Cyber-Physical Systems in Manufacturing: Future Trends and Research Priorities

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Abstract

In the last decades, the manufacturing ecosystem witnessed an unprecedented evolution of disruptive technologies forging new opportunities for manufacturing companies to cope the ever-growing market pressure. Moreover, the race to create value for the customers has been hindered by several issues that both small and large companies have been facing, such as shorter product life cycles, rapid time-to-market, product complexity, cost pressure, increased international competition, etc. In this scenario, ICT represent a crucial enabler for preserving competitiveness and fostering industry innovation. In particular, among these technologies, Cyber-Physical Systems (CPS) is growing an ever-high interest of industry stakeholders, researchers, practitioners and policy makers as they are considered the key technology that will transform manufacturing industry to the next generation. Indeed, CPS is a breakthrough research area for ICT in manufacturing and represents the cornerstone for achieving the EU2020 "smart everywhere" vision. At this early development phase, there is the urgent need to set the ground for future research streams, create a common understanding and consensus, define viable migration paths and support standards definition. This paper describes the identified research challenges and the future trends that will drive to the adoption of CPS in manufacturing. The main evidences on researches challenges expected for CPS in manufacturing are outlined by the authors that have been involved in the sCorPiuS project 'European Roadmap for Cyber-Physical Systems in Manufacturing', promoted by the European Commission to define a roadmap for future CPS in manufacturing adoption research agenda.

Keywords: Cyber-Physical Systems, Manufacturing, Future Trends

1. Introduction

In the last decades, the manufacturing ecosystem witnessed an unprecedented evolution of disruptive technologies forging new opportunities for manufacturing companies to cope the ever-growing market pressure. In this scenario, ICT has represented the crucial enabler for preserving competitiveness and fostering industry innovation. In particular, Cyber-Physical Systems (CPS) is a breakthrough research area for ICT in manufacturing and represents also the new innovation frontier for accomplishing the EU2020 "smart everywhere" vision. Thus, an important factor for a successful innovation strategy is a more aware and widespread use of the CPS engineering in the manufacturing environment to ensure a competitive advantage for business success and jobs creation. This paper wants to describe the Research Priorities identified within the first release of sCorPiuS Roadmap addressing the role of CPS in manufacturing.

2. Cyber-Physical Systems in Manufacturing

2.1 Definition of Cyber-Physical Systems

Several experts already tried to provide definitions for CPS. Thus, in the literature it is possible to find several similar interpretations of CPS rather than a standard definition. Most of them state the scope of CPS and describe how the interaction between the virtual and the physical world is made (e.g. enabling technologies). Some authors assert that as an application domain, CPS is not new (Nosbusch 2011), affirming for example that early automotive embedded systems already in the 1970s combined closed-loop control of the brake and engine subsystems (physical parts) with the embedded computer systems (cyber parts). As a conceptual domain, CPS represent for sure an ever-growing terminology of the new integration of computation and physical capabilities (Melih Soner Celiktas 2015). In fact, with the emergence of high speed broadband and the Internet of Things (IoT), the embedded world is meeting the internet world and the physical world meets the cyber world (European Commission 2013). It is exactly here that the concept of CPS arises. In a recent official report of the European Commission, CPS are introduced with this sentence:

"The confluence of the embedded and Internet worlds has led to the concept of Cyber-Physical Systems (CPS)" (European Commission 2013)

The term "Cyber-Physical System" was coined at the National Science Foundation (NSF) in the United States around 2006 (Gunes et al. 2014) and it describes a broad range of complex, multi-disciplinary, physically-aware next generation engineered systems that integrates embedded computing technologies (cyber part) into the physical world (Gunes et al. 2014). This integration mainly includes observation, communication, and control aspects of the physical systems from the multi-disciplinary perspective. One of the earlier definitions states that "Cyber-physical systems are integrations of computations and physical processes" where embedded computers, and networks monitor and control the physical processes (Lee 2008; Lee 2006; Li et al. 2011), and so that they are "smart systems that encompass computational (i.e., hardware and software) and physical components, seamlessly integrated and closely interacting to sense the changing state of the real world. These systems involve a high degree of complexity at numerous spatial and temporal scales and highly networked communications integrating computational and physical components." (National Institute of Standards and Technology 2013).

