5

Internet of Things Applications in Future Manufacturing

John Soldatos[1], Sergio Gusmeroli[2], Pedro Malo[3] and Giovanni Di Orio[3]

[1]Athens Information Technology, Greece
[2]Politecnico di Milano, Italy
[3]UNINOVA & FCT NOVA, Portugal

5.1 Introduction

Future manufacturing is driven by a number of emerging requirements including:

- **The need for a shift from capacity to capability**, which aims at increasing manufacturing flexibility towards responding to variable market demand and achieving high-levels of customer fulfillment.
- **Support for new production models**, beyond mass production. Factories of the future prescribe a transition from conventional make-to-stock (MTS) to emerging make-to-order (MTO), configure-to-order (CTO) and engineer-to-order (ETO) production models. The support of these models can render manufacturers more demand driven. For example, such production models are a key prerequisite for supporting mass customization, as a means of increasing variety with only minimal increase in production costs.
- **A trend towards profitable proximity sourcing and production**, which enables the development of modular products based on common platforms and configurable options. This trend requires also the adoption of hybrid production and sourcing strategies towards producing modular platforms centrally, based on the participation of suppliers, distributors and retailers. As part of this trend, stakeholders are able to tailor final products locally in order to better serve local customer demand.

- **Improved workforce engagement**, through enabling people to remain at the heart of the future factory, while empowering them to take efficient decisions despite the ever-increasing operational complexity of future factories. Workforce engagement in the factories of the future is typically associated with higher levels of collaboration between workers within the same plant, but also across different plants.

The advent of future internet technologies, including cloud computing and the Internet of Things (IoT), provides essential support to fulfilling these requirements and enhancing the efficiency and performance of factory processes. Indeed, nowadays manufacturers are increasingly deploying Future Internet (FI) technologies (such as cloud computing, IoT and Cyber-Physical Systems (CPS) in the shop floor. These technologies are at the heart of the fourth industrial revolution (Industrie 4.0) and enable a deeper meshing of virtual and physical machines, which could drive the transformation and the optimisation of the manufacturing value chain, including all touch-points from suppliers to customers. Furthermore, they enable the inter-connection of products, people, processes and infrastructures, towards more automated, intelligent and streamlined manufacturing processes. Future internet technologies are also gradually deployed in the shopfloor, as a means of transforming conventional centralized automation models (e.g., SCADA (Supervisory Control and Data Acquisition), MES (Manufacturing Execution Systems), ERP (Enterprise Resource Planning)) on powerful central servers) towards more decentralized models that provide flexibility in the deployment of advanced manufacturing technology.

The application of future internet technologies in general and of the IoT in particular, in the scope of future manufacturing, can be classified in two broad categories:

- **IoT-based virtual manufacturing applications**, which exploit IoT and cloud technologies in order to connect stakeholders, products and plants in a virtual manufacturing chain. Virtual manufacturing applications enable connected supply chains, informed manufacturing plants comprising informed people, informed products, informed processes, and informed infrastructures, thus enabling the streamlining of manufacturing processes.
- **IoT-based factory automation**, focusing on the decentralization of the factory automation pyramid towards facilitating the integration of new systems, including production stations and new technologies such as sensors, Radio Frequency Identification (RFID) and 3D printing. Such

integration could greatly boost manufacturing quality and performance, while at the same time enabling increased responsiveness to external triggers and customer demands.

Within the above-mentioned categories of IoT deployments (i.e. IoT in the virtual manufacturing chains and IoT for factory automation), several IoT added-value applications can been supported. Prominent examples of such applications include connected supply chains that are responsive to customer demands, proactive maintenance of infrastructure based on preventive and condition-based monitoring, recycling, integration of bartering processes in virtual manufacturing chains, increased automation through interconnection of the shopfloor with the topfloor, as well as management and monitoring of critical assets. These applications can have tangible benefits on the competitiveness of manufacturers, through impacting production quality, time and cost. Nevertheless, deployments are still in their infancy for a number of reasons including:

- **Lack of track record and large scale pilots**: Despite the proclaimed benefits of IoT deployments in manufacturing, there are still only a limited number of deployments. Hence manufacturers seek for tangible showcases, while solutions providers are trying to build track record and reputation.
- **Manufacturers' reluctance**: Manufacturers are rather conservative when it comes to adopting digital technology. This reluctance is intensified given that several past deployments of digital technologies (e.g. Service Oriented Architectures (SOA), Intelligent Agents) have failed to demonstrate tangible improvements in quality, time and cost at the same time.
- **Absence of a smooth migration path**: Factories and production processes cannot change overnight. Manufacturers are therefore seeking for a smooth migration path from existing deployments to emerging future internet technologies based ones.
- **Technical and Technological challenges**: A range of technical challenges still exist, including the lack of standards, the fact that security and privacy solutions are in their infancy, as well as the poor use of data analytics technologies. Emerging deployments and pilots are expected to demonstrate tangible improvements in these technological areas as a prerequisite step for moving them into production deployment.

In order to confront the above-listed challenges, IoT experts and manufacturers are still undertaking intensive R&D and standardization activities. Such research is undertaken within the IERC cluster, given that several topics dealt within the cluster are applicable to future factories. Moreover, the Alliance for IoT Innovation (AIOTI) has established a working group (WG) (namely WG11), which is dedicated to smart manufacturing based on IoT technologies. Likewise, a significant number of projects of the FP7 and H2020 programme have been dealing with the application and deployment of advanced IoT technologies for factory automation and virtual manufacturing chains. The rest of this chapter presents several of these initiatives in the form of IoT technologies and related applications. In particular, the chapter illustrates IoT technologies that can support virtual manufacturing chains and decentralized factory automation, including related future internet technologies such as edge/cloud computing and BigData analytics. Furthermore, characteristic IoT applications are presented. The various technologies and applications include work undertaken in recent FP7 and H2020 projects, including FP7 FITMAN (www.fitman-fi.eu), FP7 ProaSense (http://www.proasense.eu), H2020 MANTIS (http://mantis-project.eu), H2020 BeInCPPS (http://www.beincpps.eu/), as well as the H2020 FAR-EDGE initiative. The chapter is structured as follows: The second section of the chapter following this introduction illustrates the role of IoT technologies in the scope of EU's digital industry agenda with particular emphasis on the use of IoT platforms (including FITMAN and FIWARE) for virtual manufacturing. The third section is devoted to decentralized factory automation based on IoT technologies. A set of representative applications, including applications deployed in FP7 and H2020 projects are presented in the fourth section. Finally, the fifth section is the concluding one, which provides also directions for further research and experimentation, including ideas for large-scale pilots.

5.2 EU Initiatives and IoT Platforms for Digital Manufacturing

5.2.1 Future Manufacturing Value Chains

The manufacturing Industry has recently evolved from rigid, static, hierarchical value chains to more flexible, open and peer-to-peer value ecosystems. Moreover, the added value produced by manufacturing (15% of the overall GDP (Gross Domestic Product) in the 28 EU Member States) has dramatically changed its pattern, where production and assembly of physical goods has constantly decreased its value added, in favor of pre-production and post-production activities.

The so-called SMILE challenge (Figure 5.1) is also emphasizing the role of ICT in this radical transformation of manufacturing value chains. In the central production stages, IoT is mostly at the service of Factory Automation and represents the major vehicle for connecting Real World (and its Cyber Physical Production Systems) with Digital-Virtual worlds in a green sustainable economy; in the pre-Production stages, closed loop collaboration ecosystems for new product-service design as well as Digital-to-Real world 3D printing ecosystems have been enabled by IoT and support creative economy; in the post-Production stages, new IoT-driven business models, supporting service- sharing- circular- economy, have been developed with success with the aim to compensate the loss of jobs derived from factory automation. For all the stages, it is necessary to proceed with the formation of new competencies and curricula centered on IoT and its related digital technologies, in order to attract young talents to Manufacturing and to up- re-skill existing workforce (blue and white collar workers).

Following paragraphs discuss the relevance of IoT in Manufacturing Value Chains, in consideration of two major events, which have characterized this year (i.e. 2016): the "Digitising EU" Industry policy communication and the enormous success of Industrie 4.0 initiatives and projects. A bi-directional convergence and innovation reference framework for digitizing EU Manufacturing value chains through IoT adoption is also proposed.

