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Introduction to Industry 4.0 and the Digital Shopfloor Vision

John Soldatos

Kifisias 44 Ave., Marousi, GR15125, Greece
E-mail: jsol@ait.gr

This chapter is an introduction to the fourth industrial revolution (Industry 4.0) in general and digital automation platforms in particular. It illustrates the main drivers behind Industry 4.0 and presents some of the most prominent use cases. Accordingly, it introduces the scope and functionalities of digital automation platforms, along with digital technologies that enable them. The chapter ends by introducing the vision of a fully digital shopfloor, which sets the scene for understanding the platforms and technologies that are presented in subsequent chapters.

1.1 Introduction

In the era of globalization, industrial organizations are under continuous pressure to innovate, improve their competitiveness and perform better than their competitors in the global market. Digital technologies are one of their most powerful allies in these efforts, as they can help them increase automation, eliminate error prone processes, enhance their proactivity, streamline their business operations, make their processes knowledge intensive, reduce costs, increase their smartness and overall do more with less. Moreover, the technology acceleration trends provide them with a host of opportunities for innovating in their processes and transforming their operations in a way that results not only in marginal productivity improvements, but rather in a disruptive paradigm shift in their operations. This is the reason why many industrial organizations are heavily investing in the digitization of their processes as part of a wider and strategic digital transformation agenda.

In this landscape, the term Industry 4.0 has been recently introduced. This introduction has signalled the "official" start of the fourth industrial revolution, which is based on the deployment and use of Cyber-Physical Systems (CPS) in industrial plants, as means of fostering the digitization, automation and intelligence of industrial processes [1]. CPS systems facilitate the connection between the physical world of machines, industrial automation devices and Operational Technology (OT), with the world of computers, cloud data centres and Information Technology (IT). In simple terms, Industry 4.0 advocates the seamless connection of machines and physical devices with the IT infrastructure, as means of completely digitizing industrial processes.

In recent years, Industy 4.0 is used more widely, beyond CPS systems and physical processes, as a means of signifying the disruptive power of digital transformation in virtual all industries and application domains. For example, terms like Healthcare 4.0 or Finance 4.0 are commonly used as derivatives of Industry 4.0. Nevertheless, the origins of the term lie in the digitization of industrial organizations and their processes, notably in the digitization of factories and industrial plants. Note also that in most countries Industry 4.0 is used to signify the wider ecosystem of business actors, processes and services that underpin the digital transformation of industrial organizations, which makes it also a marketing concept rather than strictly a technological concept.

The present book refers to Industry 4.0 based on its original definition i.e. as the fourth industrial revolution in manufacturing and production, aiming to present some tangible digital solutions for manufacturing, but also to develop a vision for the future where plant operations will be fully digitized. However, it also provides insights on the complementary assets that should accompany technological developments towards successful adoption. For example, the book presents concrete examples of such assets, including migration services, training services and ecosystem building efforts. This chapter serves as a preamble to the entire book and has the following objectives:

- To introduce the business motivation and main drivers behind Industry 4.0 in manufacturing. Most of the systems and technologies that are presented in this book are destined to help manufacturers confront such business pressures and to excel in the era of globalization and technology acceleration.

- To present some of the main Industry 4.0 use cases in areas such as industrial automation, enterprise maintenance and worker safety. These use cases set the scene for understanding the functionalities and use of the platforms that are presented in this book, including use cases that are not explicitly presented as part of the subsequent chapters.
- To illustrate the main digital technologies that enable the platforms and technologies presented in the book. Note that the book is about the digitization of industrial processes and digital automation platforms, rather than about IT technologies. However, in this first chapter, we provide readers with insights about which digital technologies are enabling Industry 4.0 in manufacturing and how.
- To review the state of the art in digital automation platforms, including information about legacy efforts for digitizing the shopfloor based on technologies like Service Oriented Architectures (SOA) and intelligent agents. It's important to understand how we got to today's digital automation platforms and what is nowadays different from what has been done in the past.
- To introduce the vision of a fully digital shopfloor that is driving the collaboration of research projects that are contributing to this book. The vision involves interconnection of all machines and complete digitization of all processes in order to deliver the highest possible automation with excellent quality at the same time, as part of a cognitive and fully autonomous factory. It may take several years before this vision is realized, but the main building blocks are already set in place and presented as various chapters of the book.

