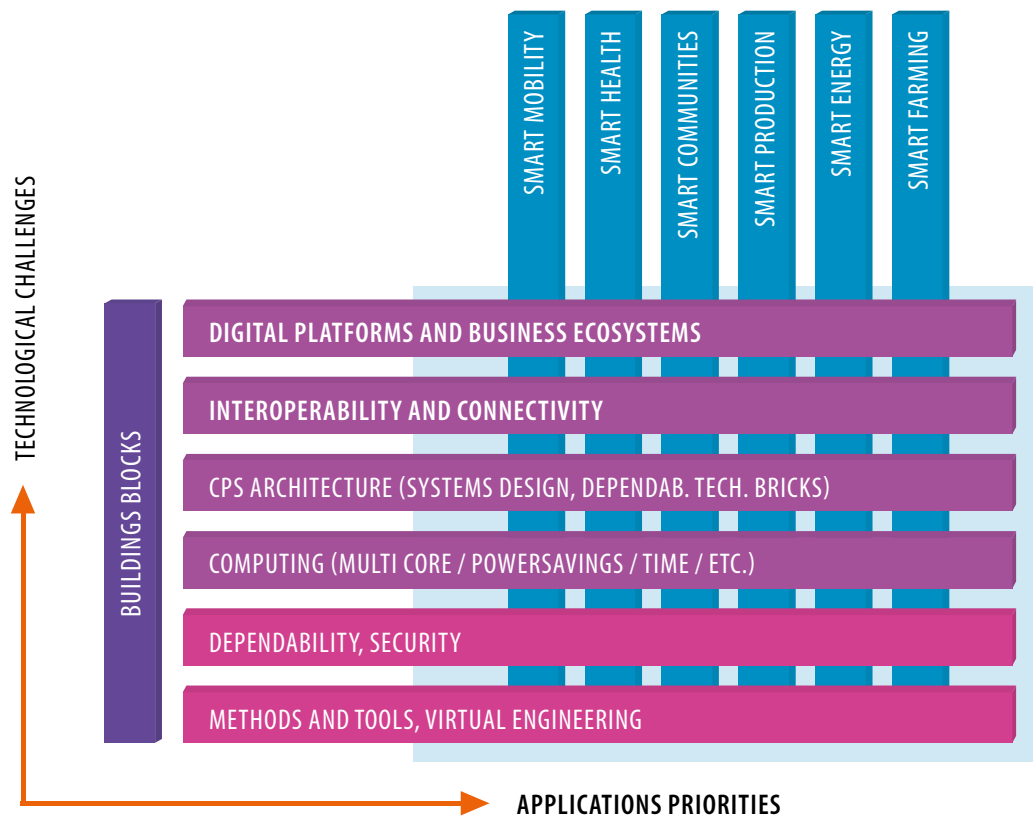
Figure 9 *SRA 2016 Matrix*

To deliver the expected services and solutions, a number of **technological challenges and opportunities** were considered:

- ‣ Safety-critical Secure Systems
- ‣ Virtual World
- ‣ Big Data/Data Analytics
- ‣ Systems of Systems
- ‣ Cloud Services
- ‣ Internet of Things
- ‣ Autonomous, Adaptive and Predictive Control
- ‣ Computing & Multicore

5.3.2 STRATEGIC RESEARCH CHALLENGES

ARTEMIS RESEARCH DIRECTIONS

In order to break domain barriers and boost innovation, research activities should continue to foster the cross-domain approach and seek greater synergies to develop common building blocks. Building such predictable CPS components is needed to maximise the reuse, accelerate the development cycle and, consequently, time to market.

Therefore, in the present ARTEMIS SRA, a number of 'Building Blocks' has been defined to fit in an Ideal House construction to smoothly feed the innovation across the CPS system design flow all over the supply chain.
The target of this new strategy is to meet the Cyber-Physical Systems challenges to fulfil the cost effectiveness and time to market (acceleration), time on market, while leaving enough flexibility for products to develop, to scale to the requirement of their environment, such as trust and security, ease of use and scalability, ….
Foster the building-blocks approach (building the Ideal House)

ARTEMIS feeds innovations through

BUILDINGS BLOCKS   STANDARDS AND   KNOW-HOW   ENGINEERING   ARCHITECTURES
                        INTEROPERABILITY
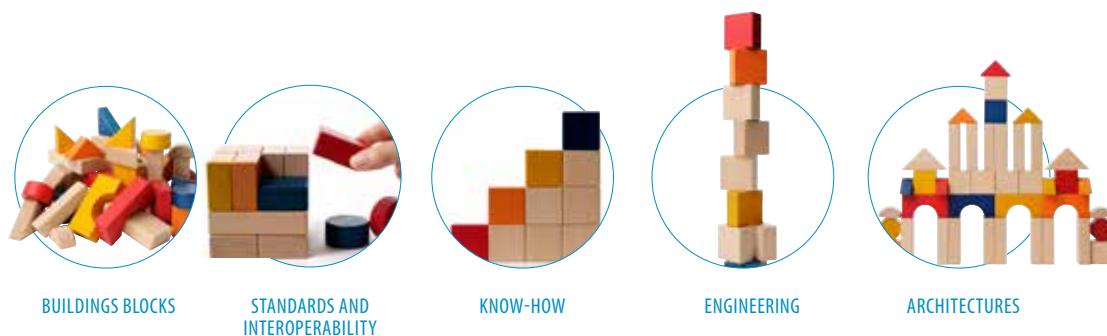
Across the CPS System design flow / supply chain

To make significant advances in 'design by composition'
To meet the challenges of dependability, cost effectiveness, time to market, …

Figure 10 *CPS System Design Flow*

ARTEMIS will feed innovation across the entire life cycle and thereby boost the system design flow including the complete supply chain – in terms of speed, cost and quality.

Such CPS components should respond to 'industrially accepted open standards.

THE BUILDING BLOCKS APPROACH

The development of smart and connected, highly automated and smart products and systems compared to conventional ones is more complex by far. Thus, new core elements and development and validation technologies are needed for such new smart products.

For example, it is no longer possible to build and thoroughly test such products with conventional approaches only: it would simply not be possible to cover all possible usage scenarios, to frontload testing, or to efficiently validate and certify such smart products. There is a need to extend the adaption of model-based engineering.

Model centric development and virtualisation of testing (e.g. by simulation) are among the techniques to cope with the complexity:

- ‣ Architecture of automated products, both system and infrastructure.
- ‣ Sensors and actors including their SW for real-time data acquisition management
- ‣ Big data: handling and analytics of big data in order to enable real-time decision making
- ‣ Development and standardisation of common environment model
- ‣ Communication and transfer of relevant information between vehicles and between vehicles and infrastructure.
- ‣ Safety and security aspects, especially for communication (inside and outside vehicle)
- ‣ Human interface aspects, human-centric design
- ‣ Legal aspects

The smart products development path will build on achievements in the domains of Cyber-Physical Systems technologies and information systems as well as the infrastructure in which they will evolve: smart products include today functionalities that are necessary, for example, for navigation and positioning, communication, information awareness systems and/or traffic management, and also to access a wide range of applications and services (booking, ticketing, tolling and billing, etc …). **This necessitates the development of both big data applications using high-performance computing systems and deeply embedded systems** using versatile hardware, software and communication to optimise these integrated functionalities.

The **creation of an open, common, secure and trustworthy architecture** is a major research topic to provide built-in security and privacy from component to overall system level. It is needed for the interplay between systems in a

comprehensive and intelligent way, for the development and deployment of applicable technologies and services, and for setting standards of interfaces regarding **interoperability, efficiency, robustness, safety and security.** These goals require intense work on highly dependable **multi-communication platform(s).**

Seamless integration and interaction in a broad co-modal sense (e.g. from road and energy infrastructure, traffic management to the individual types of transport, from ships, trains and aircraft to cars, busses, trucks and off-road machines) will be facilitated by significantly **advanced connectivity** in various forms and by the intelligent use of consumer electronics or low-cost configurable devices along with tailor-made, built-in technology.

Such systems will have to be **validated under virtual, semi-virtual and real world conditions**. This requires smart mobility systems provide dependable solutions for advanced sensors and actuators, data and ontology fusion, efficient computation and connectivity, security, novel man-machine interfaces and human interaction technologies, cyber security, energy efficiency and (real-time) simulation concepts.
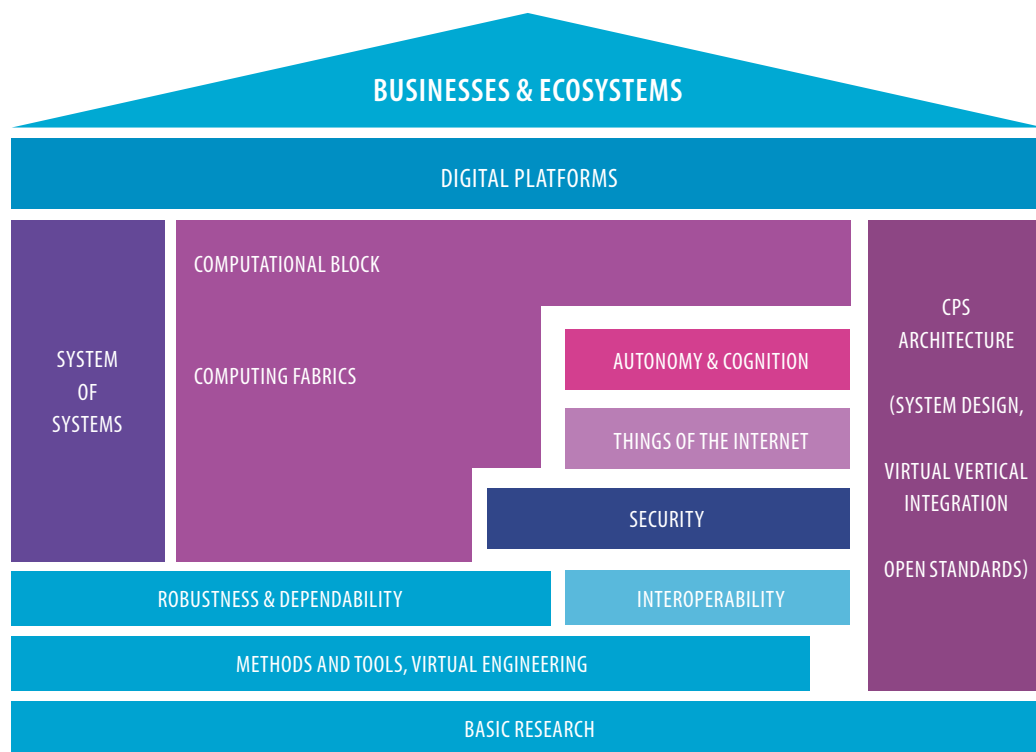
Figure 11 *Building Blocks approach: the Ideal House*

The Building Blocks approach is illustrated in Figure 11, in a coherent construction of an Ideal House, where each block support and complement the others.

Each of the block describes hereafter the major research priorities for

A. CPS Architectures Principles

B. Methods and Tools, Virtual Engineering

C. Robustness and Dependability

D. Interoperability and Connectivity / Internet of Things

E. Autonomy and Cooperation

F. System of Systems

G. Computational Block (Computing Platforms and Energy Management for Cyber Physical Systems)

H. Digital Platforms

I . Basic Research

5.3.2.1 CPS ARCHITECTURES PRINCIPLES (REFERENCE DESIGN AND ARCHITECTURE)

The complexity of modern Cyber-Physical Systems is increasin g at an enormous rate. The major reasons for this increase in complexity are (i) the ever increasing functionality of the individual products (e.g., a single car) or a single aircraft and (ii) the increasing connectivity and interactions among such products on a higher system level (e.g. on System-of-System where cars communicate with each other and with their infrastructure or where unmanned aircrafts are able to interact for a specific task and with the existing infrastructure). The specific challenges include:

- ‣ Increasing openness and interconnection while retaining security and safety properties
- ‣ Providing safety and enabling certification (ISO 26262) in highly complex and non-deterministic environments
- ‣ Cooperation in the entire development process
- ‣ Self-Maintenance of CPS
- ‣ Optimal partitioning of real-time workload between field devices and the cloud
- ‣ Wireless techniques and protocols for real-time control traffic
- ‣ On-line evolution of large real-time systems
- ‣ Emergent behaviour caused by the interaction of autonomous agents

It would be futile trying to tackle this complexity challenge with a pure bottom-up development approach. In order to be competitive we have to establish generic reference architectures and platforms on all relevant implementation levels to meet the development requirements of future CPS.

A sound reference architecture or platform should accomplish the following:

- ‣ **Separation of concerns:** To increase the productivity, we have to enable the engineers to concentrate on the parts that are truly relevant for solving their particular problem. Without a sound architectural approach developers have to care about a lot of important side topics (communication, fault tolerance, storage, security and access rights management, scalability …) instead of focusing on the particular problem they want to solve. In a platform-based approach, such common functionalities are realized within the platform and can be reused by the applications that are based on the platform. The architecture has to ensure that the platform and its features can be developed independently of the actual applications in such a way that separation of concerns is achieved. Platform developers concentrate on platform development and the users of the platform can invest their resources in providing added value at a higher layer.
- ‣ **Provision of common services:** The platform has to provide common services which are required by most of the applications that will be realised on that platform. Examples of such services are:
  - ᛫ Security and access rights management
  - ᛫ Fault tolerance services
  - ᛫ Communication services
  - ᛫ Monitoring and maintenance services
  - ᛫ Services for deployment (e.g., Update-over-the-air)
  - ᛫ Scaling services
  - ᛫ Registration and discovery services
  - ᛫ …

▸ **Efficient reuse and composability:** Efficient re-use of independently developed components is a cornerstone to reach higher abstraction levels in the design process and to meet the stringent time-to-market and productivity constraints of future CPS. A platform that follows a sound architecture should enable the creation of new products by composing them from a library of pre-validated building blocks. Particular challenges with respect to composability are real-time behaviour, fault tolerance and security.

  ▸ **Establish a (de-facto) standard:** reference architecture or a platform has only real value if it is widely used and the strategy to become a successful platform has to be considered from the very beginning. Open interfaces are a key issue and existing standards in the related domains have to be taken into account. The entry barrier has to be as low as possible and potential adaptors have to be supported by appropriate development kits, examples and documentation. In addition the creation of ecosystems and related communities (e.g., implementer forum) has to be actively pushed.

  ▸ **Dependability by design:** CPS will be used in critical applications and therefore have to be highly dependable (summarizing attributes such as: available, reliable, real-time, safe, secure, trustworthy and maintainable). As dependability is not a component or a service that can be simply added to a system (of systems), but rather an aspect that affects every single component of a system (of systems), the design of a CPS architecture needs to consider dependability from the outset and dependability needs to be properly reflected in every single component and in the interactions among all components.

Research Challenges: System and System-of-Systems (SoS) - Level

Developing a CPS that works mostly in isolation is already big challenge, but in future many CPS will be required to work in concert to provide their functionality. In particular in the fields of smart home, smart city, smart mobility and smart factory we will be faced with highly interconnected devices and systems that have to work towards a common goal without losing their operational and managerial independence. A depictive example is the collaboration of vehicles in proximity to avoid collisions.