5.2.2 Recent EU Research Initiatives in Virtual Manufacturing

In commissioner Oettinger's speech at Hannover Messe on April 14$^{\text{th}}$ 2015, four main pillars for Europe's digital future were identified: i) Digital Innovation Hubs; ii) Leadership in platforms for Digital Industry; iii) Closing the digital skills gap and iv) Smart Regulation for Smart Industry.

On this basis, DG CNECT elaborated a yin-yang metaphor (Figure 5.2) to pictorially represent the two main challenges for achieving a strong EU Digital sector (against the GAFA US dominance) supporting a pervasive digitalization of EU industry. The "Collaborative Manufacturing and Logistics" FoF11 2016 call was partly focused on digital automation platforms for collaborative manufacturing processes, i.e. addressing together the first two pillars of Mr. Oettinger's speech: EU leadership in digital platforms to digitize EU manufacturing and logistics industries.

Many of the new FoF11 projects (currently under Grant Preparation phase in DG CNECT) are based on FIWARE and FITMAN Industrial IoT platform (Figure 5.3) and will bring new ideas and contributions to the IoT (IERC)

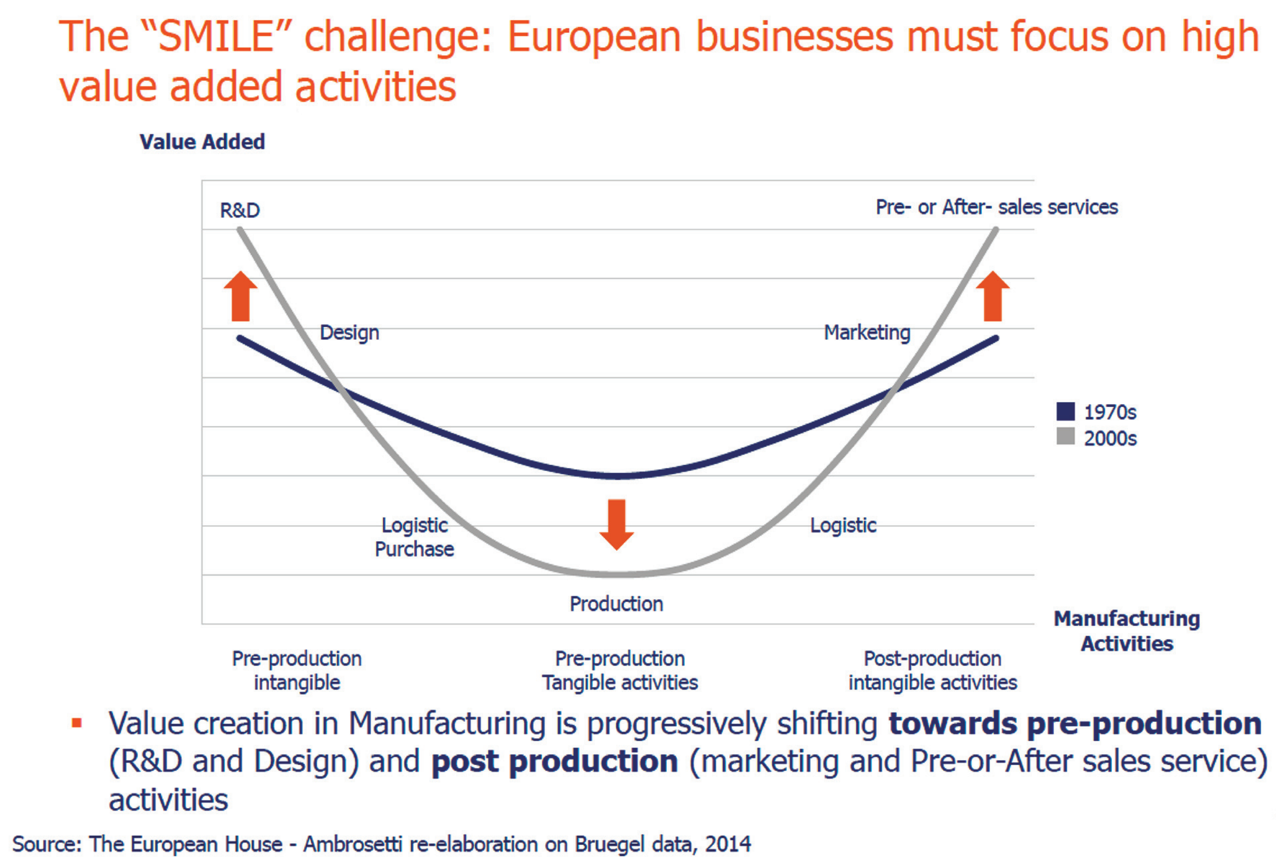

Figure 5.1 Role of ICT in the transformation of manufacturing value chains.

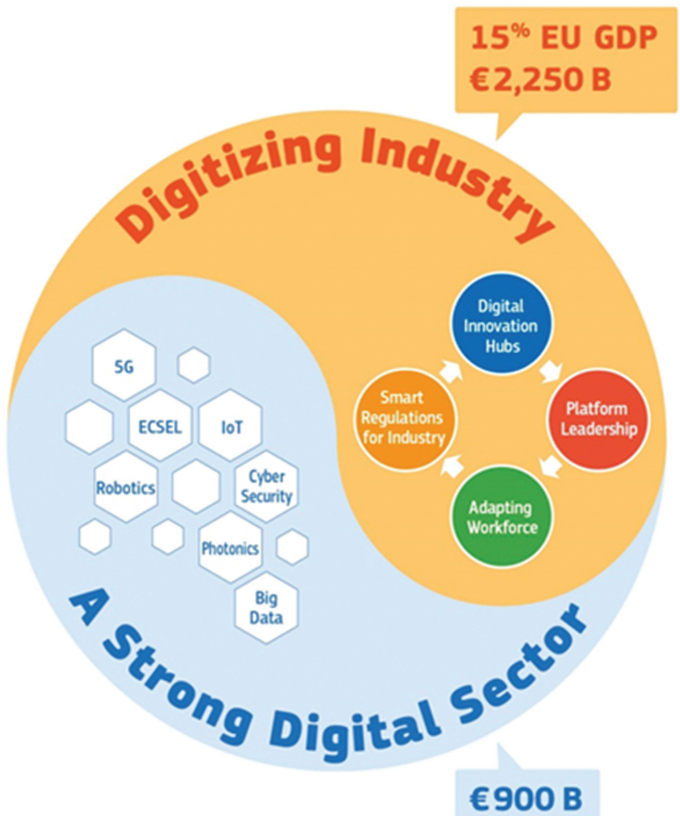

Figure 5.2 Elements of industry digitization according to EU's vision.

Cluster in the next 2–3 years. They will also adhere and support AIOTI WG11 Smart Manufacturing, which is currently chaired by EFFRA (European Factories of the Future Research Association).

The convergence and coordination between IoT-focused projects (supervised by IoT European Platforms Initiative (EPI)) and other DG CNECT initiatives such as the aforementioned FIWARE (FITMAN), many FoF ICT projects such as I4MS BEinCPPS (based also on OpenIoT open source platform) and CPS/SAE initiatives represents the real challenge in the coming years for the IoT for Manufacturing domain of IERC.

In fact, the common research topic to be addressed by all the projects in the area of IoT-driven Digital Manufacturing Value Chains lies in the interrelation between the different aspects of IT (Information Technology, in this

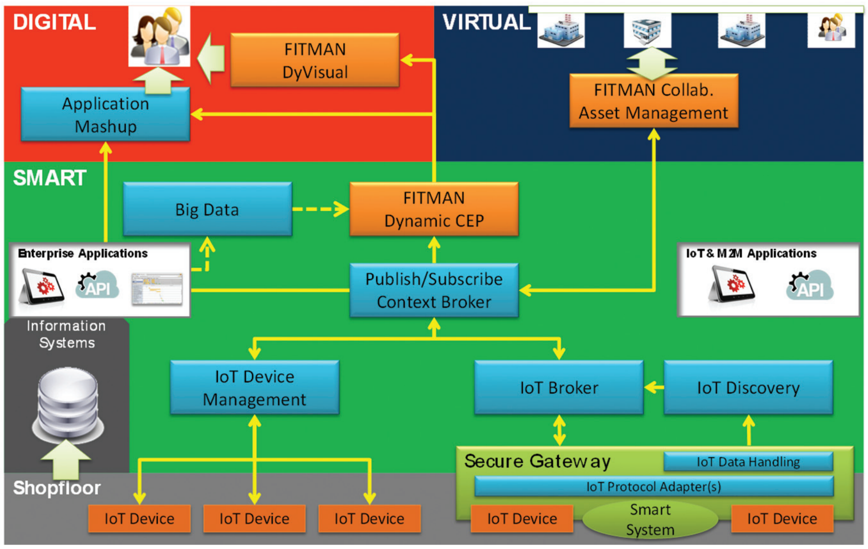

Figure 5.3 FP7 FITMAN and FIWARE projects include several IoT building blocks for digital manufacturing and virtual manufacturing chains.

case represented by IoT and CPS areas) and OT (Operation Technology) technology (in this case represented by Manufacturing Industries): stakeholders, reference architectures, platforms, physical and human resources, innovation and business models.