In-line with the above-listed objectives, the chapter is structured as follows:

- Section 2 presents the main business drivers behind Industry 4.0 and illustrates some of the most prominent use cases, notably the ones with proven business value;
- Section 3 discusses the digital technologies that underpin the fourth industrial revolution and outlines their relation to the systems that are presented in the latter chapter;
- Section 4 reviews the past and the present of digital automation platforms, while also introducing the vision of a fully digital shopfloor;
- Section 5 is the final and concluding section of the chapter.

1.2 Drivers and Main Use Cases

The future of manufacturing is driven by the following trends, which stem from competitive pressures of the globalized environment:

- **New production models and mass customization**: Manufacturers are increasingly seeking ways of producing more customized products that are tailored to customer needs. As a result, there is a shift from mass production to mass customization. Likewise, conventional Made-to-Stock production models are giving their place to more customized ones such as Made-to-Order, Configure-to-Order and Engineering-to-Order.
- **Production Reshoring**: Globalization has led to the off-shoring of production operations for the places of innovation to low-labour countries. This was typically the case with several Western countries (including the USA (United States of America) and many EU (European Union) countries), which opted to keep the innovative design processes at home, while outsourcing manufacturing and production operations to Eastern countries (e.g., China, India). In recent years, several organizations are working towards reversing this trend through moving production processes back to the place of innovation, which is commonly called reshoring as opposed to off-shoring. Increased automation is a key enabler of reshoring strategies as it reduces the significance of the labour cost in the overall production process.
- **Proximity Sourcing**: Manufacturers are also employing proximity sourcing strategies as an element of their competitiveness. These strategies strive to ensure that sourcing is performed in close proximity to the plant that will use the source materials. This requires intelligent management of information about supply chain and logistics operations, which is also a main driver of the Industry 4.0.
- **Human-centred manufacturing**: Workers remain the major asset of the production process, yet a shift from laborious tasks to more knowledge intensive tasks is required. In addition to supporting other trends (such as mass customization and reshoring) this can be a key to improving workers' engagement, safety and quality of life. The digitalization of industrial processes obviates the need for laborious error-prone tasks and provides opportunities for improving workers' knowledge about the production processes. Hence, it's a key for placing the worker at the centre of the knowledge-intensive shopfloor and for transitioning to human centred processes.

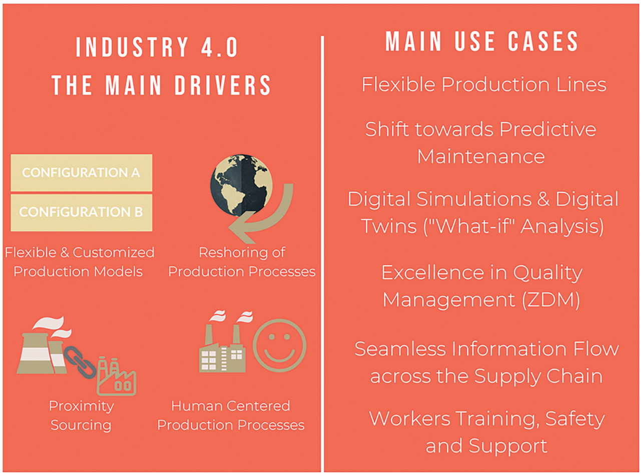


Figure 1.1 Main drivers and use cases of Industry 4.0.

The deployment of CPS systems in the shopfloor enables the seamless collection of digital data about all production processes, which increases the agility of automation operations, enabling the acquisition of knowledge about processes and facilitates optimal decision making. At the same time, CPS systems are able to initiate and execute digitally driven operations in the shopfloor. Coupled with digital technologies that are described in the next section, CPS systems can deliver endless possibilities for automation, optimizations and complete restructuring of industrial processes.