To master this challenge, it would be highly beneficial if we could efficiently translate established architectures and design principles for closed applications to open-world applications, e.g., control applications that connect to the Internet. While in the closed world embedded systems typically need to satisfy real- time, robustness and fault-tolerance requirements, additional flexibility, coping with variable latency and bandwidth and security requirements are imposed by open access.

We can expect that future CPS with stringent real-time and safety requirements will be augmented with further "intelligence" from the cloud. Such Systems of Cyber-Physical Systems can only be realised if the services in the cloud, the software of the CPS and the associated communication services are well aligned and developed according to common architecture principles. Model-based single-source-of-truth approaches can be employed to ensure consistency (e.g., interfaces, data models, state machines …) among the constituting components. The overall prerequisite is the close collaboration between the cross-cutting engineering communities to establish joint terminologies, ontologies and architectures.

When moving into the cloud, also new challenges arise with respect to the design of Graphical User Interfaces. We will observe the co-existence of rich GUIs for real-time systems providing sophisticated authoring functionalities (e.g., control boards for test benches, control boards for industry automation systems …) and their clients realising smart apps for simple control and monitoring purposes. Model-based single-source-of-truth development will be required to efficiently generate these multiple GUIs from a single and consistent specification.

The concrete challenges include the following:

‣ Develop adjustable and holistic solutions to satisfy the (sometimes contradicting) requirements for fault tolerance, real-time emergent behaviour, security and openness.
‣ Deal with heterogeneous communication infrastructures and requirements (with respect to reliability and bandwidth) in CPS and larger System-of-Systems (e.g., on-chip-networks, reliable cable-bound networks, wireless networks …)
‣ Provide networked control strategies that offer robust control performance over often unreliable wireless and open networks
‣ Resilience to physical attacks where an attacker cannot just send messages over a network to remotely attack a CPS, but can physically tamper with embedded devices that are everywhere and therefore hard to protect
‣ Provide architectures and platforms that establish evolvability and composability on a System-of-Systems level
‣ Enable interaction of hard real-time CPS with services in the cloud
‣ Enable model-based single-source-of-truth development for CPS and SoS
‣ Architectures for smart services located on devices and/or in the Cloud.
‣ Usability, GUI design including augmented reality and interactive documentation
‣ Enable independent validation and certification of individual CPS that are part of a larger System-of-Systems.
‣ Enable independent validation and certification of Cyber-Physical Systems-of-Systems developed and implemented as complete industrial Cyber-Physical Systems based solutions.
‣ Enable interaction with existing standards

Research Challenges: Multi/many-core systems / System-on-a chip/ Network-on-a-chip

Multi-core and SoC architectures have been extremely successful in the consumer, desktop and high-performance market. For the application in safety-critical, real-time CPS there are still important challenges that have to be solved. These challenges include:

‣ Enable devices with low energy footprints
‣ Support guaranteed real-time behaviour in a multi-core context
‣ Provide strong spatial and temporal partitioning in a multi-tasking environment
‣ Enable certification of highly complex and performant multi-core SoCs
‣ …

5.3.2.2 Design Methods, Tools, Virtual Engineering

Effective design methods, tools and technologies are the way by which ideas and requirements are transformed into innovative, producible and testable CPS based products. They provide the link between the ever-increasing technology push and the demand for new innovative products and services of ever-increasing complexity that are needed to fulfil societal needs, while at the same time aim at increasing productivity, reducing development costs and time-to-market, and ensuring the level of targeted requirements such as on quality, performance, cost and energy efficiency, safety, security, and reliability.

While these objectives have been pursued even for the very first instances of electronic systems embedded into products, a number of new challenges arise with CPS.

The **networked nature of Cyber-Physical Systems** and their communication and cooperation capabilities implies a higher risk of being vulnerable to cyber-attacks. Both, **Security** per se as well as **Security Impact on Safety** are thus major issues when designing CPS. As part of a Cyber-Physical System of Systems (cf. 5.3.2.6) CPS even communicate and cooperate with other systems designed by different manufactures. An example would be autonomous cars, which communicate with each other as well as with roadside infrastructure, to ensure safe and efficient traffic. This raises the need **for standardised communication**, on both a syntactical and semantic level, and requires cooperation strategies to incorporate and **handle uncertainty** with respect to different levels of trust placed in internally generated information and information received from different external sources.

The **increasing level of automation** (up to **autonomy**) of Cyber-Physical Systems and the new functionality of ever increasing complexity that they implement, implies an explosive increase in possible system behaviour. This poses an enormous challenge for **formal Verification and Validation** (V&V) technologies, and even for **testing** systems, since the amount of testing needed to be even only 'reasonably sure' of the systems' good behaviour is prohibitive to undergo. As an example, it is estimated that for the thorough validation of an autonomous car, more than 100 million km of traditional road driving tests would be needed. **Elaborate decision-making capabilities** and **handling of uncertainty** – since the observation of the environment needed as a basis for decision making is often incomplete -- are another source of complexity and thus **a further challenge for V&V technology**; for (self) **learning systems** it is not even completely clear today how to analyse them and ensure their safe functionality at all.

CPS interact with **human** beings; they are supposed to assist them in their activities, transport them safely from one place to another, support their well-being, and help them to live a comfortable life. **Human-Machine Interaction, Human-Machine Cooperation** and **adaptation of machines to human needs** thus are major design issues when constructing CPS.

CPS in general have a **long lifetime** (up to several decades, e.g. for aircraft), during which they might encounter **new situations** in the environment in which they are supposed to act, **new other systems** (with new capabilities) which whom they are supposed to interact and cooperate with, and **new behavioural requirements** (e.g. changing regulations, etc.). All of these might not even have been envisioned during the design time, yet correct functionality of the CPS even under these new conditions is required. This also applies the other way around, in that CPS

are supposed to cope (i.e. communicate and cooperate) with legacy systems. **Adaptability, upgradability and evolvability** (in the field) are therefore required capabilities of CPS. **Ensuring safety and security** for these kinds of systems is a major challenge for the design process, and gives rise to techniques like online safety assessment and similar.

A completely different set of challenges arises from **changes in the development processes** in companies: CPS will be built by multi-disciplinary design teams which are often **physically distributed** and may even **span more than one company**. The traditional supplier chains employed e.g. in automotive industry, will change to become supplier networks, where the OEM is not necessarily the (sole) integrator anymore. The challenge here is to **adapt and enrich the design methodologies** and have **corresponding tools to support** these changes, i.e. allow for virtual engineering across disciplines, location and organisations.

A final set of challenges arise from the fact that Cyber-Physical Systems span **more than one application domain**. Examples include Embedded Systems and the Internet / Cloud, or consumer electronics and assistance systems in cars. Different **lifecycles/lifetimes**, different possibilities for **upgrades, modifications and evolution**, **feature interaction** and **emergent behaviour**, different **reliability** and **trustworthiness** (of information) constraints, different **qualities of services** (e.g. latency, accuracy,…) and different **safety and security requirements** are just some of the disparities that a design methodology for CPS has to cope with.

Research Challenges

To overcome these challenges, the following topics must be addressed by future basic and applied research (see also the description of CPS Systems of Systems and the more detailed descriptions of research topics in   5.3.2.6):

▸   **Model-based Design**
     Model-based design methods and tools have been more and more established in industrial practice in recent years, at least for 'traditional' embedded systems. These methods must be enriched to allow **multi-domain, multi-dimensional and multi-objective specification and modelling**. The methodology must support (semantic) integration of **heterogeneous models** and also support **re-use of models** on different levels of the design process, i.e. to allow for usage of the same components (e.g. sensors) in different systems, for system variants, as well as for evolution of systems (i.e. the adaptation and integration of new or modified components and functionality). A closely related topic is the usage of **models for certification** in a model-based certification process. Security engineering has to become an integral part of these methods, supporting **model-based combined safety and security development processes**. These methods and processes have to be supported by appropriate development tools, including tools for model management, integration of models from different domains and incorporation of legacy systems. Multi-domain, multi-dimensional and multi-objective specification and modelling

▸   **Virtual Engineering**
     Collaborative virtual engineering environments for the design, analysis, V&V, simulation and testing of CPS spanning **multiple applications and engineering domains** and supporting **design teams in different locations and organisations** to support the **specification, the adaptation and the continuous evolution and maintenance** of CPS over their complete life cycle (cf. 5.3.2.6).

▸ **Multi-objective Optimisation**

Techniques and tools for the **optimisation of heterogeneous models** with **multiple objectives** stemming from **different application and engineering domains** as well as **across the supply chain** will be needed to explore the design space and efficiently develop Cyber-Physical Systems and fully exploit the potential of model-based design for them across application domains.

▸ **V&V - Verification and Validation Methodology and Tools**

V&V technologies (including formal verification, simulation, and testing) need to be extended and adapted to cope with and ensure **safety and security for complex, extendable, upgradable and evolvable Cyber-Physical Systems**. These techniques have to enable **incremental analysis and certification** and support **integration of heterogeneous models** as well as **model-/software-/hardware-/system-in-the-loop simulation and testing**. New V&V technologies must be able to handle the complexity stemming from increasing levels of automation and new functionality as well as handle uncertainty stemming from incomplete environment observations or different levels of trust placed in external information. They must also be able to **cope with the dynamic behaviour of CPS, their adaptability, upgradability and evolvability** and establish properties such as their **real-time behaviour and quality of service guarantees for the communication mediums** they employ. These techniques should be supported by **appropriate tools**, enabling automatic analysis of these systems.

▸ **Monitoring and Diagnosis in the Field**

Due to the large scale and the complexity of the systems, as well as their long lifetime, failures in CPS will be the norm rather than the exception. Mechanisms to **detect these failures** and take appropriate measures like **adaptation, fail-safe degradation,** and even **self-healing** are needed, which also have to cope with the aspect of upgrades and evolution of CPS. Extensive monitoring also allows data from systems in the field to be observed and collected, enabling 'lifelong learning' to reduce uncertainty.

▸ **Human Aspects**

For designing CPS that safely interact with human beings and efficiently support them in their needs and cooperate with them, we need to research into **Human-Machine Interaction**, **Human-Machine Cooperation** and **machine adaptation to human needs**. Methods and tools to support the design and analysis of appropriate cooperation and decision making capabilities, combining the respective capabilities and strength of humans and machines, monitoring and anticipating human needs and establishing valid models of their behaviour have to be investigated and incorporated in the design process.

▸ **Pushing Open, Horizontal Standards**

  · on Interoperability of design and analysis tools

  · on communication, cooperation and coordination for testing, V&V scenarios (c.f. standardization challenge of 5.3.2.3)

▸ Build Eco-System for processes, methods and tools for the cost-efficient design, analysis and testing of safe and secure CPS based on standards, including the whole value chain.

5.3.2.3 Trust, Security, Robustness and Dependability

Security cannot usually be just added later on; it must be planned and designed during development process – Security and Privacy by Design are now well known as engineering methods. However, security provision does not end with system deployment; it should be addressed like a process that needs to be maintained throughout the entire product lifetime. During development it is possible to test and assure product immunity against current threats, but in time new threats will appear and security can be impaired by new methods of attack.

Dependability

Cyber-Physical Systems are an integral part of our everyday lives and they are getting more connected and smarter. We are surrounded by smart mobility applications as connected vehicles, smart cities, smart grids, smart energy solutions, smart healthcare applications, and so on. These systems rely heavily on the dependable operation of embedded sensors and actuators despite limited computational capabilities and limited power/energy resources.

Dependability of a system is "the ability to avoid service failures that are more frequent and more severe than acceptable". It is measured against the following criteria: **Availability** - readiness for correct service; **Reliability** - continuity of correct service; **Safety** - absence of catastrophic consequences on the user(s) and the environment; **Integrity** - absence of improper system alterations; **Maintainability** - ability to undergo modifications and repairs; **Security** - the degree of resistance to, or protection from, harm.

The goals of CPS – in particular in safety-critical environments - include 24/7 reliability, with 100% availability, and 100% connectivity, in addition to the real-time response (time-critical, i.e. deadlines defined by the system integrators).

Dependability can no longer be considered as an aspect of single, separate and encapsulated devices, but in a more and more connected world must be regarded as dependability of **systems of systems** (SoS).

Dependability in the context of CPS can broadly be classified at two interdependent levels that, combined, can provide a trustworthy platform for building applications:

- ‣ **Infrastructure dependability** – how dependable are the underlying infrastructure components (e.g., sensors, networks, actuators, computing/storage elements, software environments) in the presence of diverse failures that may lead to disruptions.
- ‣ **Information dependability** – how dependable is the information generated by the underlying infrastructure given errors/uncertainty in information input (e.g., sensor readings) and data analysis mechanisms.

The **threats to dependability** and **robustness** are failures, errors and faults, which may be introduced in different phases of the system's lifecycle (e.g. development faults during the development phase, faults introduced during maintenance or misuse). These threats can be avoided by fault prevention, fault tolerance, redundancy (fail-operational), fault removal and fault forecasting.

Fault prevention encompasses the improvement of development processes to reduce the number of faults introduced in the produced systems. Fault tolerance aims at failure avoidance and is carried out through error detection and system recovery. Fail-operational systems rely on hardware and/or software redundancy. Fault removal occurs during system development (e.g. by verification) or during system use. Fault forecasting consists of evaluating the system's behaviour with respect to fault occurrence.

Recent incidents confirm that Cyber-Physical Systems in various application fields are targets of attackers. Due to the openness and connectivity of this new generation of systems, **cyber-security** is becoming an important issue for CPS.

Robustness

A computing system is robust if it retains its ability to deliver a service in conditions which are beyond its normal domain of operation. This definition makes clear that robustness is concerned with a system's behaviour (delivering its function, i.e., avoiding severe service failures) in unforeseen conditions. Only if a system is taken out of the scope of its specification can we observe its robustness or fragility. This attention to out-of-specification behaviour is one point where robustness brings us something new compared to dependability.

Resilience

Resilience, in our context, is defined as the capability of a component to compensate for temporary degradation in a requested service. In other words, resilience is the capability of a component to compensate for errors and perturbations in the input. Resilience is then defined as the **persistence of dependability when facing changes**. Self-organising systems are permanently confronted with changes. This definition of resilience thus applies directly to self-organising systems.

One big challenge of resilient CPS design is the need for an integrated resilient design methodology including a rigorous analytical framework to allow the co-design of control and incentive tools. This framework will enable designers and operators to build resilience into CPS by maintaining synergistic integrations of human-centric elements with automated diagnostic and control processes.