CPS take advantage from the integration of cloud-based and Service-Oriented Architecture (SOA) to deploy end-to-end support from the cradle to the grave perspective. Both product and factory lifecycle will be strongly impacted. For the first case, by considering even the last phases of the product life-cycle (e.g. de-manufacturing, after sales services, etc.). Instead, on a factory life-cycle perspective, CPS able to interact with all the hierarchical layers of the automation pyramid (i.e. ERP, MES, SCADA, PLC, field level) will empower the exchange of information across all the phases, resulting in a better product-service development (in terms of efficiency, timing, quality, etc.). CPS are suitable for many different industrial sectors and their adoption is always tailored for the specific case in which they are engaged. From this, further research is needed in order to understand how CPS will change the future of manufacturing industry.

2.2 Relevance of Cyber-Physical Systems in European Manufacturing

CPS have the potential to impact massively the European economy and society. Europe accounts for 30% of world production of embedded systems specifically in the automotive, aerospace and healthcare sectors. For this reason, Europe is focusing on capitalizing this market through several financial supports (e.g. FP7, Horizon 2020, ARTEMIS, I4MS). However, providers of this technology have to create new business models in order to make CPS be adopted both in small and large companies. In doing so, several challenges need to be addressed in order to spread the adoption of CPS: privacy, security, dependability, genitive abilities, human interaction, ubiquity, standardization, robust connectivity and governance. In the manufacturing context, CPS exploit advancements achieved in computing systems on modelling in combination with the big amount of data produced from the surrounding environment through low power sensors and actuators. These technologies led to the creation of smart factories (where the machines are able to reconfigure themselves in line with external conditions and thanks to their embedded computing power) and virtual factories (able to orchestrate the factory's resources and the information across the entire value chain through IoT, cloud computing and smart products paradigms). In the last years, CPS have been extensively adopted in aerospace, electric, transportation, healthcare, and housing industries to support both vertical and horizontal integration of IT systems. However, since CPS are implemented in heterogeneous environments, companies need new architectures able to seamlessly integrate several heterogeneous automation software conceived in diverse domains (e.g. control, diagnostic, modelling, process rendering, human machine interfaces, etc.) of the factories. The standard IEC 61499 is currently adopted as a component-based modelling approach able to deal both with software and hardware systems. Accordingly, the fundamental requirements for introducing CPS in industry have been specified in the literature as it follows:

- Adaptable to heterogeneous environments: integration with cutting-edge information systems, smart-devices and the existing environment (from old PLCs to smart object embedded in computing power).
- Capable of working in distributed networks: they should gather, transfer and store in a reliable manner all the information provided by smart sensors and actuators through the use of the IoT.
- Based on a modular open architecture: the interoperability has to be ensured across different platforms provided by several vendors along the value chain.
- Incorporate human interfaces (HW & SW based): integration of user-friendly and reliable service to make decision makers aware about the real time situation of the factory.
- Fault tolerant: given by the encapsulation of models to activate prediction control loop and correctness of automation systems.

2.3 Methodology

In order to access the current status of CPS in Manufacturing, to evaluate the possible exploitations, and so to identify the research priorities to be addressed, other than pursuing a literature analysis, it is important to assess directly how the key stakeholders are moving forward and what is the perception of the people involved in this field.

To such purpose, the current status of CPS in manufacturing was investigated with two actions aiming to collect information and knowledge from the *sCorPiuS* network of experts.