The fourth industrial revolution has an horizon of several decades, where it will deliver its full potential based on the interconnection all machines and OT systems, but also based on the employment of the ever evolving digital technologies such as Artificial Intelligence (AI), Big Data and the Industrial Internet of Things (IIoT). Nevertheless, during the first years of the Industry 4.0 movement, manufacturers have successfully deployed and validated the first set of use cases, which can directly deliver quick wins and business value. These use cases span the following areas:

- **Flexibility in Automation Architectures and Configuration:** Agility and flexibility in automation are key prerequisites for the transition to the range of future production models that enable mass customization. These models ask for flexibility in the way each individual product is produced, effectively reducing production lot to size one. In this context, digital technologies can be used to change the configuration of production lines at the digital/IT rather than at the physical/OT layer of production systems, yielding the configuration of a production line much faster and much more flexible. Hence, digitally transformed productions lines are able to produce products with different (rather than fixed) configurations.

- **Shift towards Predictive Maintenance:** Nowadays, most industrial organizations are employing preventive maintenance in order to avoid the catastrophic consequences of unplanned downtime and unscheduled maintenance. Hence, they replace tools and parts, at regular intervals before their estimated End of Life. Even though preventive maintenance techniques are much more effective than reactive maintenance, they are still far from delivering optimal Overall Equipment Efficiency (OEE), as they tend to perform maintenance earlier than actually required. Digital technologies and Industry 4.0 hold the promise to facilitate a transition to predictive maintenance that will enable the accurate prediction of parameters such as the End-of-Life (EoL) and the Remaining Useful Life (RUL) of machines and their parts, as a means of optimizing OEE, minimizing unscheduled downtimes and scheduling maintenance and repairs at the best point in time. Predictive maintenance is usually based on the collection and analysis of large digital datasets about the condition of the equipment, such as data from vibration, acoustic and ultrasonic sensors, data from thermal images, power consumption data, oil analysis data, data from thermal images, as well as quality data from enterprise systems. As such predictive maintenance is a classical Big Data and Artificial Intelligence problem in the industry, which is relevant not only in manufacturing, but also in other industrial sectors such as energy, mining, oil & gas and more.
- **Quality Management Excellence and Zero Defect Manufacturing (ZDM):** The advent of CPS systems and Industry 4.0 will enable manufacturers to collect large datasets about their processes, including data about the physical aspects of these processes. Equipment maintenance data is one example of such datasets. Other examples include datasets about the quality of the operations and of the resulting products, supply chain indicators, data about the quality of the source materials, data about the accuracy and consistency of assembly processes and more. By consolidating and analysing these datasets, manufacturers will be in a position to optimize their quality management processes and to meet stringent goals set from their quality management standards such

as SixSigma and Total Quality Management (TQM). Early quality management and predictive maintenance deployments that take advantage of CPS systems provide such evidence. Moreover, the expanded digitalization of the shopfloor will in the future enable the proactive identification of defect causes, as well as the activation of related remedial actions on the fly, as means of achieving the vision of Zero Defect Manufacturing (ZDM). Likewise, digital technologies will facilitate the implementation of continuous improvement disciplines, through continuous collection of data and the employment of self-learning systems that continually improve themselves based on past data and evidence. Overall, in the Industry 4.0 era, manufacturers will become able to implement more efficient and cost-effective ZDM processes, while lowering the barriers of transition from current approach to quality management excellence.

- **Digital Simulations and Digital Twins:** Industrial processes are generally inflexible given that it is practically impossible to cancel or undo an action once the latter has taken place in the shopfloor. Therefore, it's extremely difficult to test and validate alternative deployment configurations without disrupting production. Digital simulations provide the means of circumventing field testing, through using digital data for what-if analysis at the digital world and without a need of testing all scenarios in the field. Industry 4.0 technologies empower much more reliable and faster digital simulations, based on the use of advanced technologies for the collection, consolidation and analytics of very large datasets. Moreover, the Industry 4.0 era will be characterized by the wider use of a new disruptive concept i.e. the concept of a "digital twin". A digital twin is a faithful digital representation of a physical entity, which is built based on the development of a proper digital model for the physical item and the subsequent collection of a host of digital data about the item, in-line with the specified model. The design of a digital twin can be very challenging as a result of the need to consolidate the physical properties of an item, its behaviour, aspects of the processes where it is used and business aspects regarding its use in a single model. Digital twins provide plant operators and automation solution providers with the means of running credible simulations in the digital world, prior to deploying new automation ideas and algorithms in the physical world. In several cases, digital twins' instances can be connected and fully synchronized with their physical item counterparts as a means of configuring systems and processes at the IT rather than the OT layer of the Inudstry4.0 systems. As already outlined, this can greatly facilitate automation flexibility, as well.