Standardization

Dependability is a multi-concern issue, as defined by IFAC 10.4 (Lapries, Kopetz t. al.). An overview of the major properties is shown in **Figure 12**.
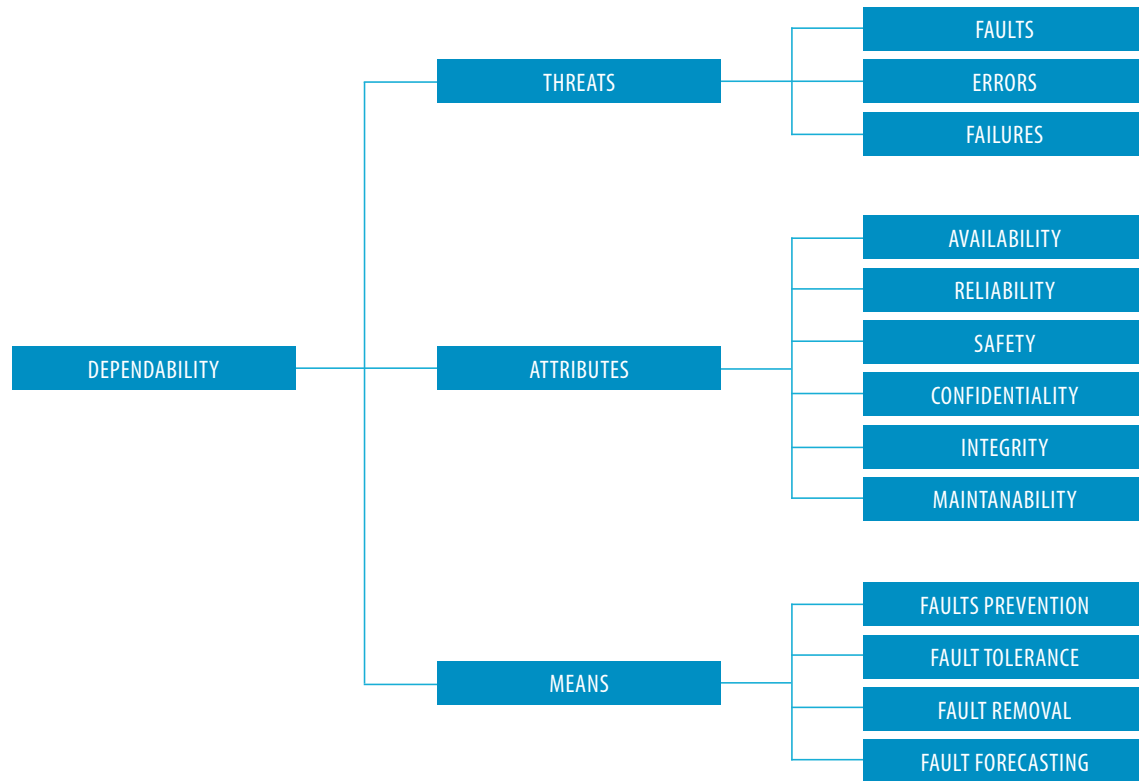
Figure 12 *Dependability – an umbrella term*

The International Electro-technical Commission Technical Committee 56 (IEC TC 56) develops and maintains international standards in the field of dependability. The following figure gives an overview of the structure of the available standards in this context. These standards cover the former "Reliability" issues (the initial name of TC 56 was "Reliability"), focused mainly on methods and formulas (mathematics).

CORE STANDARDS

DEPENDABILITY
MANAGEMENT

VOCABULARY

PROCESS STANDARDS

| RELIABILITY AND AVAILABILITY | MAINTAINABILITY AND SUPPORTABILITY | RISK ASSESSMENT | SYSTEM DEPENDABILITY |

SUPPORT STANDARDS

| ANALYSIS TECHNIQUES | MAINTAINABILITY | RISK ASSESSMENT | SYSTEM ENGINEERING |

| DATA, ESTIMATIONS AND ASSESSMENT | SUPPORTABILITY | | HUMAN ASPECTS |

| RELIABILITY TESTING AND SCREENING | | | SOFTWARE |

RELIABILITY GROWTHS

ASSOCIATED STANDARDS STANDARDS

TCS6 COLLABORATION WITH OTHER COCMMITTEES IN SUPPORT OF
STANDARDS WITH DEPENDABILITY RELEVANCE

Figure 13 *Structure of available standards of TC56*

IEC TC65 has defined the majority of functional safety standards (generic: IEC 61508, and most domains except
road vehicles: ISO 26262) (see Figure14-). TC65 is the main safety-standardisation group looking primarily at the
system (safety, security are system properties and rather holistic) not on reliability evaluation and calculation
methods created the Ad-Hoc Group AHG2, "Reliability of Automation Devices and Systems", which looks at the
demand for reliability design, testing, verification and operational life of automation devices and systems. This will
be based on the analysis of the applicability of relevant standards in automation devices and systems and define the
standardisation framework on reliability in automation devices and systems.

Here, systems mean low-level systems, like control loops, control modules, other than plants, excepting any
programming for controller (covered already by IEC 61131).

IEC 61508 FAMILY OF FUNCTIONAL SAFETY STANDARDS

OTHER SAFETY STANDARDS: AVIATION
(Do 178B, ARP 4754, ARINC, JAR-25, ...)

IEC 61508

STANDALONE
Ed 2.0

* MT: Maintainance updating

IEC 61508

SUBSYSTEMS
&
COMPONENTS
(E.G. PLC'S)
RAILWAYS: EN 50128, 50129

COMPLIANCE
TO IEC 61508

ISO/DIS 26262*
AUTOMOTIVE SECTOR

ISO/IEC 62061:
MACHINERY SECTOR

MEDICAL SECTOR
IEC 60601*

IEC 61511: MT*
PROCESS SECTOR

IEC 61131-6
PLC SECTOR

IEC 61513:
NUCLEAR SECTOR

SECTOR IMPLEMENTATIONS

Figure 14 *Family of IEC 61508 Functional safety Standards*

Research challenges for dependability and robustness

Dependability and robustness are essential aspects for future CPS especially when considering the growing degree of automation. Smart CPS environments incorporate a variety of sensing and actuation devices in a distributed architecture; such a deployment is used to create a digital representation of the evolving physical world and its processes for use by a broad range of applications. CPS applications, in particular, mission critical tasks, must execute dependably despite disruptions caused by failures and limitations in sensing, communications, and computation.

Given the physical nature of these CPS applications and the critical nature of some information, some issues may pose serious challenges, such as determining priorities perhaps through context-awareness and/or through criticality-based capabilities, and containment of the effect of propagated timing errors.

The following research and development challenges have to be faced in **future highly dependable and robust CPS**:

▸ Systematic **software engineering methods** to reduce the development complexity and increase reliability and robustness by using appropriate software models and abstractions.

▸ **Dynamic configuration:** as components appear and disappear as CPS devices, and communication links are established/released depending on the actual availability of network connectivity.

▸ **Self-diagnostic tools** and **robust control algorithms** that ensure adaptability and survivability in the presence of security attacks, random faults, unpredictable events, uncertain information, and so-called sensor false positives (sensor misinterpretations). Inclusion of models of the incentives of human decision makers in the design process to improve CPS resilience.

▸ **Scalable Health Management Architectures,** integrating diagnostic and prognostic capabilities from CPS to system of systems (from single board to complete aircraft) for reducing logistic impacts and Life Cycle Costs

▸ **Evaluation and experimentation** using extended simulation and test-bed infrastructures for an integration of Cyber-Physical Systems Platforms that directly interface with human decisions.

▸ **Architectures** which support distribution, modularity, and fault containment units in order to isolate faults.

▸ Secure real-time systems
  · Secure fault diagnosis and maintenance, e.g., remote downloading of control software remotely into the flash memory of a vehicle
  · Security of nomadic systems connected by wireless protocols
  · Security in dynamically reconfigurable real-time CPS.

▸ Transparent **fault tolerance**
  · Advanced hardware-related and software-implemented **fault-injection** for dependability evaluation.
  · Provision of a generic fault-tolerance layer, independent of the application
  · Tolerance with respect to arbitrary failure modes of components
  · On-line maintenance of fault-tolerant systems
  · Automated reconfiguration
  · Low power

▸ **Certification** and component-based **recertification** of high-dependability applications
- Modular certification of a composable design
- Validation of high dependability
- Proof of absence of failure modes with high impact (safety criticality)
- Independent validation of component interface properties
- Integration and validation of legacy systems
- Worst-case execution time (WCET) research (hardware, algorithms, tools)
- Standardised procedures and processes to develop and design dependable SoS

Many systems in different industrial domains have obvious risks associated with failure. In mission-critical applications such as aircraft flight control or automated driving (SAE level 4 and 5), severe personal injury or equipment damage could result from a failure of the embedded computer. Such systems require the employment of **fail-operational and multiply-redundant** CPS or distributed consensus protocols in order to ensure continued operation at any time in any situation. However, many CPS that could cause personal or property damage cannot tolerate the added cost of redundancy in hardware or processing capacity needed for traditional fault tolerance techniques. Furthermore, rigorous **qualification procedures** are necessary in some systems after design changes in order to assess and reduce the risk of malfunction or unanticipated system failure.

Consequently, **low-cost reliability** with **minimal redundancy** and **reliable software** are important design challenges for CPS as well as **partitioning/synthesis** to minimise **recertification** costs.

Creating dependable CPS presents new challenges as autonomous operation is attempted in unconstrained operational environments. The extremely high safety level required of such systems means that validation approaches will need to consider not only normal operation, but also operation with system faults and in exceptional environments. Additional challenges will need to be overcome in the areas of defining **dependability requirements**, trusting the **dependability and robustness of multi-vendor distributed system components**, tolerating **environmental uncertainty**, and ensuring sufficiently rigorous **validation of autonomous CPS** in order to attain very low failure rates.

5.3.2.4 Autonomous and Robotic Systems

Mastering the complexity while reducing the cost and increasing the performance is a key challenge, as already pointed out in the ARTEMIS SRA 2011/13. It is still a high priority goal for ARTEMIS-IA to meet this challenge, but since then Embedded Systems have further evolved to so-called Cyber-Physical Systems and highly connected Systems-of-Systems. The "Internet of Things (IoT)" as the overarching term for the highly connected, widely distributed large amount of devices and "things" cooperating in context of an overarching architecture exponentially increased the complexity and challenges further, implying an even higher impact on society, particularly in terms of opportunities and societal risks. Ensuring correct and secure collective and autonomous behaviour of the heterogeneous interconnected elements will be at the core of the challenge, so a certain autonomy and redundancy of the "things"

or compounds of "things" is the major issue where such systems may work together and the overall systems and Systems-of-Systems can provide stable services, including operation via robust and secure cloud computing and communication. It will encompass a multi-disciplinary approach, various levels of tooling and methodologies, standardisation issues and multi-concern system engineering.

The issue of autonomy is a very generic, horizontal and cross-domain, and required at a high level in all the application areas 4.3.1 to 4.3.4 and in robotics. Although robotic devices, technology and methodology are becoming an increasing part of the functionality in the other application contexts mentioned above (e.g. an autonomous car is somehow a robot, advanced manufacturing and production lines, some smart city and home functionality or advanced surgery systems are robots), robotics is an application area on its own, which has been taken into account e.g. by ISO standardisation in the creation of a separate TC (Technical Committee) TC 299 Robotics, including the respective working groups of SC4 from TC 184, Automation Systems and Integration.

Advanced robots are autonomous, cooperative, perceptive (cognitive) and situation-aware devices and systems, applied in many contexts as service units, in homes, smart mobility, for people with special needs, healthcare, medical, hospitals, manufacturing, logistics, smart farming, in dangerous environments (emergency, rescue, disaster management), cleaning, inspection, surveillance, repair and maintenance under harsh conditions or environments that are difficult to access. Robotics has the potential to become a disruptive technology, changing markets and societal conditions, including workforce, enterprise organisation and making many human activities less dangerous, but also partially dispensable. Advanced robots can save lives, perform activities not possible for humans, even "improve" humans, e.g. exoskeletons. All these robotic units for service and support have to be innovated, produced, brought to market and serviced themselves.

From the innovation and technology point of view, manifold challenges have to be managed: from energy harvesting to safety, security and robustness, from sensors and actors to mechatronics, M2M-communication and HMI, vision and machine-understanding, predictive methods to be applied, and self-learning (e.g. via data taken from the "cloud"). Software ranges from basic operating systems to middleware and sophisticated, powerful application software of mixed criticality, particularly directed at cognition, perception and situation awareness (e.g. in safety engineering beyond managing component and system failures by taking into account "SotiF", Safety of the intended Function, when even a system without failure does not fulfil its function because of a misconception about the environment). This adds a particular challenge to resolve for CPS and CPSoS – a new kind of advanced system engineering. Last but not least "certifiability" of such systems are critical challenges and maybe somehow generic in their nature (i.e. domain-independent). This allows many topics that are independent of the application to be handled and justifies treatment as a separate research area.

Research Challenges

Some research challenges required for autonomous and cooperative systems:

▸ *Safe and robust environmental perception of environment*. Robust recognition of the environment is one of the most complex tasks a robotic system has to handle. While for restricted environmental conditions (e.g. limited number of objects, simple scenery structure, constant and well-defined illumination) good results can be achieved today, existing solutions exhibit little robustness in more open environments.

   Three major aspects have to be considered:

   • *Dealing with complexity*. Solutions will only work when they can cope with arbitrary complex situations and scenarios in real-time.
   • *Sensor data fusion*. Combination of several sensor modalities are seen as important means to dealing with complexity and increasing robustness, but also implies new issues to be solved.
   • *Robustness verification*. Due to the complexity of input data, assessing application-specific robustness requires appropriate V&V methods

▸ *Learning and adaptive behaviour*. It is impossible to implement all potentially required behaviour in advance. Instead, autonomous robotic systems must be able to adapt to changing environments and learn to understand and cope with complex situations. As for perception, novel analysis and testing methods are needed to verify that learning and adaptive systems are sufficiently safe. On-line verification is an example for such a technique.

▸ *Advanced mobility and manipulation capabilities*. Interaction with humans, underwater inspection of ship hulls, or maintaining wind energy plants require special capabilities of ego-motion and manipulation, e.g. finding flexibly and in real-time safe path of a grasping tool for moving a glass of water.

▸ *Cooperation.* It involves communication and interaction. In particular cooperation with humans requires several issues to be solved, such as understanding humans (e.g. gestures, mimics, or verbal expressions) and informing them about the robot's intentions (verbally and non-verbally). In contrast to HRI (human-robot interaction), RRI is considered less critical, because wireless communication over standardised protocols is regarded as sufficient in most cases.

5.3.2.5 Seamless Connectivity & Interoperability

Connectivity for CPS System of Systems

In the past, most of the Embedded Systems operated in isolation. This limited the possible intelligence of these products controlled by embedded systems due to the limited number of information channels to the outside world.

Therefore many new products containing intelligent embedded systems operate in concert with other systems in order to produce desired physical effects at a larger scale. To enable this concerted action, the embedded systems are connected into clusters of systems. As the communication often takes place in the cyber space, these embedded systems are often called Cyber-Physical Systems (CPS). But very often, the clusters of CPSs interact also in the physical space. Some of the connectivity may be statically configured while others may be dynamically established. An example of the developments is the rapidly growing number of applications in the Internet of Things domain,

The next level of sophistication in CPS is the usage of knowledge from back-end cloud computers. This allows embedded CPS to acquire additional intelligence from data in large backend cloud computer systems. Big data analysis provides knowledge from historical data are used in real-time control and automation tasks. On the one hand, CPS systems can provide data to the big data cloud computers while, on the other hand, they can take advantage of the processor-intensive evaluation and learning procedures from cloud computer systems. Thus many new business models are possible.

One of the most successful business models is the concept of double-sided markets. One large company or industry group creates a cloud backend service, which acts as a communication platform between companies developing and selling new applications and costumers taking advantage of these new applications. The users often get the applications either for free or cheaply in exchange for data. The data are collected by the CPS and communicated to the cloud services. The cloud backend provider takes advantage of the data and sells the results of big data applications. The local CPS systems become more intelligent through sophisticated applications in the cloud.