5.2.3 Levels of Manufacturing Digitisation

The recent EU communication about Digitising EU Industry of April 19th 2016 is exactly addressing this key topic, which is also the key topic for this interest group in IERC. The purpose of this Communication is to reinforce the EU's competitiveness in digital technologies and to ensure that every industry in Europe, in whichever sector, wherever situated, and no matter of what size can fully benefit from digital innovations. The communication aims at overcoming current barriers (e.g. high- vs. low-tech sectors, frontrunners vs. hesitators EU Countries, micro vs. small vs. large multinational enterprises), which prevents all EU manufacturing industries to achieve the following three progressive evolutionary levels of digitalization:

- **Digital Products**: driven by the development of the IoT to smart connected objects, it includes developments of markets like the connected car, wearables or smart home appliances.

- **Digital Processes**: driven by the development of IoT-enabled CPS, it includes Industrie 4.0, the further spread of automation in production and the full integration of simulation and data analytics over the full cycle from product design to end of life (circular economy).
- **Digital Business Models**: driven by service-oriented IoT-based business models, it includes the re-shuffling the value chains and blurring boundaries between products and services with the final aim to increase profitability by up to 5.3% and employment by up to 30% (in 2020).

According to the same EU communication, the achievement of this threefold objective is enabled by Digital Platforms, i.e. initiatives aiming at combining digital technologies, notably IoT, big data and cloud, autonomous systems and artificial intelligence, and 3D printing, into integration platforms addressing cross-sector challenges. In particular, leadership in IoT has recently seen an investment of the Commission in demand-driven large-scale pilots and lighthouse initiatives in areas such as smart cities, smart living environments, driverless cars, wearables, mobile health and agro-food. The investment will address notably open platforms cutting across sectors and accelerate innovation by companies and communities of developers, building on existing open service platforms, such as FIWARE. The accompanying staff-working document on IoT outlines among others standardisation and regulation challenges and opportunities for IoT and the role of the Alliance for IoT Innovations (AIOTI).

The Digitising Industry initiatives are aimed at a pervasive adoption of Information Technologies (IT) into Operations Technologies (OT), so they all implement the IT→OT way to do it. There is another perspective of the same topic (or the other side of the coin): the perspective of Manufacturing Industry, from OT→IT migration journey. This viewpoint is mostly represented by the German Industrie 4.0 and its subsequent EU-wide regional and national initiatives.

5.2.4 Industrie 4.0 Principles for CPS Manufacturing

The key focus of Industrie 4.0 is in the adoption of Cyber Physical Production Systems and in the consequent enablement of IoT and IoS applications (Figure 5.4).

Recently, several analysts identified so called "Industrie 4.0 readiness levels" to help manufacturing industries and especially SMEs to unleash the

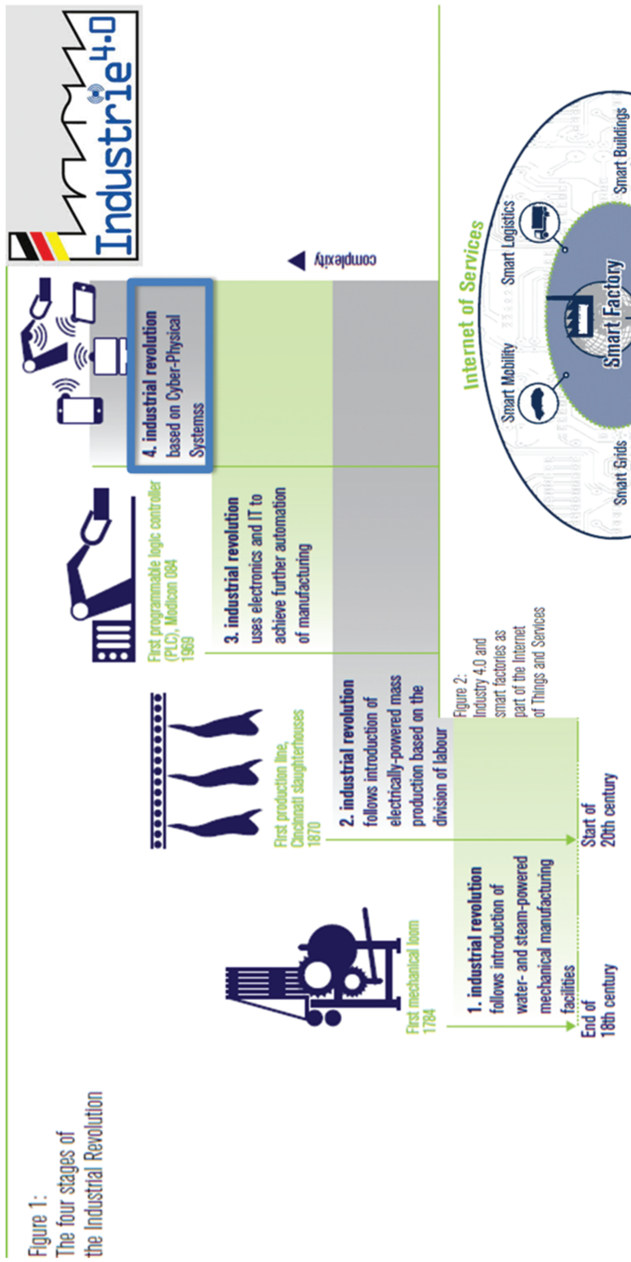

Figure 5.4 Industrial revolution steps: towards industrie 4.0.

full potential of digitalization of products, processes and business processes. In its most recent publications and in its speech at the World Manufacturing Forum 2016 in Barcelona, Max Blanchet, Senior Partner Automotive Industry, Process and Materials, Roland Berger, presented its model and the undoubtable benefits to Manufacturing Industry, deriving from a full adoption of seven key principles:

- From Mass Production to Mass Customisation.
- From volume Scale Effect to localized and flexible Units.
- From planned Make to Stock to dynamic Make to Order.
- From Product to Usage.
- From Cost driven to ROCE (Return on Capital Employed) driven.
- From Taylorism to flexible work organization.
- From hard working conditions to attractive work spaces.

The implementation of these seven principles in the manufacturing industry implies a migration of its resources towards IoT and the new IT.

As underlined before, the main research issue to be addressed in the Collaborative Digital Manufacturing Industry domain is the development of a bi-directional, win-win symbiotic model between IT and OT, in this case between IoT and Manufacturing. In this perspective, Europe is already playing a leading role worldwide in several so-called Key Enabling Technologies (KETs), such as micro- and nano-electronics, nanotechnology, industrial biotechnology, advanced materials, photonics, and advanced manufacturing technologies. When talking about bridging the Valley of Death between Research and Innovation, even at the small scale, such KETs are able per se to achieve a strong and immediate impact. In fact, in the first and second Phases of the I4MS initiative, some high-impact KETs (such as laser, robotics, High Performance Computing (HPC) simulation and CPS) have been and are being successfully transferred to Industry and SMEs in particular via a consistent ecosystem of local, small scale, almost independent champion experiments, grouped in Innovation Hubs. In the KETs domains, Technology Transfer approaches are based on increasing the TRL at the supply side, and on experimented lead-by-example success stories and best practices at the demand side, in order to give evidence to the whole ecosystem of the business benefits achieved. Once the effectiveness of the new KETs has been experimented on the field, the main barriers to their full adoption are mostly economic and financial: where and how to find the relevant resources to cover the sometimes huge investments required.