- **Seamless and accurate information flows across the supply chain:** For over two decades, enterprises are heavily investing in the optimization of their supply chain operations, as a core element of their competitiveness. Supply chain management has always been a matter of properly acquiring, exchanging and managing information across the manufacturing chain, based on information sources and touch points of all supply chain stakeholders. Industry 4.0 comes to disrupt this information management, through adding an important element that was typically missing in traditional supply chain management: The information about the status of the physical world, such as the status of machines, equipment, processes and devices. Indeed, the advent of CPS systems and Industrial Internet of Things technologies enable the integration of this information across the supply chain. Furthermore, CPS systems and Industry 4.0 provide the means of influencing the status of the physical processes across the supply chain, in addition to changing the status of business information systems [e.g., production schedules in an Enterprise Resource Planning (ERP) system or materials information in a Warehouse Management System (WMS)]. This gives rise to disruptive supply chain innovations, which result in increased automation, less errors, increased efficiency and reduced supply chain costs.
- **Worker Training, Safety and Well Being:** Industry 4.0 emphasizes the importance of keeping employees engaged and at the centre of industrial processes, while alleviating them from the burden of laborious, tedious and time-consuming tasks. In this direction, several Industry 4.0 use cases entail the deployment of advanced visualization technologies such as ergonomic dashboards, Virtual Reality (VR) and Augmented Reality (AR) in order to ease the workers' interaction with the digital shopfloor and its devices. Note that AR and VR are extensively used in order to train employees under safe conditions i.e. through interaction with cyber representations of the physical equipment and/or with remote guidance from experienced colleagues or other experts. Likewise, wearables and other pervasive devices are extensively deployed in order to facilitate the tracking of the employee in the shopfloor towards ensuring that he/she works under safe conditions that do not jeopardise his/her well-being.

While the presented list of use cases is not exhaustive, it is certainly indicative of the purpose and scope of most digital manufacturing deployments in recent years. Later chapters in this book present practical examples of Industry 4.0 deployments that concern one or more of the above use cases. However, we expect that these use cases will gradually expand in sophistication as part of the digital shopfloor vision, which is illustrated in a following section of this chapter. Moreover, we will see the interconnection and interaction of these use cases as part of a more cognitive, autonomous and automated factory, where automation configuration, supply chain flexibility, predictive maintenance, worker training and safety, as well as digital twins co-exist and complement each other.

1.3 The Digital Technologies Behind Industry 4.0

Industry 4.0 is largely about the introduction of CPS systems in the shopfloor, in order to digitally interconnect the machines and the OT technology with IT systems such as Enterprise Resource Planning (ERP), Computerized Maintenance Management (CMM), Manufacturing Execution Systems (MES) and Customer Relationship Management (CRM), Supply Chain Management (SCM) systems. Based on CPS systems, the entire factory or plant can become a large scale CPS system that employs Industrial Internet of Things (IIoT) protocols and technologies for data collection, processing and actuation. In practice, an Industry 4.0 deployment takes advantage of multiple digital technologies in order to endow the digital automation systems with intelligence, accuracy and cost-effectiveness. Hence, Industry 4.0 is largely propelled by the rapid evolution of various digital technologies, which enable most of the use cases listed above. For example, predictive maintenance is greatly boosted by Big Data technologies that provide the means for analysing maintenance related data from a host of batch and streaming data sources. As another example, Industry 4.0 quality management and supply chain management use cases ask for fast exchange of data from and to the shopfloor, including interactions with numerous devices. The latter are propelled by advanced connectivity technologies such as 5G and LPWAN (Low Power Wide Area Networks).