1. Guru interviews: with the collaboration of the sCorPiuS team eco-system, it was possible to identify a number of experts who, thanks to their background, are involved and influence the adoption of CPS in several manufacturing industries and are playing a central role along the evolution of the industry organization, ICT adoption and its strategic

approach. We started from an initial set of 37 selected experts and in the end we interviewed 21 "Gurus" who gave us their availability.
2. Knowledge Capture Events (KCE): we organized 4 events where experts from different industrial and technological backgrounds were invited to discuss about their experiences, views and expectations in adopting CPS in the manufacturing industries of the future. The presence of experts coming from different fields stimulated the discussion and it was a catalyst for identifying new ideas.

A common method in both the approaches was taken, following the same logical schema to come to the identification of the experts' views

The purpose is not to figure out where a specific technology can be applied, but to identify the application areas more suitable to bring value with the adoption of CPS. Furthermore, through this investigation, it was possible to understand the future trends and the research priorities related to CPS implementation in Manufacturing. The outcome of this study is reported in the following chapters where 6 CPS enabled breakthroughs and the research priorities coming from each breakthrough are described.

2.4 Cyber-Physical Systems enabled breakthroughs

In order to consolidate the results of this exercise, with the support of the experts taking part to the KCE and of the interviewed Gurus, it was possible to define 6 clusters under which the breakthroughs related to CPS implementation in Manufacturing industry were classified:

1. **New data-driven services and business models:** It relates the company as a whole, regarding top managerial decisions. CPS, with its digital world, opens a wide range of new business possibilities. Not only to already configured enterprises, e.g. giving the possibility of being closer to customers and offering high value services, but the appearance of new business models exploiting the capabilities of this new technology.
2. **Data-based improved products**: It concerns the breakthroughs coming from the digitalization of the product. The product behaves as an intelligent component inside and beyond the factory, sharing information at different levels, enabling a better understanding and configuration of the processes and services, and bringing a high value added to its usage.
3. **Closed-loop manufacturing:** It corresponds to an "expansion" of the limits of the company. Takes into account other stakeholders in the value network, such as suppliers and customers, integrating their feedback into the production.
4. **Cyberized plant/ "Plug & Produce":** Embraces the benefits that the adoption of CPS has in the plant. Permits a more holistic insight of the production processes, a better information management, and facilitates tasks performance by mean of digital support.
5. **Next step production efficiency:** Compromise breakthroughs that enable a better utilization of management assets translated into a more efficient production.
6. **Digital ergonomics:** Corresponds to breakthroughs that make easier the integration of people with the new CPS environment. Although the processes are getting more complex with CPS, e.g. more data is analysed, people have to access them in an easy and understandable way.

In the following figure, these clusters are mapped according to product and process lifecycle phases they have an impact on.

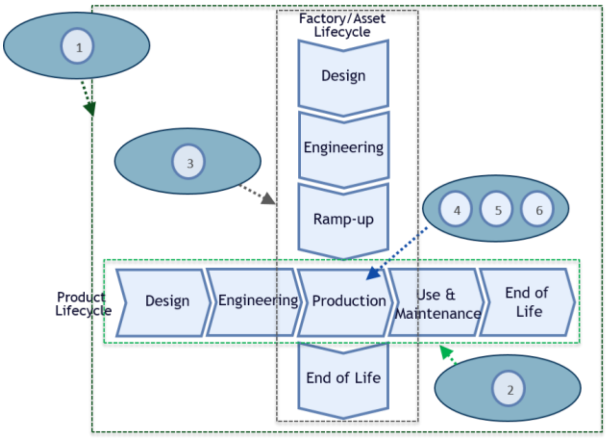

Figure 1 CPS breakthroughs on the Product and Process Life Cycle

3. Research Priorities

In the following chapters, Research Priorities are listed and described according to the cluster of breakthroughs they have an impact on.