5.2.5 Digital Manufacturing and IoT Platforms

In terms of IoT, several Reference Architectures and Digital Platforms have been developed in diverse Research and Innovation actions at EU, National and Regional level, with the common aim to digitize manufacturing and logistics collaborative business processes. In the EC-funded FP7 and H2020 landscape, several R&I projects have been funded addressing the digitalization of manufacturing and logistics industries, not just in the Factories of the Future PPP (especially the recent C2Net, CREMA projects about Cloud Manufacturing and the Product Service System cluster), but also in other research environments such as Net Innovation (e.g. FIWARE for Industry, FITMAN and the Sensing Enterprise cluster), Cyber-Physical Systems (e.g. many H2020 ICT1 projects and the Smart Anything Everywhere cluster), IoT (e.g., 2015 Clusterbook of IERC Chapter 5, the AIOTI WG11 Smart Manufacturing and several "IoT for Manufacturing" workshops held at the recent and coming IoT WEEK events), Cloud Computing and Big Data (e.g. FIWARE PPP, IDS and BDVA) and even Technology Enhanced Learning (e.g. the TEL cluster for Manufacturing).

Many of these initiatives have been presented during several workshops organized along 2015 by DG CNECT. In particular, during the workshop of 5–6 October 2015, also initiatives not coming from EC-funded initiatives have been successfully demonstrated and discussed, such as Industry 4.0 RAMI (Reference Architecture Model Industrie 4.0) [1], Virtual Fort Knox, Industrial Data Space and the US Industrial Internet Reference Architecture IIRA. More recently, the newborn BEinCPPS Innovation Action in FoF I4MS phase II is aiming to integrate several of these platforms and to connect them via RAMI reference architecture also to National/Regional initiatives such as Virtual Fort Knox and Industrial Data Space.

However, the flourishing in EU of such an ecosystem of Research-driven IoT driven Platforms has not yet led to a successful and effective digitalization of all the aspects and resources of manufacturing and logistics industries involved in collaborative business processes: this is mainly due to the heterogeneity of the IT supply side (too many technologies and too many reference architectures, impossible to integrate into a common digital platform) and to the heterogeneity of the domains to be addressed and transformed in the Industry demand side (not just production systems, but also organizational, human resources, educational, business and just ultimately IT systems). Is IoT properly addressing the issues of data ownership and IPR management? Is Cloud Manufacturing a real opportunity for all manufacturing business processes, also those to be executed in real time? Have performance and security issues been solved? Is the Industrie 4.0 revolution based on CPPSs easy to be implemented in low-tech SMEs may be located in Eastern EU? If we look at the technological supply side, many of the above issues have been "solved" with advanced ICT solutions, but are the manufacturing industries ready for this revolution? Is there any Digital Platform to support their internal transformations, evolution to the new technologies?

In fact, when speaking of IoT-oriented Digital Platforms unleashing the full potential of collaborative business processes along the whole supply chain of manufacturing and logistics stakeholders, the process of digitizing industry requires complex, multi-domain and multi-disciplinary Large Scale Pilots (LSP) and cannot be effectively supported by simply putting in place mono-directional technology adoption initiatives based on increasing TRLs and Technology Transfer approaches.

In the case of Large Scale Pilots for Digital Platforms, TRLs are in fact not an absolute metric and often are dependent on contextual information, which cannot be ignored, such as size, sector, domain, digital literacy, location of the industries and their supply chains.

Moreover, as already said, often the activation of a huge ecosystem of Technology Transfer experiments is not the most effective option to create impact, in the presence of not well-prepared target industries and with respect to more holistic approaches like the creation of cross-domain interlinked regional ecosystems and Large Scale Pilots.

On the contrary, such a merely technology-driven approach risks to deepen the Digital Divide among industries, by favoring the excellence of leading edge champions, but offering inadequate support to lagging behind and low-tech industries. If not well prepared and conducted just via a mono-directional TRL-based technology transfer approach, Digital Automation risks to sharpen the divide between Eastern-Western EU Countries; between high- and low-tech sectors; between large multinational and local SMEs and mid-caps manufacturing industries.

More recently, in particular inside the AIOTI WG2 Innovation Ecosystem community led by PHILIPS and ELASTICENGINE, a new approach has been proposed: the appropriate way to measure the impact of these early adopter models would have to account for:

- The level of risk;
- The number of potential early adopters;
- Potential to yield data from early adoption; and finally
- The technology readiness.

We call them Market Adoption Readiness Levels (MARLs). This interesting approach for the very first time poses the increase of TRL as just one of the factors (the fourth one) to achieve innovation and not the unique way to impact. However, such an approach is mostly targeting consumer-centric and creative industries and needs substantial improvements and extensions to be applied to manufacturing domain, but in any case it is a quite promising starting point for a holistic approach to digital transformation of EU industry.

5.2.6 Maturity Model for IoT in Manufacturing

As indicated in the following picture, a Manufacturing Adoption Readiness Model:

- A first dimension considers the size and the investment capability of the manufacturing industry and its collaborative supply chain. Sometimes micro enterprises ecosystems are the fastest and most disruptive innovators, but they find difficult to create a real impact in the society, due to scarcity of investments. On the other side, large multi-national industries are seen as champions and archetypes for ICT-driven innovation, but often their migration processes are slow and bureaucratic. Economic feasibility and sustainability is the major maturity criterion addressed in this dimension;
- A second dimension considers the sector and industrial domain and its ICT awareness, where high-tech industries have already familiarity with certain technologies and young talented employees well prepared with respect to digital skills. On the contrary, low-tech industries heavily depend on knowledge and experiences of aging workers and engineers and the migration assumes in many cases the meaning of a generational knowledge transfer. Social sustainability is the major criterion addressed in this dimension.
- A third dimension considers the political and societal environment where the manufacturing supply chain operates. According to the Industry 4.0 readiness quadrant developed by Roland Berger consultants, four clusters of EU Countries could be identified according to two orthogonal variables: the Industry 4.0 readiness index (including degree of automation, workforce skills, innovation intensity and high value-added collaborative value networks) and the manufacturing vs. GDP ratio (the target 20% in 2020 for EU-28 countries according to former Commissioner Tajani's agenda). Hesitators are countries (such as Spain, Portugal and Estonia, plus presumably some EU associated countries like Serbia and Turkey)

with low readiness level and low GDP ratio; Traditionalist Countries (such as Italy, Poland, Croatia, Hungary, Slovenia) have a solid tradition in manufacturing – high GDP ratio – but a low readiness level and penetration of ICT into manufacturing industry; Potentialist Countries (such as UK, France, Denmark and the Netherlands) are good in ICT innovation but their manufacturing industry is not as developed as needed to achieve a deep societal impact; finally Frontrunners Countries (such as Germany, Ireland, Sweden and Austria) are leading edge environments where manufacturing digital innovation and societal impact are both well developed. Political sustainability is the major criterion addressed in this dimension.

A reference architecture for IoT-driven Digital Industry Collaborative Ecosystems could be inspired by the Industrie 4.0 RAMI, where hierarchical levels (from single components, to devices, to the whole connected world) are crossed with abstraction layers (from assets data, to information, to business knowledge) along the lifecycle of product typology and product instances (things lifecycle).

A first dimension of the IoT RAMI (Figure 5.5) (hierarchical technological levels, Y axis) considers technological assets and platforms, where Smart Networks, CPSs, IoT, Cloud, Big Data and Applications Marketplaces are considered.

This dimension is crossed with the second dimension (abstraction layers, Z axis) of the different types of Connected Factory resources involved in the migration processes: production resources, human resources, business resources, organizational resources and IT resources.

The third dimension (lifecycle, X axis) represents the evolution of digitalization patterns from smart products and production shop floors (digital inside, smart connected objects), to intelligent digitized M&L process (shop floor automation, energy optimization, preventive maintenance), to new business opportunities and innovation models (servitisation, sharing and circular economy), enabled by the migration to ICT.

In conclusion, the success of IoT-driven Digital Manufacturing Value Chains (Figure 5.6) depends on the simultaneous and coordinated implementation of a digitising Industry IT→OT roadmap aiming at increasing the TRL of IoT solutions and to extend the number of early adopters and success stories in manufacturing through Large Scale Pilots and of a migration to Industrie 4.0 OT→IT roadmap aiming at evolving manufacturing value chains' resources towards IoT and its technologies, by considering multi-dimensional maturity models and reference architectures derived from RAMI 4.0.