In following paragraphs, we provide a list of the main digital technologies that empower the Industry 4.0 vision and highlight their importance for the factories of the future.

- **CPS and Industrial Internet of Things:** As already outlined, CPS systems are considered as the main building blocks of Industry 4.0 systems. In the medium term, most machines will be CPS systems that will provide the means for collecting digital data from the physical worlds, but also interfaces for actuating and control over them. CPS systems are conceptually Industrial Internet of Things (IIoT) systems, which enable interaction and data exchange with physical devices. Note however that IIoT systems provide also the means for interconnecting legacy machines with IT systems and ultimately treating them as CPS systems. This is mainly achieved through the augmentation of physical devices with middleware that implements popular IoT protocols, such as MQTT, OPC-UA, WebSocket and more. Overall, CPS and IIoT systems will be at the very core of all Industry 4.0 deployments in the years to come.
- **5G Communications:** Industrial plants are characteristic examples of device saturated environments, since there are likely to comprise thousands of sensors, edge gateways, machines and automation devices. Early Industry 4.0 involves only a small subset of these devices and hence can dispose with state of the art connectivity technologies such as Wi-Fi and 4G/LTE (Long Term Evolution) technologies. Nevertheless, in the medium and long term, a much larger number of machines and devices should be supported, as they will gradually connect to Industry 4.0 deployments. Likewise, much larger volumes of data and mobility of smart objects (e.g., drones and autonomous guided vehicles) should be handled, in several cases through high performance and lower latency. For these reasons, future deployments will require the capabilities advocated by 5G technologies which are currently being tested by several telecom operators worldwide. In particular, 5G technologies will enable low-latency data acquisition from thousands of devices at plant scale, which offering spectrum efficiency and ease of deployment.
- **Low Power Wide Area Networks:** In recent years, low power wide area network technologies (such as LoraWAN, NB-IoT and SigFox) have emerged, in order to support IoT devices connectivity at scale, notably the connectivity of low power devices. These technologies offer flexible and cost effective deployment, while at the same time supporting novel applications in both indoor and outdoor environments, including the accurate localization of items in indoor environments. We envisaged that such technologies will be also used in order to provide "location-as-a-service" capabilities in industrial plants. Their deployment will

come to enhance rather than replace the connectivity capabilities that are currently provided by 4G and WiFi technologies, notably in the direction of accurate item localization that existing technologies cannot deliver.

- **Cloud Computing:** CPS manufacturing systems and applications are very commonly deployed in the cloud, in order to take advantage of the capacity, scalability and quality of service of cloud computing. Moreover, manufacturers tend to deploy their enterprise systems in the cloud. Likewise, state of the art automation platforms (including some of the platforms that are presented in this book) are cloud based. In the medium term, we will see most manufacturing applications in the cloud, yielding cloud computing infrastructure an indispensable element of Industry 4.0.
- **Edge Computing:** During the last couple of years, CPS and IIoT deployments in factories implement the edge computing paradigm. The latter complements the cloud with capabilities for fast (nearly real time) processing, which is performed close to the field rather than in the cloud [2]. In an edge computing deployment, edge nodes are deployed close to the field in order to support data filtering, local data processing, as well as fast (real time) actuation and control tasks. The edge computing paradigm is promoted by the major reference architecture for IIoT and Industry 4.0 such as the Industrial Internet Consortium Reference Architecture (IIRA) and the Reference Architecture of the OpenFog consortium.
- **Big Data:** The vast majority of Industry 4.0 use cases are data intensive, as they involve many data flows from multiple heterogeneous data sources, including streaming data sources. In other words, several Industry 4.0 use cases are based on datasets that feature the 4Vs (Volume,Variety, Velocity, Veracity) of Big Data. As mentioned in earlier sections, predictive maintenance is a classic example of a Big Data use case, as it combines multi-sensor data with data from enterprise systems in a single processing pipeline. Therefore, the evolution of Big Data technologies and tools is a key enabler of the fourth industrial revolution. Industry 4.0 is typically empowered by Big Data technologies for data collection, consolidation and storage, given that industrial use cases need to bring together multiple fragmented datasets and to store them in a reliable and cost-effective fashion. However, the business value of these data lies in their analysis, which is indicative of the importance of Big Data analytics techniques, including machine learning techniques.