An additional challenge is posed by the need to create the fast growing ecosystems of application developers, providers of cloud backend systems, CPS product developers and user communities. Very often only one of the many ecosystems in one domain comes out on top in global competition.

These new capabilities in the CPS, fusing with other important evolutions of technologies such as Social Media, Mobile Computing, Cloud Computing, and Big Data Analytics, are expected to bring transformational changes to the economy, society, our knowledge of the world and, ultimately, the way people live. It is important that a CPS Framework should foresee and accommodate the engagements and interactions between the CPS and these important technological developments.

Without reliable, powerful and secure communication and connectivity, these new successful and attractive business models are not possible. The complex structure is visualised in Figure 15 on page 86.
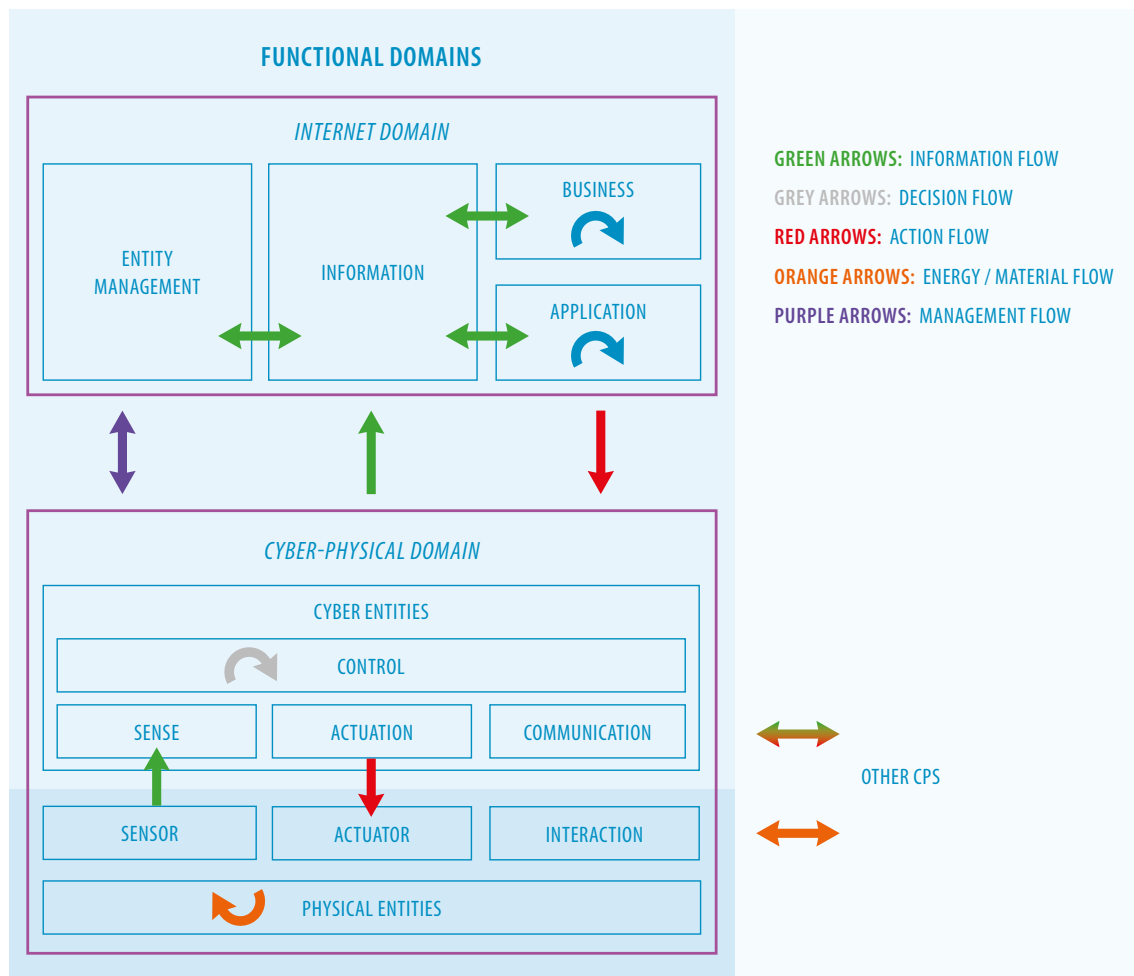
Figure 15 *Structure of CPS with extended intelligence from cloud services (System of Systems)*
(Source: Framework for Cyber-Physical Systems, Release 0.8, Sep 2015 by the
Cyber-Physical Systems Public Working Group, USA.)

This leads to significantly greater challenges to development teams as they have to cope with the development of embedded software (mostly driven by resource restrictions like power consumption, CPU, memory, etc,), reliable communication and service-based cloud software development, including big data analytics as well as knowledge about social media.

Inputs for this section were taken from the Framework for Cyber-Physical Systems, Release 0.8, Sep 2015 by the Cyber-Physical Systems Public Working Group, USA.

Security and Connectivity

CPS often exists on resource-constrained platforms. As a result, security mechanisms must be lightweight in terms of storage space, memory use, processor use, network connectivity and electrical power consumption. Furthermore, these platforms are often distributed; the individual components must perform global tasks using local information exchange and limited computation at the nodes.

Cyber-security for CPS must generally accommodate the in-situ business processes. Access controls along with authentication and authorisation mechanisms must accommodate the fact that CPS are often deployed in operational situations that require immediate access to control systems or access by any member of a group. "Strong" passwords, passwords that are lengthy or complicated to enter, or passwords that require frequent updates are often inappropriate for such environments. On the shop floor, passwords are often shared among all the individuals holding a particular role to eliminate potential discontinuity between shifts and provide rapid emergency access to the system. New mechanisms to establish trust between machines and people are needed for these conditions.

Applications enabled by connected CPS

The vast additional intelligence brought to embedded CPS enabled products enable many new applications and business models. Many of them are called Internet of Things applications or Smart X applications such as:

- ‣ Industry 4.0 applications using IoT technologies
- ‣ Smart health applications
- ‣ Smart mobility applications as connected vehicles
- ‣ Smart homes
- ‣ Smart cities
- ‣ Smart power
- ‣ etc.

Research Challenges for connectivity and communication

Seamless connectivity is therefore vital for future Embedded &Cyber-Physical Systems. Its requirements pervade the middleware, operating systems and other functions required to link the physical world, as seen by the networked nodes, and also the higher layer applications, as well as hardware features needed to support efficient and effective interoperability implementation.

While connectivity is important for many systems of CPS to operate, it is important to note that connectivity should, by design, be a non-deterministic factor in maintaining the operations of CPS, at least for most of the cases. In the event that connectivity becomes unavailable, the CPS should be able to continue to operate locally-based programmed logic or autonomous smart control, albeit in a non-optimal or even degraded mode of operations.

A major challenge in the area of communication is the provision of ubiquitous wireless connectivity under the constraints of minimum power consumption and limited bandwidth. The vision of ambient intelligence critically depends on the availability of such an information infrastructure.

The syntactic and semantic integration of systems developed in different domains will give rise to Systems of Systems that will provide emergent services of high utility. Developing ubiquitous connectivity schemes that support the syntactic and semantic integration of heterogeneous sub-systems and networks of Embedded & Cyber-Physical Systems as well as cloud services, under the constraints of minimum power consumption and limited bandwidth but often with predictable service levels are among the challenges that should be addressed in priority.

This requires ontology driven development for Embedded & Cyber-Physical Systems including semantic integration and standardisation.

The following research topics to develop in this area are:

- **Certifiable operating systems** (micro-kernels and hypervisors) that can be distributed and composed, and are able to support dynamic reconfiguration.
- **Opportunistic flexibility**: taking advantage of the currently accessible opportunities e.g. network connection to a cloud, to dynamically improve the quality of service.
- **Ubiquitous connectivity schemes** that support the syntactic and semantic integration of heterogeneous sub-systems, under the constraints of minimum energy usage and limited bandwidth. Wire-based as well as wireless communication.
- **Self-X**: Self-configuration, self-organisation, self-healing and self-protection of the computational components in order to establish connectivity and services in a particular application context, using knowledge autonomously acquired from the environment and enabling dynamic reconfiguration.
- **Cyber security and reliable and secure communication**.
- **Communication with predictable real-time capabilities**.
- **Perception techniques for object and event recognition** in order to increase intelligence in embedded systems and make distributed monitoring and control tasks in large-scale systems possible.
- **Ontology based development of embedded SW**.
- **Cloud-based services and reliable communication**, including semantic communication schemes.
- **"Single source of truth"** development concepts are advisable, in order to cope with the complexity in the development.

5.3.2.6 Cyber-Physical System of Systems

The next generation of energy systems, transportation networks, industrial production systems and large buildings will consist of many smart elements that are globally networked and respond to the challenges that the world faces today: reducing emissions, improving energy and resource efficiency, providing better services at a lower cost and in a sustainable manner. These infrastructures constitute Cyber-Physical Systems of Systems (CPSoS) - they consist of many, often spatially distributed, physical subsystems which tightly interact with and are controlled by a large number of distributed and networked computing elements and human users, and they exhibit the features of Systems of Systems (SoS). These features include partial autonomy of the subsystems, continuous evolution over their life-cycle, frequent and dynamic reconfiguration of the overall system, and the possibility of emerging behaviours.

Systems of Systems are not a new phenomenon. Railway systems and electric grids, to name just two examples, have existed for centuries. And for a long time, the element of these Systems of Systems have been Embedded Systems in which computing elements and physical system elements interact tightly, e.g. in the locomotives of railway systems. Also, computer-based systems for the support of the operation and management of large systems have been in use for decades, in air traffic, rail, electric grids, power plants, chemical plants, etc.

However, up till now the flow of information in these systems was costly to establish and difficult to change, and their management followed a hierarchical top-down approach. Subsystems, e.g. power plants or units of a chemical plant or cells or large machines in manufacturing, were managed independently, and coordination was achieved mostly by direct interaction of the operators. With increased connectivity information will be available from a huge number of sensing devices and will be accessible throughout the system. Also, it will be possible to actuate physical variables and to propose actions to human operators flexibly.

Thus, Cyber-Physical Systems of Systems are emerging. They are characterised by the fact that they consist of a large number of physical devices and computing elements that are interconnected both physically, by flows of energy and material and by the use or resources, and by highly flexible flows of information. Due to these interactions, the resulting systems become highly complex and difficult to engineer and to manage. The vastly increased amount of information and the new level of connectivity offer unprecedented potentials for more efficient operation, higher flexibility and adaptability, improved levels of reliability and better quality of products and services.

To realise these potentials and to master the complexity of the Cyber-Physical Systems of Systems of the future, new tools and methods for their engineering over the complete lifecycle and their efficient, safe and reliable operation are needed.

In the world of tomorrow, there will be a myriad of technical systems which are connected via the internet and can exchange information freely. This is also called the *Internet of Things (IoT)*. Until now, most of the IoT research and development have been focused on wireless sensors and on providing connectivity. In the future using the information provided by the sensors and networks in a smart fashion and connecting sensing to actuation will be the key points that bring value to the users and to society. The connectivity provided by the Internet of Things will become an enabling technology **for Cyber-Physical Systems of Systems that close the loop from the sensor information to actions performed by physical systems in transportation, energy systems, production plants, logistics, smart buildings, etc.**

With regards to the aerospace domain, in particular, it is worth to highlight that in an all-connected world, aircraft (manned and unmanned) are no longer the sort of high-tech vehicles that are isolated from the rest of the world, but, in fact, flying crews requires real-time connection to download the latest flight and service details, passengers want a connection to the internet or want to be entertained from the moment they board and on-board systems need to communicate with the ground for mission or maintenance reasons.

These scenarios provide great promise for personal and machine-to-machine communication, remote system maintenance and information management and retrieval. Moreover, ubiquitous computing is also very promising for the aerospace industry to produce even more competitive products and services. As a matter of fact, Cyber-Physical Systems of systems are expected to play a major role in the design and development of future engineering systems with new capabilities that far exceed today's levels of autonomy, functionality, usability, reliability, and cyber security. Future Cyber-Physical Systems will require hardware and software components that are highly dependable, reconfigurable, and in many applications, certifiable and trust-worthiness must also extend to the system level.

One of the key technical challenges to apply CPS to the airspace domain involves verification and validation of complex flight-critical systems with a focus on promoting reliable, secure, and safe use. As the complexity of systems increases, new design tools and methodologies will be defined with the required and proper level of interoperability.
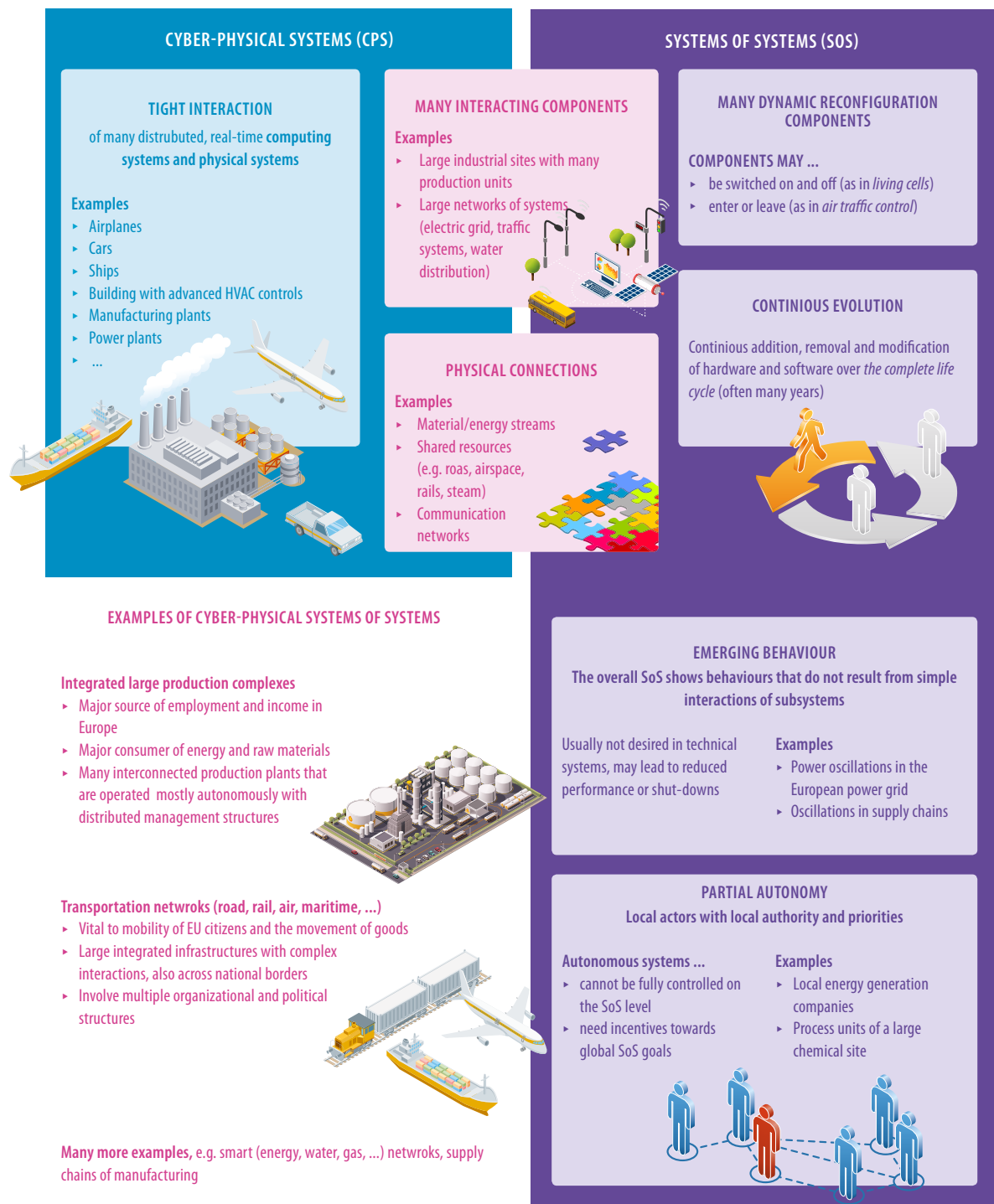
CYBER-PHYSICAL SYSTEMS (CPS)

TIGHT INTERACTION

of many distrubuted, real-time **computing systems and physical systems**

Examples
- Airplanes
- Cars
- Ships
- Building with advanced HVAC controls
- Manufacturing plants
- Power plants
- ...