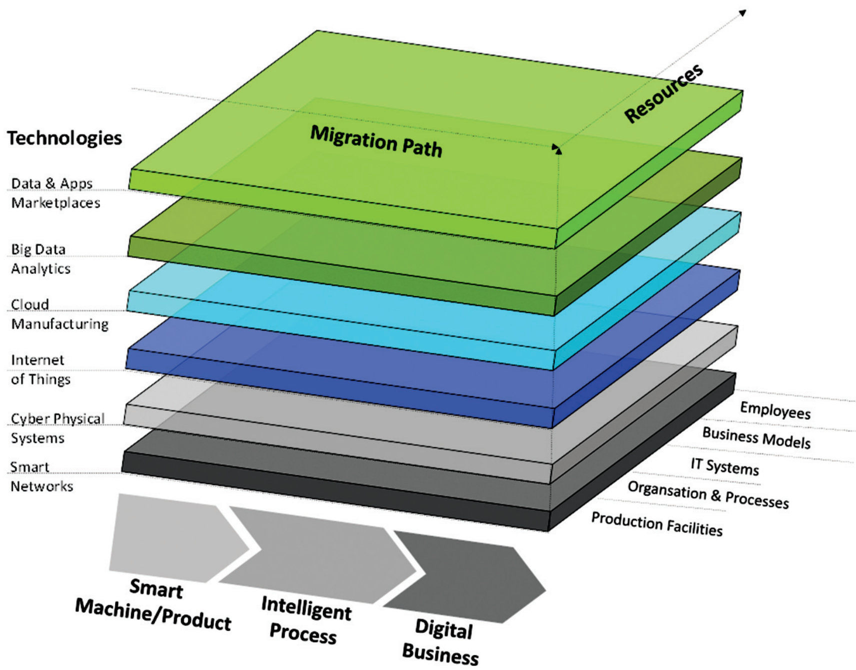

Figure 5.5 Dimensions of the reference architecture model industrie 4.0.

5.3 Digital Factory Automation

5.3.1 Business Drivers

Globalization has created a new and unprecedented landscape changing significantly the way manufacturing companies operate and compete: one of fierce competition, shorter response time to market opportunities and competitor's actions, increased product variations and rapid changes in product demand are only some challenges faced by manufacturing companies of today. As in other domains, production market has deeply felt the effects of globalization on all different layers [2–4]. The increasing demand for new, high quality and highly customized products at low cost and minimum time-to-market delay is radically changing the way production systems are designed and deployed. Success in such turbulent and unpredictable environment requires production systems able to rapidly respond and adapt to changing markets and costumer's needs. To capitalize on the key markets opportunities and winning the competition for markets share, manufacturing companies are caught between the growing needs for:

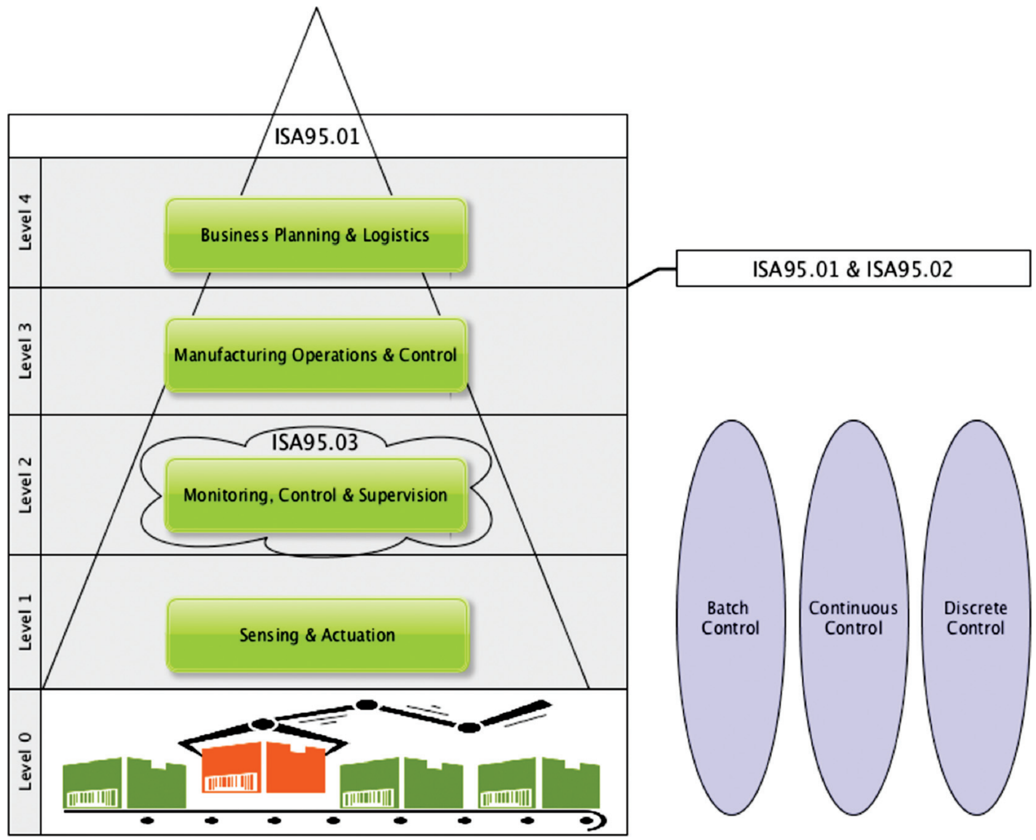

Figure 5.6 Manufacturing company functional hierarchical decomposition according to the ISA-95/IEC62264 standard.

- implementing more and more exclusive, efficient and sustainable production systems to assure a more efficient and effective management of the resources and to produce innovative and appellative customized products as quickly as possible with reduced costs while preserving product quality;
- creating new sources of value by providing new integrated product-service solutions to the customer [5].

In order to meet these demands, manufacturing companies are progressively understanding that they need to be internally and externally agile, i.e. agility must be spread to different and several areas of a manufacturing company from devices data management at shop floor level rising up to business data management while going beyond the individual company boundaries to intra enterprises data management at organization level. Therefore, agility implies being more than simply flexible and lean [6].

Flexibility refers to the ability exhibited by a company that is able to adjust itself to produce a predetermined range of solutions or products [7, 8], while lean essentially means producing without waste [9]. On the other hand, agility relates to operating efficiently in a competitive environment dominated by change and uncertainty [10].

Thus, an agile manufacturing company should be capable to detect the rapidly changing needs of the marketplace and propagate these needs to the lower levels of the company in order to shift quickly among products and models or between products [11]. Therefore, it is a top down enterprise wide effort that supports time-to-market attributes of competitiveness [12].

Thus, to be agile a manufacturing company needs a totally integrated approach i.e. to integrate product and process design, engineering and manufacturing with marketing and sale in a holistic and global perspective. Such holistic and global vision is not properly covered in the manufacturing company of today.