- **Artificial Intelligence:** Even though there is a lot of hype around the use of AI in the industry, most manufactures and plant operators are familiar with this technology. Indeed, AI has been deployed in industrial plants for over two decades, in different forms such as fuzzy logic and expert systems. In the Industry 4.0 the term is revised and extended in order to include the use of deep learning and deep neural networks for advanced data mining. The use of these techniques is directly enabled from the Big Data technologies that have been outlined in the previous paragraph. Hence, they have a very close affiliation with Big Data, as deep learning can be used in conjunction with Big Data technologies. AI data analytics is more efficient than conventional machine learning in identifying complex patterns such as operation degradation patterns for machines, patterns of product defect causes, complex failure modes and more. In industrial environments, AI can be embedded in digital automation systems, but also in physical devices such as robots and edge gateways.
- **Augmented Reality:** AR is another technology that has been used in plants since several decades. It is also revisited as a result of the emergence of more accurate tracking technologies and of new cost-effective devices. It can be used in many different ways in order to disrupt industrial processes. As a prominent example, AR can be used for remote support of maintenance workers in their service tasks. In particular, with AR the worker needs no longer to consult paper manuals or phone supports. He/she can rather view on-line the repair or service instructions provided by an expert (e.g., the machine vendor) from a remote location. As another example, AR can be used for training workers on complex tasks (e.g., picking or assembly tasks), through displaying them cyber-presentations of the ways these tasks are performed by experts or more experienced workers.
- **Blockchain Technologies:** Blockchain technologies are in their infancy as far as their deployment in industrial settings is concerned. Despite the hype around blockchains, their sole large scale, enterprise application remains their use in cryptocurrencies such as Bitcoin and Ethereum. Nevertheless, some of the projects that are presented in this book are already experimenting with blockchains in industry, while also benchmarking their performance. In particular, the FAR-EDGE project is using blockchain technology for the decentralization and

synchronization of industrial processes, notably processes that span multiple stations in the factory. However, other uses of the blockchain are also possible, such as its use for securing datasets based on encryption, as well as its use for traceability in the supply chain. It's therefore likely that the blockchain will play role in future stages of Industry 4.0, yet it has not so far been validated at scale. Note also that in the scope of Industry 4.0 applications, permissioned blockchains can be used (like in FAR-EDGE), instead of public blockchains. Permissioned blockchains provide increased privacy, authentication and authorization of users, as well as better performance than public ones, which makes them more suitable for industrial deployment and use.

- **Cyber Security:** Industry 4.0 applications introduce several security challenges, given that they are on the verge of IT and OT, which pose conflicting requirements from the security viewpoint. Any Industry 4.0 solutions should come with strong security features towards protecting datasets, ensuring the trustworthiness of new devices and protecting the deployment for vulnerabilities of IT assets.
- **3D Printing and Additive Manufacturing:** Along with the above-listed IT technologies, CPS manufacturing processes benefit from 3D printing, as an element of the digital automation platforms and processes. 3D printing processes can be driven by the digital data of an Industry 4.0 deployment, such as a digital twin of a piece of equipment or part that can be printed. Additive manufacturing processes can be integrated in a digital manufacturing deployment in support of the above-listed use cases. For example, 3D printing can be used to accelerate the maintenance and repair process, through printing parts or tools, rather than having to order them or to keep significant inventory. Likewise, printing processes can be integrated in order to flexible customize the configuration of a production line and subsequently of the products produced. This can greatly boost mass customization.

None of the chapters of the book is devoted to the presentation of digital technologies, as the emphasis is on digital automation systems and their functionalities. However, all the presented systems comprise one or more of the above digital building blocks. Moreover, some of the chapters are devoted to automation solutions that are built round the above listed technologies such as edge computing, cloud computing and blockchain technology.