MANY INTERACTING COMPONENTS

Examples
- Large industrial sites with many production units
- Large networks of systems (electric grid, traffic systems, water distribution)

PHYSICAL CONNECTIONS

Examples
- Material/energy streams
- Shared resources (e.g. roas, airspace, rails, steam)
- Communication networks

SYSTEMS OF SYSTEMS (SOS)

MANY DYNAMIC RECONFIGURATION COMPONENTS

COMPONENTS MAY ...
- be switched on and off (as in *living cells*)
- enter or leave (as in *air traffic control*)

CONTINIOUS EVOLUTION

Continious addition, removal and modification of hardware and software over *the complete life cycle* (often many years)

EXAMPLES OF CYBER-PHYSICAL SYSTEMS OF SYSTEMS

Integrated large production complexes
- Major source of employment and income in Europe
- Major consumer of energy and raw materials
- Many interconnected production plants that are operated mostly autonomously with distributed management structures

Transportation netwroks (road, rail, air, maritime, ...)
- Vital to mobility of EU citizens and the movement of goods
- Large integrated infrastructures with complex interactions, also across national borders
- Involve multiple organizational and political structures

Many more examples, e.g. smart (energy, water, gas, ...) netwroks, supply chains of manufacturing

EMERGING BEHAVIOUR

The overall SoS shows behaviours that do not result from simple interactions of subsystems

Usually not desired in technical systems, may lead to reduced performance or shut-downs

Examples
- Power oscillations in the European power grid
- Oscillations in supply chains

PARTIAL AUTONOMY

Local actors with local authority and priorities

Autonomous systems ...
- cannot be fully controlled on the SoS level
- need incentives towards global SoS goals

Examples
- Local energy generation companies
- Process units of a large chemical site

Figure 16 *Cyber-Physical Systems of Systems (courtesy of the CPSoS project, www.cpsos.eu)*

Key features of Cyber-Physical Systems of Systems

Cyber-Physical Systems of systems are characterised by the following features:

Size and distribution

The components of Cyber-Physical Systems of Systems (CPSoS) are physically coupled and together fulfil a certain function, provide a service or generate products. Some of the components can provide useful services independently, but the performance of the overall system depends on the "orchestration" of the components. CPSoS may be geographically distributed over a large area as a railway network or be locally concentrated as e.g. a factory with many processing stations, and materials handling and transportation systems or a smart building complex.

Distributed control and management

Due to the scope and the complexity of the overall system and often also due to the ownership or management structures, the control and management of CPSoS cannot be performed in a completely centralised or hierarchical top-down manner, with one authority tightly controlling and managing all the subsystems. Instead, there is a distribution of authority with partial local autonomy and decision making, where both global and local decisions are driven not only by technical criteria, but rather by economic, social and ecological performance indicators, e.g. profitability, environmental impact and, in particular, the acceptance and satisfaction of users. CPSoS are managed by humans and have to be addressed as socio-technical systems in which the technical/physical structure determines the possible services of the system.

Partial autonomy of the constituent systems

Partial autonomy is essential in the definition of CPSoS and is understood in this context as the fact that the subsystems pursue local goals in a manner that cannot be fully controlled by the central management of the CPSoS. Rather, incentives or constraints are communicated to the subsystem controllers in order to make them contribute to the global system targets. Often, subsystems are managed and controlled by humans, so there always is a certain degree of autonomy, and their actions are not fully predictable.

Partial autonomy is advantageous and needed because with local autonomy the subsystems can cope with certain tasks, disturbances and faults on their own, without intervention at the global CPSoS level. The partly autonomous sub-systems can absorb variability and to the outside show more predictable behaviour than would result without their ability to regulate, react and compensate disturbances. This kind of autonomy can lead to self-organising systems in which the autonomous actions of the agents lead to improved resilience of the overall system.

Continuous evolution and dynamic reconfiguration

Cyber-Physical Systems of Systems are large systems that operate and are continuously improved over long periods of time. While the IT infrastructure and communications architectures in many industrial and infrastructure systems are often replaced or updated frequently, the physical hardware and software infrastructures are in productive operation for decades, and new functionalities or performance improvements have to be implemented with only limited changes of some parts of the overall system. Thus**, the separation between the design phase and operational phases blurs in such systems (this is called the design-operations continuum), and the engineering of CPSoS requires methods and tools that can be used seamlessly during design as well as operation.**

Dynamic reconfiguration, i.e. the frequent addition, modification or removal of components, is a widespread phenomenon in CPSoS. This includes systems where components come and go (as in air traffic control) as well as the change of system structures and management strategies following changes of demands, supplies or regulations. In particular, the detection and handling of faults and abnormal behaviours is a key issue in Cyber-Physical Systems of systems design and operation, since failures are the norm, not the exception in CPSoS due to their large scale and complexity.

Emerging behaviors

The behaviour of CPSoS results from the interaction of their components, both by the exchange of signals and information and by physical connections as e.g. in the electric grid. This can lead to the occurrence of oscillations, or instabilities on a system-wide level, like oscillations in large power systems or periodic bottlenecks in transportation systems. Also self-organisation and structure formation may take place. While emerging behaviours are usually seen as problematic in technical systems due to their lack of predictability, the formation of stable structures on a higher level of a CPSoS due to interactions between the subsystems despite their local diversity may enable the design and management of the overall system without precise knowledge of all its elements.

Cyber-Physical Systems of systems pose big challenges in their management and operation as well as in engineering throughout their life cycle.

Research Challenges
Distributed, Reliable and Efficient Management of Cyber-Physical Systems of Systems
Due to the scope and the complexity of Cyber-Physical Systems of Systems as well as due to ownership or management structures, control and management tasks in such systems cannot be performed in a centralised or hierarchical top-down manner with one authority tightly controlling all subsystems. In Cyber-Physical Systems of Systems, there is a significant distribution of authority with partial local autonomy. The design of such management systems for reliable and efficient management of the overall systems poses a key challenge in the design and operation of Cyber-Physical Systems of Systems. The following sub-topics must be addressed by future basic and applied research:

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

Decision structures and system architectures
The interaction and coordination of dynamic systems with partial autonomy that constitute systems of systems, possibly with dynamic membership, must be studied broadly. Examples of applicable methods are population dynamics and control and market-based mechanisms for the distribution of constrained resources. The partial

autonomy of the components from the overall system of systems perspective leads to uncertainty about the behaviour of the subsystems. Therefore the system-wide coordination must take into account uncertain behaviour and must nonetheless guarantee an acceptable performance of the overall system. Stochastic optimisation and risk management must be developed for CPSoS. It must be understood better how the management structure (centralised, hierarchical, distributed, clustered) influences system performance and robustness.

Self-organization, structure formation, and emerging behaviour in technical systems of systems

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

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

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

Adaptation and integration of new or modified components

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

Humans in the loop and collaborative decision making

Human operators and managers play a crucial role in the operation of Cyber-Physical Systems of Systems because of their ability to understand the global behaviour of the system and to react to previously unencountered situations. On the other hand, the interventions of humans introduce an additional nonlinearity and uncertainty in the system. Important research issues are the human capacity of attention and how to provide motivation for sufficient attention and consistent decision making. It must be investigated how the capabilities of humans and machines in real-time monitoring and decision making can be combined optimally. Future research on the monitoring of the actions of the

users and anticipating their behaviours and modelling their situation awareness is needed. Social phenomena (e.g. the dynamics of user groups) should also be taken into account.

Cognitive systems

Systems of Systems present a myriad of operational challenges. To cope with these challenges there is a need for improved support by managers and operators by cognitive systems. With more data becoming available, operators and managers will struggle even more with the data deluge that will result from the increased interconnectivity and the availability of low cost sensor technologies for data acquisition. In addition to this, gaining an overview of the entire SoS is inherently complicated by the presence of decentralized management and control which also introduces difficulties in understanding the potentially large number of interactions and consequences of operator interventions.

The introduction of cognitive features to aid both operators and users of complex Cyber-Physical Systems of Systems is seen as a key requirement for the future to reduce the complexity management burden. This requires research in a number of supporting areas to allow vertical integration from the sensor level to supporting algorithms for information extraction, decision support, automated and self-learning control, dynamic reconfiguration features and consideration of the socio-technical interactions with operators and users.

Trust in large distributed systems

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

Engineering Support for the Design-operation Continuum of Cyber-Physical Systems of Systems

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

In contrast to traditional systems, CPSoS are continuously evolving, which softens, or even completely removes, the traditional separation between the engineering / design phases and the operational stages. They are highly flexible and subject to frequent, dynamic reconfiguration, and their high degree of heterogeneity and partial autonomy requires new, fully integrated approaches for their design, validation and operation. These new approaches must also take into account that failures, abnormal states and unexpected/ emerging behaviours are the norm in CPSoS, and that CPSoS are socio-technical systems in which machines and humans interact closely.

New engineering support methodologies and software tools must be developed that are tailored to handle CPSoS with all their constitutive properties in the following areas:

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

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

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

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

The introduction of model-based design techniques does not come for free. It requires an initial investment and also constrains the freedom of the engineers to proceed in an ad-hoc manner. The advantages of new tools for CPSoS engineering may therefore not be immediately apparent to the end-users, in particular in smaller companies. Thus, the demonstration of industrial business cases and applications that illustrate the benefits of these technologies is important and should be supported.

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

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

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

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

Establishing system-wide properties of CPSoS

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

Overcoming the modelling bottleneck

Model-based techniques are increasingly used in the reliable engineering of high-performance systems as well as to improve the efficiency of their operation. Currently, the application of advanced methods for engineering and operations is severely slowed down by the effort that is needed to develop the required models, to maintain them when the system that is described changes, and to assess the quality of models and their adequacy for a specific purpose. Large efforts are needed to overcome this modelling bottleneck. Key aspects to advance in this direction are:

- ▸ **Heterogeneous models and model re-use**
  In the foreseeable future, it will not be possible to describe a cyber-physical system of systems by one single monolithic model that covers all system elements and all system aspects. Rather, modelling, analysis and optimisation will focus on the critical elements of the system for which detailed models are developed while other aspects are only represented coarsely. Different aspects, e.g. computing the expected throughput and safety analysis require different model depths and formalisms. Furthermore, different models of different

accuracy often exist for the same element and aspect of a system. This poses two challenges: integration of heterogeneous models in simulation, analysis and optimisation, and documentation and management of a large variety of models and their relationships, underlying assumptions etc. The latter is also the prerequisite for the reuse of models based upon modular, object-oriented modelling.

▸ **Combining rigorous and data-based models**
When modelling physical system elements, two approaches are generally followed: Rigorous modelling, based on the laws of physics and chemistry, and data-based modelling. Both have their strengths and weaknesses. In the future it will be essential to combine both approaches into efficient modelling techniques. Basic relationships between the variables, e.g. mass balances, can easily be represented by rigorous model elements and need not be learned from data. On the other hand, the effort for modelling all effects in detail can be prohibitive so that data-based models for the detailed behaviour are easier to obtain.

▸ **Tracking of changes and model adaptation**
Even when a model initially provides a faithful description of the behaviour of the system element under consideration, this may change over time due to quantitative and structural changes of the system or changes of the operating regime. The model quality, i.e. its predictive capabilities, must be maintained during the whole lifecycle of the system. For this purpose the data gathered during operations must be used and the key parameters of the model, where the influence is the largest, must be continuously adapted. This adaptation process will also provide information on the model reliability such that the uncertainty can be quantified and taken into account when using the model. Systems are needed that connect different engineering systems based on a semantic model of the cyber-physical system of systems and propagate changes to the different engineering and operational systems involved, e.g. the information on the insertion of a new sensor and its properties, must be propagated from a CAD system to the configuration of the automation system and to a management execution system that uses this information.

5.3.2.7 Computational Blocks

The challenges for the computing fabric

Computing is the backbone of the digital industry by providing control, intelligence to all our devices. During the last ten years, a tremendous increase in performance and efficiency lead to a total change of our civilization: smart phones were not present at all 10 years ago, and now they seems indispensable for our connected life. We are expecting High Performance Computer to reach the exaflop (10^{18}) in the horizon of 2020-2025, while the petaflop (10^{15}) was reached only in 2008. It is estimated that the digital universe of 2020 will exceed 40 ZB (40×10^{21}), showing the tremendous impact that computing devices have. But the incremental change we saw in the previous decade, fuelled by the improvement of the silicon technology, is unlikely to continue for long, and we need to prepare for some more fundamental modifications.