3.1 Research Cluster: New-data based services and business models

Manufacturing as a Service (MaaS) – Servitisation of autonomous and reconfigurable production systems

Manufacturing industry and related value chains are nowadays challenged by customer-driven production dynamics requiring high product configuration, flexibility, minimum lot size and order delivery time. Time to market is as well a key success factor for competing at global level while multiple stakeholder participation to the design, engineering and distribution process is a reality to cope with, associated to the need for adoption of new business model in selling and utilizing products (e.g. servitisation). Cloud as services provider and IoT technologies providing full knowledge of status and behavior of assets and products, make available a complete new possibility to monitor and control the reality inside and outside the plant environment. This landscape requires a complete new approach for defining the very concept of manufacturing based on the new requirements and the possibility provided by technology. Availability of "fluid" production environments able to overcome traditional flexibility and elasticity features via high speed and seamless reconfiguration and self maintenance capabilities, will be key enabler for provision of innovative, high quality and competitive products for more and more demanding customers willing to be served with a fully personalized product where they were even involved in the design phase.

Next generation customer driven value networks

Collecting data about product usage, thanks to the Internet-of-Things and CPS technologies, as well analyzing social networks can create a clear definition of trends and expectations. The increasing competition requires continuous improvement and the ability to be always innovative with new value propositions for consolidating the position and attracting new markets. Common competitiveness can be reached only when all the partners cooperate in designing, producing and delivering new and innovative products and new experiences to the customers. To achieve these objective, partners must collaborate in creating a common knowledge by breaking the silos where data are stored and fusing that with the information collected along all the phases of the product lifecycle (design, planning, production, delivery, maintenance and service, disposal or re-cycling), using CPS and IoT technologies.

European Circular Economy Open Platform for CPS

Circular Economy (CE) now poses unprecedented challenges by introducing the post-life or better the evolutionary life transformation concept, which also needs to be supported by dedicated ICT systems. If we instantiate the CE/Reuse issue on CPS, quite often next generations of cyber assets and new cloud applications (e.g. condition monitoring, remote diagnosis and maintenance, fleet management and optimization) call for a retrofitting of the physical assets (or CPSisation). This is a new service-oriented business model where the most advanced CPS manufacturers could provide customers with a CPS as a service value proposition (e.g. the physical retrofitting and the cyber upgrade) also in the presence of physical assets produced by competitors. A smart CPS-driven Machine Tool manufacturer could offer customers advanced predictive maintenance services thanks to the CPSisation of its assets, but could also propose to the same customers some CPSisation services (physical retrofitting and cyber upgrade) on top of machines manufactured by competitors. The basic need in this domain is that currently the CE paradigm has been applied mostly to De-manufacturing (disassembly), raw materials recovery and Re-manufacturing/Recycling of physical products and not on the CPSisation of existing cyber-physical artefacts.

3.2 Research Cluster: Data-based improved products

Product Service Systems (PPS): products with embedded service delivery capability

Manufacturing industry has traditionally carried out its business with a product centric view, but according to several sources, by 2025 many manufacturers will get more revenue from services than from product sales. Still, services are usually added on top of existing products, to extend them, but are not conceived together with the product, as a unique value proposition. The adoption of IoT and CPS as enablers of product servitisation allows to track the product and services along the whole lifecycle and consequently enhance customers' experiences and satisfaction through the melting of the physical and the cyber/services aspects to a point where one won't exist without the other. Lifecycle management will moreover ensure the full exploitation of well-structured data and information, enabling high efficiency and added value in all the phases, from the design to the recycling

3.3 Research Cluster: Closed-loop Manufacturing

Digitisation of value networks

Increased global competition and presence, rising consumer expectations and complex patterns of customer demands are the foremost challenges that companies will have to face in the next years requiring solutions capable to manage complex customer-driven value networks. In this regard, the integration of CPS and the Internet of Things (advanced analytics, cloud-computing, big data) has the potential to turn such complexity into an opportunity by creating end-to-end digital value network solutions among heterogeneous stakeholders (geographical locations, domain, size, information systems, etc.). Pioneering ICT solutions will lead to an improved visibility across the value network giving an extraordinary opportunity to configure it in the shape of new business models at any level. This will foster the value network alignment with its actors and customers' changing needs and optimization against different perspectives (quality, time to market, costs, sustainability goals, etc.). Thanks to the enormous amount of information made available, both small-medium and large enterprises will unfold completely new grounds by proactively and timely responding to the ever-evolving ecosystems dynamics.