1.4 Digital Automation Platforms and the Vision of the Digital Shopfloor

1.4.1 Overview of Digital Automation Platforms

The vision of using digital technologies towards enhancing the flexibility and configurability of industrial automation tasks is not new. For over a decade manufacturers have been seeking for scalable distributed solutions both for manufacturing automation and for collaboration across the manufacturing value chain [3]. Such solutions are driven by future manufacturing requirements, including reduction of costs and time needed to adapt to variable market demand, interoperability across heterogeneous hardware and software elements, integration and interoperability across enterprises (in the manufacturing chain), seamless and cost effective scalability through adding resources without disrupting operations, reusability of devices and production resources, plug-and-play connectivity, as well as better forecasting and predictability of processes and interactions towards meeting real-time demand [4]. These requirements have given rise to distributed decentralized approaches for de-centralizing and virtualization the conventional automation pyramid [5].

One of the most prominent approaches has been the application for intelligent agents in industrial automation, in the scope of in distributed environments where time-critical response, high robustness, fast local reconfiguration, and solutions to complex problems (e.g., production scheduling) are required [6]. Agent-based approaches fall in general devised in the following main categories:

- **Functional decomposition approaches**, where agents correspond to functional modules that are assigned to manufacturing or enterprise processes e.g., order acquisition, planning, scheduling, handling of materials, product distribution and more.
- **Physical decomposition approaches**, where agents are used to represent entities in the physical world (e.g., machines, tools, cells, products, parts, features, operations and more). This decomposition impacts also the implementation of manufacturing processes such as production scheduling. For example, in the case of functional decomposition, scheduling can be implemented as a process that merges local schedules maintained by agents in charge of ordering. Likewise, in the case of physical decomposition scheduling can be implemented based on a negotiation process between agents that represent single resources (e.g., cells, machines, tools, fixtures etc.).

Despite the advantages of agent technology for manufacturing operations (e.g., distribution, autonomy, scalability, reliability), agents are considered inefficient when dealing with low-level control tasks that have very stringent performance requirements. Furthermore, a direct mapping between software agents and manufacturing hardware has not been realized and/or standardized [7].

In addition to software agents' technology, Service Oriented Architecture (SOA) paradigms to decentralized automation have also emerged with a view to exploiting SOA's reusability, autonomy and loose coupling characteristics. SOA approaches to manufacturing automation are based on the identification of operations that can be transformed and exposed as services. Accordingly, these operations are exploited towards implementing service-oriented automation workflows. SOA solutions come with enterprise service bus infrastructures, which decouple producers from consumers, while at the same time facilitating the integration of complex event processing. Furthermore, SOA is a standardized and widely adopted technology, which presents several advantages over software agents, while giving rise to approaches that combine SOA and agents (e.g., [8]). SOA deployments in the shopfloor have also focused on the integration of device level services with enterprise level services, including for example deployments that virtualize Programmable Logic Controllers (PLC) [9], along with implementations of execution environments for Functional Block Instances (FBI), including functional blocks compliant to the IEC 61499 standard [10]. Nevertheless, SOA architectures have been unable to solve the real-time limitations of agent technology, which has given rise to various customizations of the technology (e.g., [11]).

The rise of CPS manufacturing, along with the evolution of the digital technologies that were presented in the previous section (e.g., Cloud Computing, IIoT and Big Data technologies) has led to the emergence of several cloud-based industrial automation platforms, including platforms offered by prominent IT and industrial automation vendors (e.g., IBM, SIEMENS, BOSCH, Microsoft, Software AG, SAP) and platforms developed in the scope of EU projects (e.g., FP7 iMain (http://www.imain-project.eu/), ARTEMIS JU (Joint Undertaking) Arrowhead (http://www.arrowhead.eu), FoF (Factories of the Future) SUPREME (https://www.supreme-fof.eu/) and more). Each of these platforms comes with certain unique value propositions, which aim at differentiating them from competitors.