5.3.2 IoT Techniques for the Virtualization of Automation Pyramid

The vision of decentralizing the automation pyramid towards gaining additional flexibility in integrating new technologies and devices, while improving performance and quality is not new. Earlier efforts towards the decentralization of the factory automation systems have focused on the adaptation and deployment of SOA (Service Oriented Architecture) architectures for CPS and IoT devices [13]. However, SOA architectures tend to be heavyweight and rather inefficient for real-time problems, and therefore cannot be deployed in the shopfloor without appropriate enhancements. Furthermore, SOA deployments tend to focus on specific application functionalities and are not suitable for implementing shared situation awareness across all shopfloor applications. In recent years, the advent of edge computing architectures has provided a compelling value proposition for decentralizing factory automation systems, through the placement of data processing and control functions at the very edge of the network. Edge computing is one of the most prominent options for implementing IoT architectures that involve industrial automation and real-time control [14]. Nevertheless, the adoption of decentralized architectures (including edge computing) and IoT/CPS systems from manufacturers remains low for a number of reasons, including:

- **Lack of a well-defined and smooth migration path to distributing and virtualizing the automation pyramid**: The vast majority of manufacturers has heavily invested in their legacy automation architectures and are quite conservative in adopting new technologies, especially given the absence of a concrete and smooth migration path from conventional centralized systems to decentralized factory automation architectures. The virtualization of the automation pyramid could greatly benefit from a phased approach, which will facilitate migration, while also ensuring that the transition accelerates production, improves production quality and results in a positive ROI (Return-on-Investment).
- **IoT/CPS deployments and standards still in their infancy**: IoT/CPS deployments in manufacturing are still in their infancy. They tend to be overly focused on unidirectional data collection from sensors for remote monitoring purposes, while being divorced from the embedded and real-time nature of plant automation problems. At the same time, they tend to ignore the physical aspects of automation i.e. they pay limited emphasis on CPS aspects. Furthermore, despite the emergence of edge/fog computing architecture proposals for manufacturing (e.g., [14]) their implementation is still in its infancy.
- **Lack of shared situational awareness and semantic interoperability**: There is a lack of semantic interoperability across the heterogeneous components, devices and systems that comprise CPS-based automation environments for manufacturing. Distributed IoT/CPS components provide non-interoperable data and services, which is a set-back to creating sophisticated production automation workflows.
- **Lack of open, secure and standards-based platforms for decentralized factory automation**: The distribution of automation functions in the shopfloor is usually implemented on an ad-hoc fashion, which may

not comply with emerging architecture standards (such as the Reference Architecture Model Industrie 4.0). There is a lack of architectural blueprints for decentralized factory automation based on future internet technologies. Furthermore, emerging future internet platforms (such as FIWARE) have a horizontal nature and are not built exclusively for manufacturing domain (e.g., they do not address real-time requirements, complex security requirements and physical processes that characterize the FoF etc).

The advent of edge computing architectures, in conjunction with the emergence of IoT/CPS manufacturing as part of Industrie 4.0, promise to provide solutions for highly scalable distributed control problems which are subject to stringent real-time constraints. In particular, edge computing architectures are appropriate for processing or filtering large amounts of data at the edge of the network, as well as for performing large scale analysis of real-time data [15]. A digital automation platform based on edge computing and IoT technologies in the main objective of the H2020 FAR-EDGE project, which is currently in its contracting stage. This platform will comprise digital models of the plant, based on a proper compilation of reference/models and schemas for the digital representation of factory assets and processes (e.g., IEC-61987), notably reference schemas specified as part of RAMI. The platform will achieve distributed real-time control and semantic interoperability based on the replication and management of the state of the factory at the logical edges of the network and in a trustworthy way. The digital model of the factory and its secure sharing and distribution across the servers of the edge computing architecture will provide a foundation for the development of an operating system for factory automation, which could support a wide range of plant automation and control activities.

5.3.3 CPS-based Factory Simulation

The successful deployment of IoT analytics technologies in the shop floor hinges on the availability of digital datasets suitable for verification and validation of complex behaviors. The availability of such data cannot be taken for granted. The development of simulation services based on appropriate digital representations of plant could alleviate this limitation. Such simulation services need to consider the IoT architecture of the digital automation system along with the digital models of the representation of the plant.

The challenge lies not only to align the simulator with these models, but also to enable their sharing and synchronization across different automation processes.

5.3.4 IoT/CPS Production Workflows – Systems-of-Systems Automation

The next generation of industrial infrastructures are expected to be complex System-of-Systems (SoS) that will empower a new generation of industrial applications and associated services that are actually too hardly to implement and/or too costly to deploy [16]. There are several definition of a SoS in the literature, however, the definition that best fits the considered application context/domain is is the one provided in where SoS are defined as: [17] "*large-scale integrated systems that are heterogeneous and independently operable on their own, but are networked together for a common goal. The goal may be cost, performance, robustness, and so on*". The state-of-the-art industrial automation solutions are known for their plethora of heterogeneous smart equipment encompassing distinct functions, form factors, network interfaces and I/O (Input/Output) specifications supported by dissimilar software and hardware platforms [18]. Such systems are designed, implemented and deployed to fulfill two main objectives:

- To convert raw materials, components, or parts into finished goods that meet a customer's expectations or specifications.
- To perform the conversion effectively and efficiently to guarantee a certain level of performance, robustness and reliability while keeping the costs low.

To do that, coordination, collaboration and, thus, integration and interoperability are extremely critical issues. Several efforts have been made towards the structural and architectural definition and characterization of a manufacturing company and its production management system as pointed in [19]. Among the others, the most popular and still practical applied is the set of definitions embodied into the ISA-95/IEC62264 standard (see Figure 5.6).

According to this standard manufacturing companies and their production systems (process plus factory) are organized into a five level hierarchical model also known as "automation pyramid". Besides this representation, the standard also provides a set of directives and guidelines for manufacturing operations management such as primary and secondary processes, quality assurance, etc. Even if the ISA-95/IEC62264 is the wider used approach for modelling manufacturing companies, nowadays it does not show all the intricacies of the applications, the communication protocols, and – more in general – of the several solutions present at each one of the five levels. Heterogeneity in terms of hardware and software – as well as – data distribution (transmission of information from several signal sources) and information processing are not fully covered by the ISA-95/IEC62264 standard. In fact it defines an information exchange framework to facilitate integration of business applications with the manufacturing control applications within a manufacturing company [20]. However, lower levels of the pyramid are not addressed implying that the automation pyramid – as it is – has significant limitations regarding the increased complexity of modern networked automation systems [21], and – in particular – it has limitations when it is used to support:

a) The integration of new technologies and devices and their lifecycle management;
b) The handling of the information flow along the overall automation pyramid from the lower level to the higher ones (company visibility);
c) The handling of the information flow coming from intelligent devices spread all over the living environment that could be used as fundamental feedback shared inside the automation pyramid.

The a), b), and c) limitations can be easily considered as different perspectives under the main umbrella of system integration research stream. In manufacturing, system integration can be addressed and instantiated at different levels of a company and, thus, with different levels of abstraction according to the context of application [22]. Each level presents a peculiar perspective about integration in general, and data integration in particular. Current technological trends in both industrial and living environments are pushing more and more to the idea of pervasive and ubiquitous computing while offering – at the same time – a huge opportunity to link information sources to information receivers/users. Future internet technologies – such as IoT and CPS – facilitate the deployment of advanced solutions in plant floor, as well as, day to day applications while promoting the meshing of virtual and physical devices and the interconnection of products, people, processes and infrastructures within the manufacturing value chain. The deployment of IoT/CPS-based systems is enabling the creation of a common virtualized space to facilitate the data acquisition process across multiple heterogeneous and geographically distributed data sources while facilitating the collaboration at large scale. It is necessary to comprehend that today's problem is no longer networking (protocols, connectivity, etc.) nor it is hardware (CPU/memory power is already there, at low-cost and low-power consumption) but rather it is on how to link disparate heterogeneous data sources – that are typically acquired from distinct vendors – to the specific needs and interaction forms of applications and platforms.

Designing and operating such complex systems requires from one side the presence of a generic reference model together with models, descriptions, guidance and specifications that can be used as key building blocks for deriving IoT/CPS-based architecture. From the other side, the increasing number of devices with advanced network capabilities is forcing the presence of intelligent middleware and more in general platforms where the whole enterprise is part of and where its internal components/devices can be easily discovered, added/removed/replaced and dynamically (re-)configured according to the business needs during the system operations and especially during the re-engineering interventions [16, 23, 24]. Several research initiatives and/or projects have been conducted to facilitate the interoperability of heterogeneous data sources. The IoT-A (http://www.iot-a.eu) project has addressed the IoT architecture and proposed a reference model as a response to a galaxy of of solutions somehow related to the world of intercommunicating and smart objects. These solutions show little or no interoperability capabilities as usually they are developed for specific challenges in mind, following specific requirements [25]. The Arrowhead (http://www.arrowhead.eu) project is aimed to provide an intelligent middleware/platform that can be used to allow the virtualization of physical machines into services. It includes principles on how to design SOA-based systems, guidelines for its documentation and a software framework capable of supporting its implementations. As a matter of fact, one of the main challenges of the Arrowhead project is the design and development of a framework to enable interoperability between systems that are natively based on different technologies. Most of the specifications are based on the models and outcomes provided by the FP7 IoT-A project.