The computing infrastructure is expected to undergo drastic changes in the coming 10 years. The drives behind this (r)evolution are the following :

▸ New applications requirements:
   • the code for an application will not be executed anymore in a single location, but applications will involve several compute engines that are distributed and often physically far away. Even today, an application requires code that runs in the device, but this device is connected to other devices and even to the cloud and it is all these parts that constitute an application (see Figure 17). An application is, in fact, the result on more or less coordinated interdependent programs interacting with each other and distributed onto different systems and programmed with different approaches. We have seen the move from single core, to multi and many core, where applications are locally parallelised, now we need to consider distributed computing, where communication (bandwidth, latency, reliability, …) is an inherent part of the design of a distributed application. Systems of Systems imply distributed computing. The computing fabric is a continuum which spread over a certain distance, and the transfer of data will become the limiting factor.
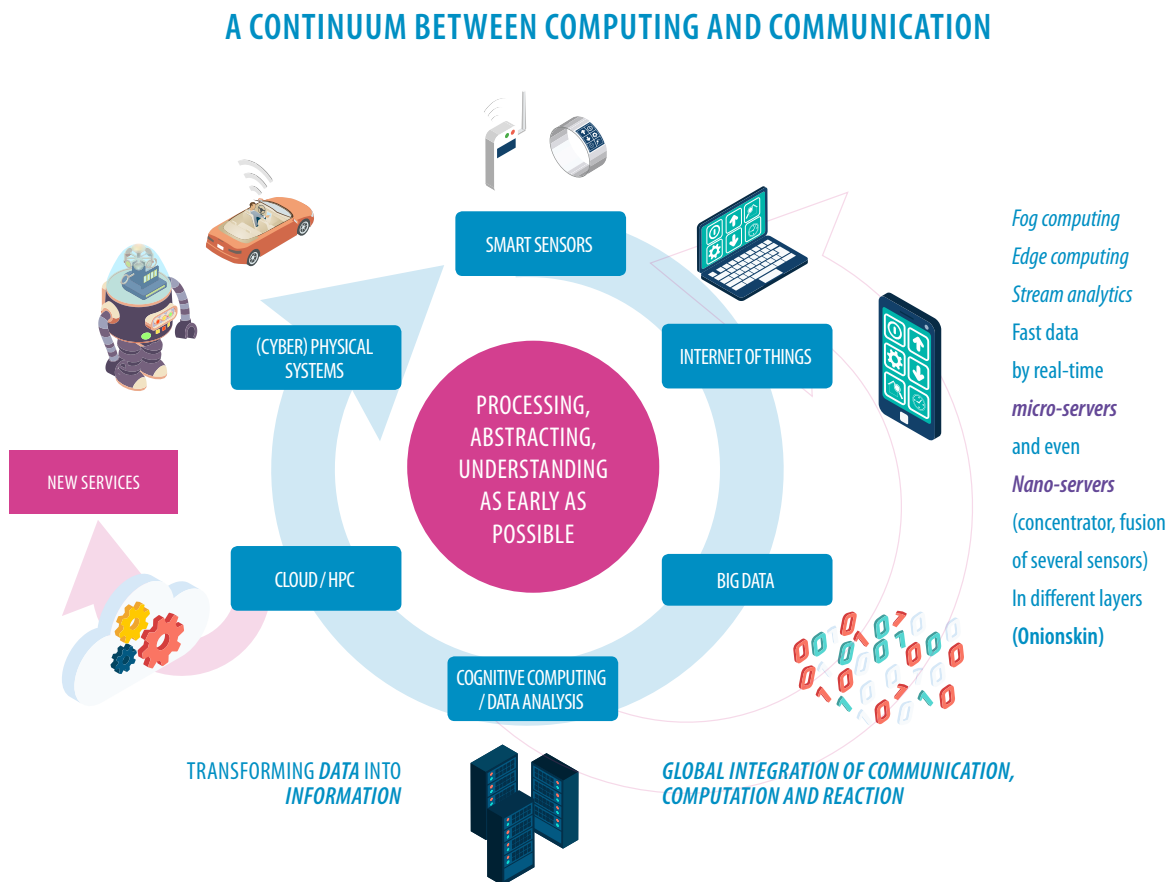
A CONTINUUM BETWEEN COMPUTING AND COMMUNICATION

Figure 17 *The computing communication continuum*

· The computing fabric will interact more and more with the physical world in CPS systems, at least in the border of the computing fabric. Good interaction will require the cyber world to cope with the constraints of the real world and not the opposite: response in due time is mandatory. Until now, all computing systems were designed to abstract and eliminate for example the notion of physical time. Response to external events are generally done using interrupts, which are considered as exceptional events for a processor: the future real-world interacting computing engine should consider external event as the main drives for computing, not anymore as exceptions. This will go paired with a wish for better predictability.

· The systems will become more "intelligent", i.e. they will analyse their data and their environment to extract relevant information. From these analyses (analytics), they will be able to derive dynamically new behaviour and adaptation. This dynamic behaviour will make the predictability of the computing substrate more challenging: for example, in a multicore system tasks can be moved dynamically from one core to another due to temperature, load and efficiency constraints. This task migration is often done by firmware which is invisible to the application.

· The "data deluge": the creation of new data is ever increasing, and processing is required to extract relevant information from data. But the paradigms seems to change: instead of sending all data to the cloud for storage and possible analysis (data analytics), the extraction of relevant information is now considered to be done as early as possible in the communication chain, ideally at the sensor level. Using the devices at the edge of the cyberspace is often called "edge computing" or "fog computing". The drivers are cost reduction (reduction of the data to be transmitted), confidentiality (only processed data, therefore abstracted, are transmitted to other devices for further processing) and global energy efficiency. Some simplified data analytics need to be performed, for example in the micro-controllers of the IoT devices or smart sensors. This could lead to a true distributed an "hierarchical" realisation of computations.

▸ Technological constraints: as highlighted in the HiPEAC vision document (http://www.hipeac.net/roadmap), the technology that brings us the "ever shrinking technology nodes" is not expected to last for very long. It will induce (and is already doing so) constrains for the computing substrate:

· The end of Dennard's scaling is still a key limiting factor with its impact on power and energy. In order to continuously increase the performance of devices, the race for ever smaller transistors is still ongoing (Moore's law), but the characteristics of the denser technology nodes are not so nice : the frequency has not drastically increased, the supply voltage has not decreased either, leading to an increase of the power density per technology node. Energy is now the first constraint for computing systems, both for mobile/end nodes (for increasing battery life) and for servers (cost of dissipating heath). Techniques, such as biologically inspired approaches, approximate algorithms, stochastic and probabilistic computing have the potential to produce more energy-efficient systems by relaxing accuracy requirements for processing "natural data".

- A logical continuation of Moore's law is to stack dies and interconnect them in the vertical direction. Besides the physical placement of dies on top of each other (e.g. using Through Silicon Vias, TSVs), monolithic 3D will allow the use the 3rd dimension at a small granularity. 3D stacking enables to change architectures by physically reducing the distance between different devices by stacking, e.g. memories on processors, and therefore increase bandwidth while reducing energy for communication. Through different combinations of dies, we may be able to regain the chip diversity lost due to the increasing costs of chip design. This also drives new challenges in standardisation, modelling, and programming to realise these complex systems in a package.

- Increase of the cost per transistor. A new phenomenon appears when we approach the sub-10 nm nodes: for the first time in the history of silicon manufacturing, the cost per transistor may increase from one technology node to the next one. For example, for IoT applications, some people estimate that the optimal technology node could be between 28nm and 22nm.

- Patterning, adding more constraints on design. Reaching the ultra-small dimensions of the new masks requires the use of EUV *[EUV]*. This technique will require changes to most of the design methodology and will impose a geometric structure on the design.

- Communication costs dwarf computation costs. Today data movement uses more power than computation. Communication and data movement even at chip level take far more energy than processing the data themselves. Moving a 64 bit word from a chip to external memory requires roughly 3 orders of magnitude more energy than a 64 bit operation. This revives the concept of « computing in memory » or that moving computations is less expensive than moving data. We are now living in a world where *communicating and storing data is more expensive* (in both power and performance) *than computing*. To adapt to this change, we need to develop techniques for exposing data movement in applications and optimising them at runtime and compile time and to investigate communication-optimised algorithms.

▸ Some other constraints related to the « Quality of Service » are even more drastic, such as :

- Reliability. The elementary components will be less reliable because the technology is more sensible to radiations, variability etc. But the composition of ever higher number of devices is also increasing the risk of failure. The future systems should be therefore self-healing and self-reconfiguring in order to continue to deliver their service even in case of failure of some of the components.

- Security, data protection and no hackability. There is an increasing concern that piracy, hacking devices is a major problem for CPS devices. Hacking a PC might have a large impact, but hacking a car or a more complex system can have immediately deadly effects. Some people call IoT the "Internet of Threat" and emphasise the fact that IoT will be successful only if the users can trust it.

▸ Another important item is the **explosion of complexity**. The computing substrate is now so complex that understanding it in details is not anymore feasible.

- **Validation**: The number of sub-systems, devices, makes it infeasible to validate a system by exhaustive simulations and test cases. Furthermore, some of the elements are dark or grey boxes: they are IPs which their internals is not accessible for the integrator, and these IPs are characterised only by their interfaces and a simplified simulation model. Their behaviour is only specified in nominal cases, not in border line utilisation, which can happen in the event of the failure of other devices.

- **Software:** the hardware has now such a hidden complexity that optimisation is better done by tools than manually, paving the way to program systems only by expressing "what" needs to be done (declarative programming) instead of "how" it should be done (imperative programming), which implies a good understanding of the inner mechanism of the system.

- **The correctness** challenge: In programming language history, the portability of performance has always been secondary to functional portability, also known as correctness. This paradigm has to be dramatically revisited, however, as the correctness of Cyber-Physical Systems directly relates to execution time, energy consumption and resource usage. In other words, performance in the broad sense is now part of the specification; it is a requirement and no longer an objective function.

- **Deep learning**: some functions, such as image analysis and classification, are now efficiently done by neural-network inspired methods, which are "set" by showing a large set of examples during a "learning" phase instead of explicitly programming the system. The success of this approach in playing the "Go" game shows that it might be extended not only for functions interfacing with natural signals such as video, sound or signals, but also to complex decision-making processes. This is also an approach to overcome the complexity of explicitly programming the system. However, it is currently impossible to have a formal proof that the resulting system will give results within specified margins: results are validated by test and trials, not formally.

All these drives will require new innovative solutions for the computing continuum, both at the hardware and software level. In a nutshell, the main message is that current technologies will prevail in the short term and will continue to be improved while new technologies trying to cope with the challenges that are shared by embedded, mobile, server and HPC domains will be required and therefore have to emerge to solve, notably:

▸ Energy and power dissipation: the newest technology nodes made things even worse;
▸ Dependability, which affects security, safety and privacy, is a major concern. The revelations by E. Snowden clearly reinforced the need to design systems for security and privacy;
▸ Complexity is reaching a level where it is nearly unmanageable, and yet still grows due to applications that build on systems of systems.

Research Challenges

The main lines of action proposed in the previous versions of the SRA (see *Insert 1*) are still valid, even with more emphasis concerning energy efficiency, dependability and the efficient management of data movements. But a few more impactful transformations need attention:

▶ **Move toward distributed systems:** The move to multi-core is not yet fully managed in term of predictability, and systems are moving now towards distribution of computation on heterogeneous compute engines. The cost of communication, in term of reliability, latency, predictability should be taken into account in all system design, realisation and evaluation, which is another challenge on top of parallelisation.

▶ **More and more heterogeneity:** specialisation is an answer to energy efficiency so we will see more and more heterogeneity in the computing fabric. GPUs are just beginning to be taken into account efficiently, but more and more specialised accelerators might emerge, if their use is easy (implying an easy use or good abstraction at the software level). To use the right amount of energy, certain devices can also use approximations (approximate computing, or better stated as "adequate computing"). Heterogeneity can also be introduced by Field Programmable Devices (FPGAs) or Coarse Grain Reconfigurable Architectures (CGRAs). Intel recently acquired Altera, following the success of using FPGA to accelerate Microsoft's Bing search engine. With HLS (High Level Synthesis), they can also be "programmed" with a C or C-like language. This heterogeneity adds even more burden to the software tools and programmers. The current existing solutions are going to be a heavy burden, and the current programmers and engineers should learn a new way of thinking or new kind of tools need to be developed to help program those heterogeneous distributed multi-core systems. In practice, this will involve the development of real heterogeneous parallel processors that can work in a distributed environment, new memory architectures and management programming approaches, the development of parallel distributed programming languages and design methods able to cope with heterogeneity, and the setting up of respective education. It will be necessary to make parallel and distributed programming as simple as sequential programming. However, most contemporary languages are primitive and low-level: they are cumbersome and require intricate knowledge of the execution model of the machine to fully optimise the performance. Most critically, they do not provide portable performance between different hardware platforms. Debugging is also a nightmare due to a dearth of advanced debugging tools for heterogeneous, parallel and distributed systems.

▶ There is therefore a need **for new tools and techniques** that provide power and performance portability, analyse software to provide high-level feedback to developers and runtime systems, and enable porting of legacy applications to modern hardware. The programmer should only express the concurrency of the application, and leave the tools to map the concurrency of the application into the distributed part of the system as well as efficiently use the parallelism of the hardware. Run-time adaptation and machine learning has demonstrated a high potential to improve performance, power consumption and other important metrics. Virtualisation is a step toward hardware independence but further progress is required to cope with truly distributed and heterogeneous systems.

‣ **The "How" it works will be more and more hidden**, requiring new disruptive effort to ensure that the system will operate always within specified limits. The "how" is hidden due to over-complexity, abstraction, IPs where the exact description of their internals are not available, or new approaches based on "learning".

‣ **Autonomic systems** should address the issue of self-adaptive and self-configuring behaviours implying close cooperation between application software and architectural support mechanisms. One challenge is to demonstrate the compatibility between such innovative dynamic behaviour and the predictable system constraints. The computing fabric should show characteristics of evolution capabilities whereby some components can be replaced while the system is in operation, while the system has to operate for a very long period of time, and must be resilient to unexpected behaviours along its lifetime – leading to a reconsideration of the lifecycle management of products. Algorithms for concept formation and data structures for knowledge representations should be developed such that self-aware systems that learn about their environment and autonomously plan to achieve a given goal can be constructed. This technology will be also used internally to reconfigure the system in the event of failure or to adapt to the current requirements. Techniques from machine learning (either explicit using rule based approaches) or from deep learning (using examples to train the system) will be more and more developed, and could lead to new paradigms both for the hardware and the programming approach.

‣ The **cost of the advanced process technologies** required the continuation of Moore's law is growing exponentially. This cost is doubling every four years, making the continuation of Moore's law not only a technical challenge but also an economic and political one. On top of that, the non-recurring engineering costs of designing new chips are also growing rapidly due to the complexities of increasing levels of functional integration and the difficulties of managing smaller transistors. One potential solution is the use of silicon interposers to integrate heterogeneous devices (various dies of various functions made of possibly different technologies) on the same substrate. This allows for cheaper dies (using only advanced processes for the most performance-critical dies) and more diversity (by integrating circuits that require optimized processes, such as analogue, digital, photonics, and sensors). Silicon interposers do not require the most advanced technology nodes, and therefore can be built in existing fabs.

New technologies, like Non Volatile Memories, could also have a drastic impact in computer architecture by simplifying the memory hierarchy; and silicon photonics to reach new limits in energy efficiency and bandwidth to transfer data.

Insert 1: Challenge from the previous SRA

Cyber-Physical Systems encompass a large range of computing devices and must integrate innovations in order to cope with the user's needs and real world requirements, such as hard real-time constraints, energy management, data access and storage, dynamic reconfiguration, application deployment, reliability and security of the data and processes. Their connectivity will enable functions and functionalities to be performed at all levels of the CPS, such as distributed computing, edge-computing or fog computing. These developments will allow the seamless integration of the Internet of Things (IoT) concept with applications to Internet of Energy (IoE), Internet of Buildings (IoB) and Internet of Vehicles (IoV), etc... The key challenges are:

1. **Energy efficiency, by all possible means:** avoiding unnecessary data communications (e.g. by processing data to extract the useful information where it is captured), pushing for new innovative architectures and protocols, holistic optimisation. New silicon technologies, new non-volatile storage technologies (which can change the existing storage paradigm), photonics, adaptive voltage and frequency control, 3D interconnect, energy-aware operating systems and middleware, data placement and retrieving, application development and so on will be required to harmoniously cooperate in order to further increase energy efficiency.