Full Product Life Cycle data collecting and analysis

In the future, machines will provide massive amounts of data (as already done until now), but the differences with today lay in the improved ways of gathering this data and to use it for various objectives within and for the different factory levels (machine, shop floor and supply chain) in Cyber Physical Systems. Data mining and real time analytics are the basement for novel supply chain approaches for innovative products and collaborative and mobile enterprises. In fact, connected objects, assets and enterprises in the supply networks can provide a new type of collaboration, permitting collaborative demand and supply planning, traceability, and execution. Data mining and real time analysis should help service engineers to design new product service systems, permitting the propagation of the servitisation, (i.e. energy efficiency as a service) and redesigning business models for Ecosystems of Product-Service. However, they cannot succeed without addressing Cyber-security, Privacy, data protection, trusted third parties, data ownership, and share value of the information (ownership of value data).

3.4 Research Cluster: Cyberized Plant / "Plug & Produce"

Predictive and preventive self-learning systems

The manufacturing of custom-made parts on demand with flexible, reliable and reconfigurable resources forces the implementation of adaptive and smart manufacturing devices, components and machines and robots systems. This changing shop floor environment is supported by embedded cognitive functions with self learning capacities. The development of a customer driven IoT-based factory with self-learning and self-optimization systems implies the development of new organizational models and a model-based approach to describe the behavior of the system and the knowledge of the plant. As self learning and self optimization must be based on data and knowledge, M2M and M2product communication along with human/machine communication is a key aspect to develop.

CPS Enabled reconfiguration of automated manufacturing systems

Self-adjusting plug and produce devices able to ensure a flexible manufacturing environment based on rapid and seamless reconfiguration of machinery and robots have become a strength to face the unpredictable, high-frequency market changes. These devices are based on CPS, smart sensors, artificial intelligence, real time control and seamless data exchange and can lead to the introduction of proper manufacturing systems able to integrate the sequence of operation steps needed to obtain customer requirements. The idea is to create a unique production environment aiming to relocate machines in a short time, maximizing use of low cost robots and demonstrating a more agile production solution, designed to be a modular system / platform with a large flexibility potential in order to be adapted to different kinds of processes and products. The main goal is to realize a specific context where machine components, machines, cells, or material handling units can be added, removed, modified, or interchanged as needed to respond quickly to changing requirements, hence ensuring the ability of a manufacturing or assembly system to switch with minimal effort and delay to a particular family of work pieces or subassemblies through the addition or removal of functional elements.

Cyber Native Factories

Factories are evolving faster than in the past and becoming more complex, expensive and geographically distributed, but the support from IT systems is limited by their monolithic architecture, by their specific focus and by the lack of interoperability solutions. Therefore, the application of advanced techniques for manufacturing systems (e.g. simulation, predictive maintenance) to achieve a holistic representation of the overall factory is impossible or at least difficult to achieve and with long returns of the investments. CPS and the wide application of IoT in manufacturing will enable a shift of paradigm. The current trend is that new machines will natively embed IoT capabilities; legacy machines will be equipped with ad-hoc hardware to "cyber-ize" them. These will offer easier connectivity and machine integration, even in data intensive scenarios where many sensors, channels and registries will be managed and recorded. IoT connectivity will be one key enabler of the future cyber-physical factories, but to achieve the highest economic impact the "digital" part has to be filled with content (e.g. behavioral models, simulation capabilities, predictive conditions) as well as the application layer has to provide high value data integration and elaboration. Easy to use apps for the digital factory will finally enable factory personnel to be included in the cyber-physical information loop provided with ad hoc and contextual content, playing a key role for flexibility and smartness in the overall factory automation.