5.4 IoT Applications for Manufacturing

5.4.1 Proactive Maintenance

As stated in [26], maintenance activities and procedures are always on high pressure from the top management levels of a manufacturing company to guarantee cost reduction while keeping the perfect working conditions of the machines and equipment installed in a production system, and in order to assure a certain degree of continuity in the productive process and – at the same time – the safety of the people that are part of it.

To do that, several policies and strategies for maintenance have been defined, developed and adopted, namely:

- Corrective Maintenance (CM);
- Preventive Maintenance (PM);

- Predictive Maintenance (PdM); and
- Proactive Maintenance (PrM).

In fact, maintenance owes its development essentially to the industrial progress in the recent centuries and to the growing need for manufacturing companies to be competitive [27].

Corrective Maintenance also called Run-to-failure reactive maintenance is the oldest policy and envisions the repair of a failure whenever it happens. It implies that a plant using run-to-failure management does not spend any money on maintenance until a machine or system fails to operate [28].

Preventive Maintenance is a time-driven policy and envisions the advanced definition of the time of intervention in order to anticipate the failure of complex system [27]. In preventive maintenance management, machine repairs or rebuilds are scheduled based on the mean time to failure (MTTF) statistic [28].

Predictive Maintenance also called condition-based maintenance is a policy that envisions the regular monitoring of machine and equipment conditions to understand their operating condition and schedule maintenance interventions only when they are really needed. In predictive maintenance management, machine repairs and/or rebuilds – i.e. maintenance interventions – are programmed in real-time avoiding unforeseen downtimes and their related implications [27]. As stated in [28]: Predictive maintenance is a philosophy or attitude that, simply stated, uses the actual operating condition of plant equipment and systems to optimize total plant operation. Finally, proactive maintenance is a totally policy that is not "failure" oriented like the others. As a matter of fact, proactive maintenance envisions not the minimization of the machine/equipment downtime but the continuous monitoring of the machine and equipment conditions with the main objective of identifying the root causes of a possible failure and/or machine breakdown and proactively schedule maintenance intervention to correct the abnormal values of the root causes. Thus, in proactive maintenance policy the minimization of the downtime is only the consequence of a strategy that is aimed to improve the machine/equipment health during its lifecycle and to assure overall high production system productivity, reliability, robustness while paradoxically reducing the number of maintenance intervention [29]. Proactive maintenance is a necessary state in the main path to effective maintenance. It has not been thought as an alternative to predictive maintenance but as a complementary approach to predictive maintenance in the direction of effective maintenance.

The successful implementation of proactive maintenance strategies strictly depends on the availability of an efficient and effective monitoring infrastructure that can gather relevant operational data from the machine/equipment combine and analyze this data to identify possible breakdowns and their root causes. However, current industrial monitoring and control solutions are extremely "bit-oriented" making hard and painful the process of predicting failures and detecting root causes. However, manufacturing companies are betting on the application of intelligent and more integrated monitoring and control solution to reduce maintenance problems, production line downtimes and reduction of production line operational costs while guarantying a more efficient management of the manufacturing resources [30].

In this context, IoT/CPS technologies can enable the design and development of advanced monitoring strategies and thus maintenance policies by adding additional monitoring capabilities to industrial machines and equipment providing in such a way the following functionalities:

- **Integration of secondary processes within the main control**: IoT/CPS based technologies can be deployed in order to provide more data about machine and equipment during their operation. Such information can be used to model the machine/equipment behavior for the sake of failures/breakdowns detection;
- **Modernization of low-tech production systems**: IoT/CPS based technologies can be deployed in low-tech production processes, i.e. production processes that are not natively ready for industry 4.0, and make them industry 4.0 compatible.
- **IT/OT Integration**: IoT/CPS technologies can easily provide data to all the layers of the automation pyramid enabling a true cross-layer integration.
- **Maintenance engagement**: IoT/CPS technologies can enable a better engagement of the maintenance department in the health of the overall production system.

5.4.2 Mass Customisation

The deployment of IoT technologies in virtual manufacturing chains and decentralized factory automation systems enables reduction of the production batch side and facilitates mass-customization. IoT devices can be deployed across the supply chain (e.g., even at retail locations) in order to obtain insights on customers' preferences. At the same time, the flexible integration of new technologies (such as stations, sensors and devices) facilitates the reduction of the batch size. Overall, IoT supports mass-customization across all points of the supply chain.

5.4.3 Reshoring

Decentralized IoT-based factory automation can enable European manufacturers to re-shore activities from low-labour countries back to the EU, which could have a positive impact on both employment and GDP (Gross Domestic Product). In particular, IoT enables reshoring through facilitating integration with advanced manufacturing technologies (e.g., IoT, 3D printing, robots, etc.) thus rendering manufacturing a far less labour intensive process. In this way, IoT enables a shift of manufacturing from low labour locations to locations with higher proximity to demand and innovation, which are the factors that will determine future locations for manufacturing.

5.4.4 Safe Human Workplaces and HMIs

The scope of Industrie 4.0 includes the dynamic adaptation, reconfiguration and streamlining of manufacturing processes. This reconfiguration occurs in response to variations in demand, while taking into account the status of the plant floor (e.g., machines, tools, control systems) in order to optimize the production workflow. Nevertheless, such adaptive and reconfigurable processes tend to neglect the human factor, given that they do not adequately take into account the employees' profile characteristics (such as age, disability, gender and skills). For example, RAMI, does not make any provisions for managing workforce profiles and human-centred processes. Likewise, Industrie 4.0 roadmaps are overly focused on technological issues and pay less attention on the ever important human and social factors (e.g., requirements for human-centred manufacturing). Overall, factory workers (include elderly and disabled workers) are still expected to fully adapt to the operations of machines and automation systems, even in cases of manufacturing workplaces with poor ergonomics.

In order to address these limitations, there is a need to devise technologies and processes that could invert the above loop i.e. put factory automation in the human workforce loop. Such technologies and processes could lead to a number of important benefits for manufacturers and for the society as whole, including: (A) Optimal integration among human and technical resources towards enhancing workforce performance and satisfaction; (B) Confronting the manufacturing skills gap; (C) Leveraging those individual worker capabilities that are most advantageous to the manufacturing process, while addressing important social factors (e.g., ageing and/or other handicapped groups) and ensuring health and safety at work; (D) Introduction of new flexible models of work and organization. Overall, there is a clear need for blending leading edge production automation technologies with state-of-the-art methodologies for human-centred processes and workplaces, including techniques for the adaptation of the physical workplace to the workers' characteristics and skills.

IoT technologies can enable manufacturers to support advanced ergonomics and novel models of work and organization through providing support for the following functionalities:

- **Human-centred production scheduling (notably in terms of workforce allocation)**: IoT technologies (such as RFID tags) can be deployed in order to provide access to the users' profile and context, thus enhancing conventional techniques for distributing tasks among workers in order to take into account the (evolving) profile and capabilities of the worker, including his/her knowledge, skills, age, disabilities and more.
- **Workplace Adaptation**: IoT devices such as sensors and PLCs (Programmable Logic Controllers) can provide the means for adapting the factory workplace operation and physical configuration (i.e. in terms of automation levels and physical world devices' configuration) to the characteristics, needs and capabilities of the workers, with a view to maximizing their performance and the overall productivity of the plant, while also maximising worker satisfaction.
- **Worker's engagement in the adaptation process**: IoT technologies can enable the comparison of the performance of a worker in a given task with the corresponding performance of skilled workers, in order to fine-tune the task distribution and workplace adaptation processes. Feedback on the performance of workers will be derived based on RFID tags and wearable devices, which can provide information about the workers stress, fatigue, sleepiness, and more.
- **Enhanced Workers' Safety and Well-Being**: The deployment and use of IoT wearables (such as Fitbit devices) can enable the tracking of the workers' activity levels. Fitbit data can be accordingly used to enhanced workers' safety and reduce healthcare and insurance costs for the manufacturers.