2. **Ensuring Quality of the Service (QoS) dependability** including real-time is a major challenge that worsens with the emergence of many/multi-core systems. The solution covers real heterogeneous parallel processors, new memory architectures and chains, the development of parallel oriented programming languages and design methods, as well as software architectures and setting up respective education. Techniques continuously monitoring the performance of the CPS should be designed in order to assess the reliability of the whole system. The security of data and the global integrity of a CPS are also paramount. Other important platform requirements derived from CPS applications are reliability, safety and resilience. Distributed and heterogeneous computing will require further development to ensure a true dependability despite of unknown characteristics of the 'remote' processing (such as guaranteed latency, loss of data, 'grey boxes').

3. **Decreasing global cost (and development costs in new technology nodes)** is key to the commercial success of solutions. Development of solutions to keep diversity such as the use of silicon or organic interposers to integrate heterogeneous devices (various dies of various functions made of possibly different technologies) on the same substrate.

4. **Edge Computing:** due to connectivity functions, computing capabilities may be shared/exist outside the physical device and processed in the 'Cloud'. Deploying Cloud-dependent services (software running on the device or outside as well as software applications not embedded in the product) to provide adequate guarantees, handle issues such as latency, QoS, increase the security at SOS level… and provide methods and tools to improve quality offered by cloud-based heterogeneous service infrastructures.

The tracks identified in the SRA 10 years ago:

- ‣ Ways to bridge physics and computing…
- ‣ Automatic synthesis of control systems, taking into account distribution, heterogeneity…
- ‣ Novel computing architectures…
- ‣ Modular, heterogeneous, composable and self-organising, adaptive systems…
- ‣ Radical design and verification methodologies for correct by construction with respect to dependability….

5.3.2.8 Digital Platforms: Cyber-Physical creating smart services

Cyber-Physical Systems are increasingly connected to networks and Internet and the trend is going to continue with the consequence that the systems are exploiting the information from Internet and also using it for interaction with other systems in creating their services in a platform configuration or model.

With the large amount of data generated and exploited, and the multiplication of vertical application areas, models of the 'universal' platform are set-up by the Internet players (particularly the GAFA). Alternative platform models should be proposed in specific areas (factory, hospitals, urban areas, etc..) with more business focus. The Digital Platforms will be more user-centric than technology-centric and will constitute for their builders and users the right environment to share know-how and transfer technology.

Research Challenges
The Digital Platform will address the following research challenges:

- ‣ Model of Cyber-Physical Systems comprise models of the environment. Such models will need to take a closer look at the interface between the analogue and the digital world, since the state of the art in this area still leaves many issues open. For example, control theory needs to take a closer look at the implications of discretisation.
- ‣ In the future the Cyber Physical System research should focus on building services in smart spaces based on the capabilities of CPS and promoting the interoperability of CPS as objects or nodes in Internet. The research is taking the direction of interoperability, development in semantic web, open data and linked data [8].
- ‣ To really benefit from the added value of networking (similarly as stated in Metcalfe's law), the approach requires a common infrastructure in addition to M2M solution islands as well as a [global] systems for giving Things digital identities, the addressing of resolution services and support for managing the information. These issues are analogous to the Internet and should be handled in an open way so that smart services can be created and also innovated. This should be a major EU topic for a solution that supports the emergence of new business.

▸ It would be futile trying to tackle the complexity challenge with a pure bottom-up development approach. In order to be competitive we have to establish generic reference architectures and engineering platforms on all relevant implementation levels to meet the development requirements of future Cyber-Physical Systems.

In addition, the following topics expanded in chapter 5.3.2.1 CPS Architectural Principles are to be considered under the perspective of the present chapter 'Digital Platforms', namely:

▸ **Separation of concerns:** to increase the productivity and bring in more user centric design, the platform-based approach, allows Platform developers concentrate on platform development and the users of the platform can invest their resources in providing added value at a higher layer.

▸ **Provision of common services:** so that the platform provides common services which are required by most of the applications that will be realised on that platform

▸ **Efficient reuse and composability:** a platform that follows a sound architecture should enable the creation of new products by composing them from a library of pre-validated building blocks.

▸ **Establish a (de-f acto) standard:** a reference architecture or a platform has only real value if it is widely used and the strategy to become a successful platform has to be considered from the very beginning.

Insert 2: Challenge from the previous SRA

World-machine interaction (WMI)

Situation-awareness and reliable interpretation of real-time images will become more and more relevant to a large class of embedded systems such as driver-assistant systems in vehicles, and also through interfaces that are more natural for humans like in real life and use more and more natural sensory interaction, understand the intentions, and deliver personalised and unique responses.

For ARTEMIS-IA a particular research challenge is to reliably construct for an embedded system an accurate real-time representation of its environment. This construction is easy if the environment consists of real-time entities such as valves as the Embedded System can accurately measure its current state. The construction is significantly more complex in dynamic situations in which not even all real-time entities are present all the time. The following are research challenges that need to be addressed:

- ‣ How can we build real-time images from inherently inaccurate information?
- ‣ What are the guarantees that we can give for such real-time images?
- ‣ What aspects of state-of-the-art Embedded Systems need to be improved to increase the guarantees on the real-time images?
- ‣ How can we build a reference architecture that deterministically delivers real-time images?
- ‣ What are the knobs and dials (design guidelines) that we can use as a trade-off to increase the level of determinism for real-time images?

Human interaction with CPS[17]

To fully exploit the capabilities of CPS and facilitate a broad user acceptance, new approaches, solutions and technologies are required in the interaction between humans and computers.

If the goal is to use the networked environment as an enhancement of human capabilities, the current "human-in-the-loop" approach (enabling the operations of machines) is not enough and it needs to be replaced by a new paradigm where humans and computers cooperate in carrying out complex tasks or easing the performance of more traditional ones (often named Human-Centred Computing).

Human-Centred Computing requires the development of new interaction system designs, software and technologies to build up specific properties like **situation awareness** (to optimise the cooperation between humans and computers in highly dynamic environments), **adaptability** and **individualisation** (to cater for different situations, personal preferences, capabilities and expectations). A wide user acceptance requires also an attractive and intuitive **user experience** providing gratification and enjoyment, and enhanced **accessibility** to fulfil user expectations and capabilities in the different application environments. The system should also be able to ensure **privacy**.

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17   *[Ref: Software Technologies - The Missing Key Enabling Technology: Toward a Strategic Agenda for Software Technologies in Europe, ISTAG, July 2012]*

To achieve these properties, a substantial research effort is needed to develop interaction technologies exploiting emerging computing infrastructures (e.g. cloud computing or others specific of user environments), wireless networking and advanced integration capabilities.

With the goal of providing seamless interactions, a range of key technologies needs to be addressed like voice, vision, gestural input, retina-integrated displays and brain-machine interfaces. Multimodal integration of these technologies is required to reduce user workload, to enable the sharing of capabilities between humans and machines and mutual support, whose forms are highly dependent on the specific environment (from home to factories and other professional environments, from automotive and other transport means to education, ..)

5.3.2.9　Basic Research, Fundamental Research

R&D cycles, prepare the future, no fixed boundaries

Cyber-Physical Systems integrate systems and products autonomously perceiving, analysing and acting upon their environment with cloud-based services in order to address societal and business needs. Humans are essential elements of CPS and the modelling of humans and their interactions with other components of CPS provides new critical challenges. CPS constitutes a core technology in the ongoing process of the digitisation of our society, creating a global market of several trillion dollars.

Although we are today observing the uptake of Cyber-Physical Systems technology in many application domains, Cyber-Physical Systems concept and design, production, operation and lifecycle management follow ad-hoc, domain-specific approaches. Their related research areas span various maturity levels, and some are still lacking the appropriate level of the established engineering and scientific disciplines that make it possible to predict the properties of the constructed systems from their blueprints.

Scalable principles of combining large heterogeneous ensembles of physical systems, humans and cyber-systems while assuring that their emergent properties and behaviours to meet the overall system objectives within quantifiable tolerances are among the areas where basic research are to be fostered. This will help our society to reduce its dependence on technologies, whose risks have been insufficiently reflected upon.

To address these concerns, we consider imperative to: 1. Develop techniques making CPS predictable and dependable across their whole lifecycle; 2. Capitalise on synergies in building CPS, driving open, horizontal and vertical standards; 3. Develop open platforms and living labs for testing and experimentation with CPS; 4. Develop and exchange best practices for training and education for CPS.

> *In the above chapters (5.3.2.1 to 5.3.2.8), due to their evolving iterative nature the research challenges depicted cover a range from low to high maturity, and thus in a way address some basic research for the extension of such research to the scientific foundations which are key for sustaining a European leading position in this domain.*

Insert 3: Challenge from the previous SRA

Processing the Data Deluge [18]

In 2010 the world generated over 1.2 Zettabytes (10^{21} bytes) of new data, 50% more than it had in all of human history before that. There will be an exponential growth of data coming from data sensors and IoT. Processing, storing and retrieving all those data in due time is a phenomenal challenge that we are facing but also the source of great opportunities.

Most of the data are unstructured or coming from the physical world (like video, audio, various signals). Exact interpretation is difficult, like image analysis and recognition. The systems will increasingly have to analyse these data, for self-driving vehicle, surveillance, robotic applications, smart-*, …
To process those data, exact computation with a lot of accuracy is not always necessary. Several approaches and techniques should be developed to reduce the power, or increase the density, of processing engines, taking advantage of "less accurate" processing.

"Programming" future applications spread across different distributed, parallel and heterogeneous systems:
Another challenge is programming a network or system of computing systems (as is done in data centers, and between mobile devices and sensing devices) where an application is, in fact, the result of more or less coordinated interdependent programs interacting with each other and distributed onto different systems and programmed with different approaches.

There is also need for new tools and techniques that provide power and performance portability, analyse software providing high-level feedback to developers and runtime systems, and enable porting of legacy applications to modern hardware. The programmer should only express the concurrency of the application, and leave the tools to map the concurrency of the application into the parallelism of the hardware. Run-time adaptation and machine learning has demonstrated a high potential to improve performance, power consumption and other important metrics. Virtualisation is a step toward hardware independence but further progress is required to cope with truly distributed and heterogeneous systems.

Optimising data movement and communications:
Today data movement uses more power than computation. We are now living in a world where *communicating and storing data is more expensive* (in both power and performance) *than computing* it. To adapt to this change, we need to develop techniques for exposing data movement in applications and optimising them at runtime and compile time and to investigate communication-optimised algorithms.

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18   *From HiPEAC vision for advanced computing*

Managing complexity by giving the "What", not the "How":
Classical approaches use an explicit declaration of how to perform tasks (typical *imperative programming*), but it might be time to reinvest in paradigms where, instead of instructing the machine on how to perform its tasks, we only specify the goal(s) or the objectives. *Declarative programming* (like database query languages - e.g., SQL, regular expressions, logic programming, and functional programming) falls in this category, together with other approaches like using Neural Networks. Those approaches are promising to cope with the complexity of programming large-scale parallel and/distributed systems. Most of them can be easily mapped to parallel systems.

Developing new computing modalities:
Techniques, such as biologically inspired approaches, approximate algorithms, stochastic and probabilistic computing, have the potential to produce more energy-efficient systems by relaxing accuracy requirements for processing "natural data". Similarly, as more and more applications are about intelligent processing, the application scope of neural networks inspired technologies become significant for pattern recognition in unstructured data. Smooth integration of these approaches with classical ones, while keeping a certain level of trustworthiness, is worthy of investigation.

Learning and Reasoning System:
One of the most challenging features of CPS is that they have to act in a world which is not only already very complex, but is rapidly and constantly changing even to extents that could not be foreseen at design-time. Adaptability and evolvability are thus very desirable properties for CPS, which can be reached via upgrades and via learning. A given goal can be constructed for learning algorithms for concept formation and data structures, for knowledge representations such that self-aware systems that learn about their environment and autonomously plan to achieve. On the other hand, safety is key to CPS, given increased in V&V technologies for evolvable and (self) learning systems, which is not very well understood yet.

Adaptive Morphic Embedded Systems:
Addressing the issue of self-adaptive and self-configuring behaviours implies close cooperation between application software and architectural support mechanisms. Compatibility between such innovative dynamic behaviour and the predictable system constraints must be demonstrated.

INNOVATION ENVIRONMENT CONTEXT – MAKE IT HAPPEN

6.1 ARTEMIS-IA INNOVATION CONCEPT

ARTEMIS-IA is an Innovation Programme whose aim is to foster the Digital Transformation by supporting the development of innovative smart products, services and solutions in a large variety of activity sectors for the benefit of the users, citizens and businesses.

The term "innovation" is a broad term; the ARTEMIS-IA "Research and innovation" Strategic Agenda focuses on a number of innovation accelerators to get research results to market that will be generated from Research Programmes derived from the present SRA, i.e. from fundamental and industrial research to experimental development of new products, processes and services to enable market introduction and European added value.

MAINTAINING THE ARTEMIS-IA DIFFERENTIATORS

ARTEMIS-IA will maintain its initial differentiators and will further build on:

- ‣ Being an 'Industry driven' initiative,
- ‣ Sustaining its focus on both business competitiveness and technical excellence,
- ‣ A descriptive 'Top-down' approach based on a Strategic Agenda, supported by a bottom-up expression of needs through its Centres of Innovation Excellence (CoIE) and its constituency,
- ‣ Keeping the focus on impactful and market-oriented projects, such as large-scale projects, flagships or lighthouses;
- ‣ Having a coherent projects portfolio built on large footprint projects with support from smaller focused projects, while ensuring the balance between different research actors (large, mid and small industry as well as RTOs and Academic) to drive innovation,
- ‣ Actively supporting the creation of innovation eco-systems,
- ‣ Openness and complementarities with EU framework programmes, Eureka particularly ITEA, and the EIT KICs for getting research results to market.
- ‣ Fostering the synergies and relation with the other European initiatives, namely the European Technology Platforms (ETP), Public Private Partnerships (PPP) and Joint Undertaking JU.

These differentiators are essential to support the set of 'Innovation Accelerators' to allow technology developments to become strong market influencers, through business-driven engineering.

Among the ARTEMIS-IA Innovation Accelerators, we identified also:

- **Standards**, to ensure interoperability in its many forms, through active participation in their definition and promotion.
- **Tools**, developed from a rigorous scientific basis, to allow timely and "right first time" product/system definition, analysis and development.
- Robust, **science-based engineering processes**:
  - embrace fast-changing requirements as a fact,
  - integrate multiple and diverse technologies and non-functional aspects,
  - provable guarantee correct functionality,
  - provable guarantee immediate conformance to safety/security/privacy certification needs.