3.5 Research Cluster: Next step production efficiency

Novel production management tools and models for CPS-based production

Smart technologies and connectivity promise to improve flexibility and allow continuous control in industry that helps manufacturing firms to compete in the actual evolving context characterized by unpredictable frequent market changes and the demand for increasingly individualized products with shortened life cycles. The adaptation to this context requires companies to be able to quickly reconfigure their production systems, so as to follow the rapidly changing markets, allowing higher capacity-flexibility and smaller lot sizes, that are based both on technological support, that can be provided by smart equipment with real time monitoring and decentralized intelligence, and on managerial capabilities, such as proper production management approaches. It is expected that the technological advancements brought by CPS, such as smart technologies, smart connectivity and decentralized intelligence, could support the development of innovative production management techniques together with the possibility to have a high level of reconfigurability of production systems.

3.6 Research Cluster: Digital ergonomics

Caring for People in manufacturing Systems

With an increasing aged workforce, new interface requirements are raised regarding the physical aspects and dimensions of the human-machine interfaces. A proactive approach is required to make mobile machinery aware of the presence of humans (and vice-versa) within the shop floor for an improved safety and working experience. Indeed a great potential for dynamic adaptation of the production systems to promptly and effectively respond to the emergent request and occurrences coming from any kind of source is generated by the competent and participative design of CPPS work organization.

Novel modelling and prediction tools have to be developed to encompass the roles and behaviors of employees whether operating in the control loop of the physical process and whether interacting with the mesh of nodes and applications of the digital factory.

Different work arrangements, including remote and smart working disclose huge opportunities for increasing production and social performances. to leverage humans' intuition and creativity for flexibility, learning and evolution from inside

In the future, visual models of the production systems will allow employees to enlarge their feeling, comprehension and sense making. They will be able to interact with the models, to receive concrete feedback, to store their personals experience and their stories with reference to the individual components or to the whole. The wealth of available experiences, sense making and stories will contribute to the creation of the individual employees and collective factory identity and will be retrieved, elaborated and exploited for reflection, learning and future evolution of production systems.

Knowledge and skills for the next generation manufacturing

The strategic importance of human factor for manufacturing competitiveness and the need to identify, develop and empower new competencies are problems whose resolution is becoming more and more urgent in the modern "knowledge economy". In this context, the alignment and harmonization of these two fundamental aspects and the final training and development of modern "knowledge workers" represents one of the strategy to adopt in order to address the issue. Furthermore, the demand for highly skilled workers in manufacturing is increasing and, as a consequence, the need for educated, flexible and knowledge-based workforce has to be supported by a coherent set of tools and methodologies able to sustain the creation, development and management of advanced skills at all the levels of the company. To this end, the availability of CPS-based tools, together with novel organizational frameworks, will provide industry with the capability to act positioning at the center the humans' participation along with the manufacturing processes by changing the paradigm from people-less factory to an extended and deep social-machine and human-machine interactions. Specific human-machine interfaces, mutual and self-learning systems, speech recognition methods, augmented reality software, and the implementation of collaborative robots will allow the cooperation of human and machines in the industrial environment. Ergonomics, user acceptance, user experience criteria will be adopted in order to maximize social performances such as user well-being and satisfaction together with manufacturing performances such as productivity, flexibility and responsiveness.

4. Conclusions

CPS should be considered one of the key enabling technologies for the development of the new manufacturing environment. This paper describes the future trends and the research priorities related to their implementation in manufacturing industry. This work will be integrated in European and national programs, in collaboration with EFFRA and Cluster Nazionale Fabbrica Intelligente.

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