5.5 Future Outlook and Conclusions

5.5.1 Outlook and Directions for Future Research and Pilots

Previous paragraphs have presented a range of IoT technologies that can be used for streamlining manufacturing operations and for decentralizing factory automation. Despite the development of these technologies, there are still technological challenges especially in the following areas:

- **Security and Privacy**: IoT data in the shop floor varies in terms of volume and velocity, while including structured, unstructured and semi-structured data sources. At the same time, IoT deployments in manufacturing comprise multiple devices, which must be secured on the network. Holistic multi-layer approaches to security are therefore required in order to ensure safeguarding of personal data and control over the flow and exchange of sensitive information across the manufacturing chains and/or the shopfloor industrial network.
- **BigData Analytics**: Manufacturers need to convert data into actionable insight. Given the large volume of data, this is a significant challenge. The generation of business critical insights based on these data is still in its infancy, since data stemming from the manufacturing environment tends to be largely underutilized.
- **Adoption of Edge Computing**: Novel factory automation architectures have been largely based on the SOA and Intelligent Agents paradigm, in-line with standards such as the IEC 61499 Function Block. Emerging edge computing architectures have distinct advantages for the implementation of decentralized architectures, yet they have not been widely deployed yet.
- **Need for Standards-based Reference Implementations**: Recently, standards based organizations (such as the industrial Internet Consortium) have produced reference architectures for industrial automation and the integration of digital enterprise systems in the manufacturing chain. The provision of reference implementation of these standards will pave the way for their wider adoption and sustainable use by manufacturers.

Beyond the need to address these technical challenges, there is also a need for large-scale pilot deployments, which will combine several of the applications outlined in the previous section, in a way that considers their interactions and synergies. For example, proactive maintenance can give rise to effective production (re)scheduling, which could be also driven by information about customer demands (received via IoT devices). Likewise, IoT supported supply chain operations can drive the reconfiguration of production recipes, along with the scheduling of production. Moreover, the development of human centric workplaces requires the blending of adaptive human-centric processes (including appropriate HMIs (Human Machine Intefaces)) into IoT based factory automation architectures. Up to date, pilot deployments have been addressing only a fraction of the above listed applications, without a systematic consideration of their interactions under the prism of a standards-based reference implementation.

In addition to integrated pilots, large scale secure and privacy friendly deployments need to be evaluated in terms of quality, time and cost. Manufacturers need tangible evidence and benchmarks about IoT's ability to lead to improvements across these three axis, in order to provide a compelling proposition for adoption.

5.5.2 Conclusions

In this chapter, we have presented how IoT can transform manufacturing towards aligning to emerging trends such as proximity sourcing, support for flexible production models, human-centred manufacturing and more. We have also illustrated tangible deployments of IoT technologies based on recent FP7 and H2020 projects, notably projects focusing on the factories of the future. Despite these deployments, both technology and operational challenges exist. Reference implementation of standards compliant architectures for digital manufacturing based on IoT technologies could successfully address these challenges. Likewise, large-scale pilots combining the benefits of IoT deployments could also boost the confrontation of both technological and business/operational challenges.

Bibliography

[1] Vdi Vde Gesellschaft Mess und Automatisierungstechnik, Reference Architecture Model Industrie 4.0 (RAMI4.0), July 2015.
[2] D. F. Noble, Forces of Production: A Social History of Industrial Automation. Transaction Publishers, 2011.
[3] R. Narula, Globalization and Technology: Interdependence, Innovation Systems and Industrial Policy. Wiley, 2003.
[4] T. Levitt, "The globalization markets," The MITPress, vol. 249, 1993.
[5] S. Cavalieri and G. Pezzotta, "Product–Service Systems Engineering: State of the art and research challenges," Comput. Ind., vol. 63, no. 4, pp. 278–288, May 2012.

[6] G. Candido, “Service-oriented Architecture for Device Lifecycle Support in Industrial Automation,” FCT-UNL, 2013.
[7] A. K. Sethi and S. P. Sethi, “Flexibility in manufacturing: A survey,” Int. J. Flex. Manuf. Syst., vol. 2, no. 4, pp. 289–328, Jul. 1990.
[8] Y. P. Gupta and S. Goyal, “Flexibility of manufacturing systems: Concepts and measurements,” Eur. J. Oper. Res., vol. 43, no. 2, pp. 119–135, Nov. 1989.
[9] S. S. Shah, E. W. Endsley, M. R. Lucas, and D. M. Tilbury, “Reconfigurable logic control using modular FSMs: Design, verification, implementation, and integrated error handling,” in American Control Conference, 2002. Proceedings of the 2002, 2002, vol. 5, pp. 4153–4158 vol. 5.
[10] S. L. Goldman, R. N. Nagel, and K. Preiss, Agile competitors and virtual organizations: strategies for enriching the customer. Van Nostrand Reinhold, 1995.
[11] Y. Y. Yusuf, M. Sarhadi, and A. Gunasekaran, “Agile manufacturing: The drivers, concepts and attributes,” Int. J. Prod. Econ., vol. 62, no. 1, pp. 33–43, 1999.
[12] P. Noaker, The Search for Agile Manufacturing. 1994.
[13] Spiess, P., Karnouskos, S., Guinard, D., Savio, D., Baecker, O., Souza, L. M. S. D., & Trifa, V. (2009, July). “SOA-based integration of the internet of things in enterprise services”, IEEE International Conference on Web Services, ICWS 2009. (pp. 968–975).
[14] Industrial Internet Consortium. Industrial Internet Reference Architecture, June 2015.
[15] G. Orsini, D. Bade, W. H. Lamersdorf. Computing at the Mobile Edge: Designing Elastic Android Applications for Computation Offloading. 8th IFIP Wireless and Mobile Networking Conference (WMNC 2015), Munich, Germany, 2015.
[16] A. Colombo, T. Bangemann, S. Karnouskos, J. Delsing, P. Stluka, R. Harrison, F. Jammes, and J. L. Lastra, Eds., Industrial Cloud-Based Cyber-Physical Systems: The IMC-AESOP Approach, 2014 edition. New York: Springer, 2014.
[17] M. Jamshidi, System of Systems Engineering: Innovations for the Twenty-First Century. Wiley, 2009.
[18] G. Candido, C. Sousa, G. Di Orio, J. Barata, and A. W. Colombo, “Enhancing device exchange agility in Service-oriented industrial automation,” in 2013 IEEE International Symposium on Industrial Electronics (ISIE), 2013, pp. 1–6.

[19] T. Bangemann, S. Karnouskos, R. Camp, O. Carlsson, M. Riedl, S. McLeod, R. Harrison, A. W. Colombo, and P. Stluka, "State of the Art in Industrial Automation," in Industrial Cloud-Based Cyber-Physical Systems, A. W. Colombo, T. Bangemann, S. Karnouskos, J. Delsing, P. Stluka, R. Harrison, F. Jammes, and J. L. Lastra, Eds. Springer International Publishing, 2014, pp. 23–47.

[20] M. Dassisti, H. Panetto, A. Tursi, and M. De Nicolo, "Ontology-based model for production-control systems interoperability," 2008.

[21] G. Pratl, D. Dietrich, G. P. Hancke, and W. T. Penzhorn, "A New Model for Autonomous, Networked Control Systems," IEEE Trans. Ind. Inform., vol. 3, no. 1, pp. 21–32, Feb. 2007.

[22] L. M. Camarinha-Matos and H. Afsarmanesh, "Brief Historical Perspective for Virtual Organizations," in Virtual Organizations, L. M. Camarinha-Matos, H. Afsarmanesh, and M. Ollus, Eds. Springer US, 2005, pp. 3–10.

[23] A. W. Colombo and S. Karnouskos, "Towards the factory of the future: A service-oriented cross-layer infrastructure," ICT Shap. World Sci. View Eur. Telecommun. Stand. Inst. ETSI John Wiley Sons, vol. 65, p. 81, 2009.

[24] J. Barata, Coalition Based Approach For ShopFloor Agility. Amadora – Lisboa: Orion, 2005.

[25] IoT-A, "Initial Architectural Reference Model for IoT," D1.2, Jun. 2011.

[26] G. Palem, "Condition-based Maintenance Using Sensor Arrays and Telematics," Int. J. Mob. Netw. Commun. Telemat. IJMNCT, vol. 3, no. 3, Jun. 2013.

[27] L. Fedele, Methodologies and Techniques for Advanced Maintenance. Springer-Verlag London Limited, 2011.

[28] K. Mobley, An Introduction to Predictive Maintenance. Elsevier Science Ltd, 2002.

[29] J. Levitt, Complete Guide to Preventive and Predictive Maintenance. Industrial Press Inc., 2011.

[30] G. Di Orio, "Adapter module for self-learning production systems," FCT-UNL, 2013.