6.2 RESEARCH FUNDING PROGRAMMES

To 'Make it Happen' expresses ARTEMIS Industry Association's ambition to inspire a wide range of the research policymakers in Europe and their work programmes, mainly the EC Research Framework Programmes (such as H2020 2014-2020), the ECSEL JU work programmes and **other programmes** such as the multi-national Eureka clusters ITEA and PENTA programmes, as well as National and Regional research programmes in order to:

- Efficient use of Public available funding in the Cyber-Physical Systems arena to overcome the resource deficit for R&D and to foster innovation & collaboration in Europe,
- To help in aligning implementation of R&D&I (Research and Development and Innovation) priorities for Cyber-Physical Systems in Europe to turn European "diversity" into a strength,
- To achieve a "European Dimension" by combining the R&D efforts across Europe for future proven application domains and technologies, while pulling resources in key areas, and involving relevant players with the ability to ensure successful valorisation and uptake of the results.
- Establishing and sustaining a holistic approach to R&D&I, by undertaking projects of critical mass, reconciling the market silos/ business-efficient approach with cross-domain synergies.
- To help in sharing the risk of the software development through critical mass R&D projects that otherwise would not be undertaken,
- To pool industrial resources and "sharing" (e.g. standards and methods) to foster interoperability and synergies between various environments, in order to maintain leadership in traditional markets, and gain worldwide positions and more market in new areas.
- Setting and sharing R&D&I infrastructures.

6.3 CENTRES OF INNOVATION EXCELLENCE

In order to meet the medium to long-term research needs of European industry, ARTEMIS developed the of Centres of Innovation Excellence (CoIEs) concept and focused on a small number of systems-oriented CoIEs of a multi-disciplinary nature (e.g. computer scientists, electronic and mechanical engineers, application specialists) well complemented with respected academic groups and in-house R&D groups within the industrial companies, and specialised in specific sub-domains.

The scope of a CoIE is that of a coherent subspace of an application domain of the ARTEMIS-IA Strategic Research Agenda. It creates an Innovation Eco-system for that subspace.

Their mission is to pursue the implementation of industrial research visions, as expressed in the ARTEMIS-IA Strategic Research Agendas. They create new Innovation Eco-systems, taking advantage of the critical mass of competences and resources that have already been organised in supporting regional clusters. They focus on European research efforts and mobilise research actors to tackle the SRA challenges.

Several initiatives have already been launched to create regional high-tech clusters, primarily from CoIEs such as EICOSE, Finnish SCSTIs, ProcessIT.eu or SafeTrans (as a member of EICOSE) that actively participate in a bottom-up approach to feed technical priorities into ARTEMIS and ARTEMIS-IA strategic planning instruments such as ECSEL MASRIA, but also others such the Pôle de Compétitivité in France, Pôle de Compétitivité "Point One" in the Netherlands, Kompetenz-Netze in Germany, the cluster of Strategische Onderzoekscentra in Belgium, and 'Silicon Saxony', the microelectronics cluster around Dresden in Germany. Several of these regional innovation initiatives address the application domains of the ARTEMIS SRA.

ARTEMIS-IA will continue to cooperate and build on these existing regional clusters since it is important for ARTEMIS-IA success that these regional innovation initiatives in Europe can participate in and be integrated into the ARTEMIS-IA Innovation Environment.

Centres of Innovation Excellence will contribute to ARTEMIS-IA by:

- ▸ feeding domain-oriented requirements into the ARTEMIS Strategic Research Agenda via structured, domain-specific think-tanks;
- ▸ mobilising a critical mass at European level for driving a significant part of an application domain of the SRA;
- ▸ providing a focus for all the related capabilities required of an innovation ecosystem (education and training, a suitable domestic and social infrastructure, logistic infrastructure, etc.);
- ▸ establishing integration platforms, living labs and test-beds;
- ▸ providing business development instruments and spin-off environments;
- ▸ facilitating the translation of research results into innovative products (as part of regional, national and European programmes and as part of industry-funded JTI activities on innovation ecosystems).
- ▸ facilitating the translation of research results into industrial deployment;
- ▸ guiding the identification of new product and market opportunities and helping in the preparation of business activities.

6.4 STANDARDS AND STANDARDISATION

Standardisation is considered by the EC as a very important part in exploiting the results of research projects. In all the recent developments and initiatives, research programmes and studies of the EC, standardisation was raised as an important issue. Standardisation awareness has increased considerably during the last few years, and it was identified as a need of industry particularly in critical application areas, where dependability issues (safety, security, reliability, availability, maintainability, and some derived properties like robustness, sustainability, and resilience) play an important role and are of great public interest.

For dependability and safety standards (look at 5.3.2.3), although it is a medium to long term issue compared to the duration of a research project (normally three years), whereas standardisation schedules cover 5 years and more, and an immediate uptake requires a "window of opportunity", i.e. start of a new work item within the timeframe addressed by the project, or of a maintenance cycle of an existing standard for an update, which may take five years or more.

New topics, like IoT, Cloud Computing, Automated Vehicles (Driving), Autonomous Systems, Robotics etc. have taken up the issue that standardisation is a mandatory need in their context. It enables the interoperability of components and systems, and of tools and data, and communication in a connected world of "things". In complex systems-of-systems, like IoT or "connected autonomous vehicles", without stringent standardisation it will not be possible to make things happen, i.e. work. New project results cannot be exploited properly and brought into growing markets if standardisation does not occur in parallel – never before was interoperability so important! As a result, the H2020 Innovation Action CP-SETIS, set up by ARTEMIS partners involved in projects working in that direction, has started an effort to harmonize IOS standardisation and create a sustainable structure to maintain it.

Connected complex intelligent systems i.e. Cyber-Physical Systems-of-Systems (CPSoS) require multi-concern assurance for qualification or certification. The dependability properties have to be assured via co-analysis and developed via co-engineering methodologies, which again requires research results to be brought to standards or integrated into standards.

As an example, Safety & Security concerns are handled together now in several ARTEMIS/ECSEL projects as a key research target. In parallel, groups from research and company partners have initiated and/or supported upcoming new versions of Functional Safety Standards like IEC 61508, ISO 26262 "Cybersecurity and Safety task Groups". The new Ad-hoc WG of IEC TC65, AHG1 on "Framework towards coordination of safety, security in industrial automation", which has now started a new work item "Framework to bridging the requirements for safety and security", and AHG2 "Reliability of Automation Devices and Systems" have been supported by the same ARTEMIS partners. Another example is TTEthernet (TTTech), where development started in an FP6 Integrated Project DECOS with several partners that helped to build ARTEMIS.

The next standardisation challenges are to be expected in context of Cloud Computing (particularly security and reliability/dependability) and the whole of IoT; there are many related standards to aspects important for parts of IoT architectures, communications and dependability issues, but many issues to provide overall resilient and sustainable services are not covered.

Therefore, idealistically **RD&I** projects are required to agree a strategy for standardisation, whenever applicable. This will include a rationale for that strategy which takes into account the ARTEMIS Strategic Standardisation Agenda (available from the ARTEMIS-IA web-site). RD&I projects will be expected to communicate with relevant ARTEMIS-IA standardisation initiatives concerning their standardisation needs and opportunities, including those that may emerge during project execution.

Furthermore, related initiatives in other ETPs (European Technology Platforms and PPPs) should be contacted and cooperation envisaged. Examples could be a joint initiative with EPoSS and cooperation with euRobotics as both ETPs have similar issues and challenges concerning safety, security in general dependability, certification and qualification, interoperability of components (interfaces) and tools (to build tool chains etc.).

6.5 EDUCATION AND TRAINING

The rapid evolution of the new global Digital Economy is generating needs and challenges with such a high growth rate that even the human capital market is not able to keep pace. So, education and skill building will be a key pillar in the EU strategy to have a relevant role (and so a relevant economic impact) in the Digital Transformation of society.

While the EU is boosting the Digital Single Market taking care to make it secure and trustworthy, currently companies are struggling with what experts are calling the "largest human capital shortage in the world".

According to the "The 2015 (ISC)2 Global Information Security Workforce Study" the global demand for cyber security experts is forecast to outstrip supply by a third before the end of the decade. (ISC)2, the security certification and industry body, predicts that companies and public sector organisations will need 6 million security professionals by 2019 but only 4.5 million will have the necessary qualifications.

Effective education and training is crucial to maintaining competitive leadership. It is a pre-condition for any so-called "sustainable innovation ecosystem", and therefore an essential part of a Strategic Research Agenda. The EC took this into account when organising one workshop on Education, Training and Skills for electronic/photonic components and smart/embedded systems, one on May 5, 2014, and another one on Education, Training and Skills: Connecting students and employers – the case of electronics, on October 13, 2015, in Brussels. The outcomes addressed the Electronic Leaders Group (ELG). The EC and industry concern was the fact that the demand for ICT specialists is increasing by 3-4% per annum but the supply of graduates cannot meet demand. It is estimated that there will be a shortage of up to 900,000 ICT professionals by 2020. These workshops brought together different stakeholders in the electronic/photonic components and smart/embedded systems industry to take stock of what contributions to the skills development had already been achieved through funded EC projects, to discuss the education and training needs of industry and to define concrete actions/recommendations to fulfil these needs. The ARTEMIS E&T WG was represented by its chairperson. Besides the purely academic institutions aspect (e.g. of Marie Sklodowska Curie Actions) of E&T, the industrial requirements were discussed and the particular aspect of research projects' results to be integrated in the E&T process was brought forward:

"Make 'education' a specific deliverable for all EU Projects" was an outcome of the "Skills-Session" mentioned above. Additionally, it was noted that introducing such deliverables as research projects' results is one of the important exploitation measures and contributes to the sustainability of results and to the RD&I ecosystem.

Therefore, Cyber-Physical Systems projects should make recommendations to instigate improvements to the following with respect to E&T to capitalise in a sustainable manner on the achievements of research projects:

▸ make "education and training" output part of projects' deliverables – achievements should be brought closer to the next generations!
▸ create a highly skilled, multi-disciplinary workforce, and maintain and upgrade the existing skills of a professional workforce (life-long continuous learning);
▸ join forces and include the interests of both industry and academia, in initiatives, support actions etc., designed to overcome the gap between theory and practice of (industrial) application;
▸ establish new types of people mobility programmes with an industrial focus, additional to those with a rather academic focus;
▸ support high-tech spin-offs and start-up companies by facilitating non-technical training in entrepreneurship, finance and business practice, etc…;
▸ influence pan-European policies to better achieve long-term effects in Embedded Systems education and training,
  · providing adequate university and applied university curricula in embedded and smart systems domains, and
  · providing a platform of excellence with special curricula and educational and training institutions (separately or on top of existing organisations).

For the realisation of these targets, cooperation with the KIC EIT DIGITAL should be pursued in order to foster the link between Education &Training initiatives.

6.6 RELATIONSHIP WITH OTHER RELEVANT INITIATIVES AND PPPS

The mapping of the main PPPs and their potential interaction and synergies is illustrated in the following figure:
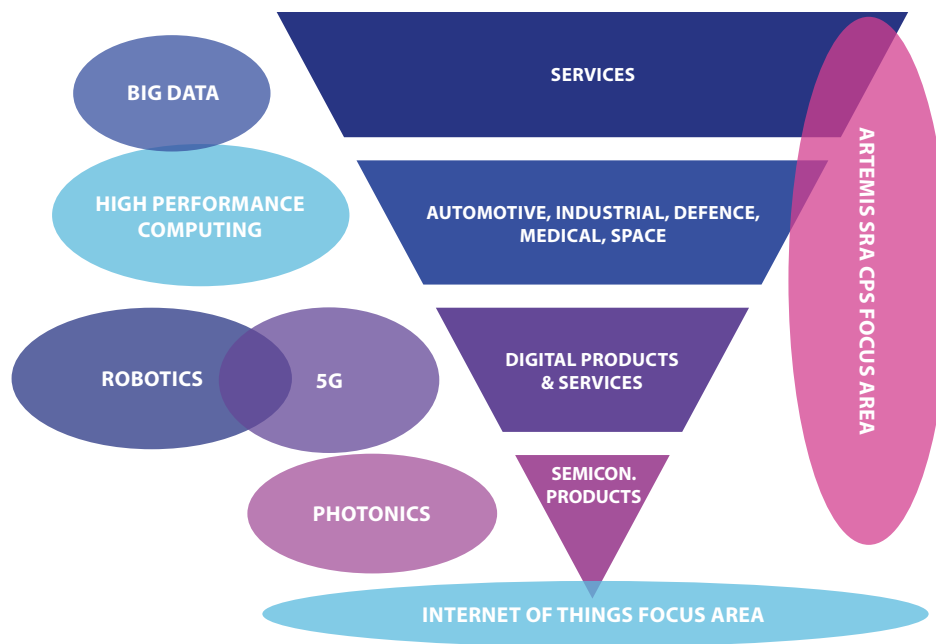
Figure 18 *ARTEMIS focus in relation to other EC initiatives*

Each of these initiatives – PPPs – shows a high commitment in its respective area. But they also have the same need of relying on each other's specificities and sharing a number of challenges and opportunities. ARTEMIS SRA focus area is transversal to them. With the embedded software development, software-based services and the Cyber-Physical Systems technologies, it constitutes an indispensable enabler.

6.7 INTERNATIONAL DIMENSION

Research and innovation are becoming global, ignoring frontiers and being performed where the creative individuals and eco-systems exist. The race is now about being 'best in the world' or the 'world of the best'.

ARTEMIS-IA will seek more openness and be open to the world through an "International Collaboration' plan that can encompass a wide range of activities, from the organisation of technical meetings, high-level meetings, conferences, schools (MOOCs and SPOCs) and, where possible, joint international projects".

International collaboration should fit into a global win-win strategy for achieving the participants' long-range aims. Defining such a vision and strategy is important for guiding international collaboration.

ARTEMIS-IA will define "modalities" for interaction between the European R&D community and the main international players in areas related, among others, with Embedded Systems and ICT, Cyber-Physical Systems and Cyber-Physical-Systems-of-Systems, including research institutions, professional organisations (ACM, IEEE, ARC Advisory Group, IFAC, IFIP), standardisation bodies (e.g.: OMG, IEEE, IEC, ISO/ISA), large consortia (e.g., the Industrial Internet Consortium (http://www.iiconsortium.org/index.htm), the Cyber-Physical Systems Public Working Group (http://www.cpspwg. org/), the Smart Manufacturing Leadership Consortium (https://smartmanufacturingcoalition.org/), funding agencies (e.g.: IST, NSF, DARPA, NSERC, ARC))

In particular, ARTEMIS-IA will foster the cooperation with the IEEE Industrial Electronics Society (IES) and "Industrial Cyber-Physical Systems" technical committee that provides a forum for researchers and practitioners to exchange their latest achievements and to identify critical issues and challenges for future investigation on lifecycle engineering, control, management, operation and optimisation of cyber physical systems for industrial applications.

ARTEMIS-IA will help Europe to develop 'brain magnet' capabilities to attract the participation of the best brains in this area throughout the world. To this end, ARTEMIS-IA will develop and communicate its Vision and Strategic Research Agenda globally. The creation of Centres of Innovation Excellence and increased international visibility through communication, the website, and other ARTEMIS-IA conferences (such as Co-Summit, Spring event, Summer Camp, Technology conference,..) are International Conference will be among the tools to foster this collaboration."

More specifically, "The added value of such openness should become visible through:

‣ Opening of new contacts, such as Asia, based on existing strengths and fostering ARTEMIS standards as a worldwide basis;
‣ With IEEEs as explained above;
‣ Compensation for weaknesses in specific areas where there is no European equivalent;
‣ Mutualisation of resources for the development of non-differentiating (business-wise) technologies;

ARTEMIS-IA will build on European strengths that include:

▸ Innovative ideas leading to international standards;

▸ An approach based on good appreciation of theoretical foundations;

▸ Ability to attract and retain top researchers in embedded systems.

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