Acknowledging the benefits of edge computing for industrial automation, Standards Development Organizations (SDOs) have specified relevant reference architectures, while industrial organizations are already working towards providing tangible edge computing implementations. SDOs such as the OpenFog Consortium and the Industrial Internet Consortium (IIC) have produced Reference Architectures (RA). The RA of the OpenFog Consortium prescribes a high-level architecture for internet of things systems, which covers industrial IoT use cases. On the other hand, the RA of the IIC outlines the structuring principles of systems for industrial applications. The IIC RA [12] is not limited to edge computing, but rather based on edge computing principles in terms of its implementation. It addresses a wide range of industrial use cases in multiple sectors, including factory automation. These RAs have been recently released and their reference implementations are still in their early stages.

A reference implementation of the IIC RA's edge computing functionalities [13] for factory automation is provided as part of IIC's edge intelligence testbed. This testbed provides a proof-of-concept implementation of edge computing functionalities on the shopfloor. The focus of the testbed is on configurable edge computing environments, which enable the development and testing of leading edge systems and algorithms for edge analytics. Moreover, Dell-EMC has implemented the EdgeX Foundry framework [14], which is a vendor-neutral open source project hosted by the Linux Foundation that builds a common open framework for IIoT edge computing. The framework is influenced by the above-listed reference architectures and was recently released. Other vendors (e.g., Microsoft and Amazon) are also incorporating support for edge devices and Edge Gateways in their cloud platforms.

The platforms and solutions that are presented in following chapters advance the state of the art in digital automation platforms, based on the implementation of advanced intelligence, resilience and security features, but also through the integration of leading edge technologies (e.g., AI and blockchain technologies). The relevant innovations are presented in the individual chapters that present these solutions. Note, however, that the FAR-EDGE, AUTOWARE and DAEDALUS solutions that are presented in the book fall in the realm of research solutions. Hence, they implement advanced features, yet they lack the maturity for very large scale digital automation deployments.

1.4.2 Outlook Towards a Fully Digital Shopfloor

The digital automation platforms that are listed in the previous paragraphs support the early stage Industry 4.0 deployments, which are characterized by the integration of a limited number of CPS systems and the digitization of selected production processes. As part of the evolution of Industry 4.0 deployments, we will witness a substantial increase of the scope of these deployments in terms of the connected machines and devices, but also in terms of the processes that will be digitized and automated. The ultimate vision is a fully digital shopfloor, where all machines and OT devices will be connected to the IT systems, while acting as CPS systems. This digital shopfloor will support all of the described functionalities and use cases in areas such as automation, simulation, maintenance, quality management, supply chain management and more. Moreover, these functionalities will seamlessly interoperate towards supporting end-to-end processes both inside the factory and across the supply chain. The interaction between these modules will empower more integrated scenarios, where for example information collected by the shopfloor is used to perform a digital simulation and produce outcomes that drive a control operation on the field.

The fully digital shopfloor will enable an autonomous factory, which will be characterized by the following properties:

- **Holistic, Integrated and End-to-End:** The digital shopfloor will deploy digital technologies and capabilities end-to-end, in order to address the digital transformation of all the production processes, rather than of selected processes which is the situation nowadays.
- **Predictive and Anticipatory:** Solutions within the fully digital shopfloor will be able to predict and anticipate important events such as machine failures and occurrence of production defects, as a means of proactively taking action in order to optimize operations.
- **Fast and Real-Time:** Solutions in the digital shopfloor will be fast and able to operate in real-time timescales, which will allow them to remedy potential problems and to perform optimizations on-line (e.g., support on-line defect repairs).
- **Flexible and Adaptive:** In the digital shopfloor of the future, automation solutions will be dynamic and adaptive to changing production requirements and manufacturing contexts. As such their digital capabilities, including their security characteristics, will be flexible and reconfigurable, in order to support dynamic control of production processes and their quality in the system life-cycle.
- **Standards-Based:** The realization of the digital shopfloor could be greatly facilitated based on the integration and use of standards-based solutions, notably solutions that adhere to mainstream digital manufacturing (e.g. RAMI4.0) and Industrial Internet of Things (IIoT) standards

(e.g., OpenFog Consortium). Adherence to such standards will greatly facilitate aspects such as integration and interoperability.

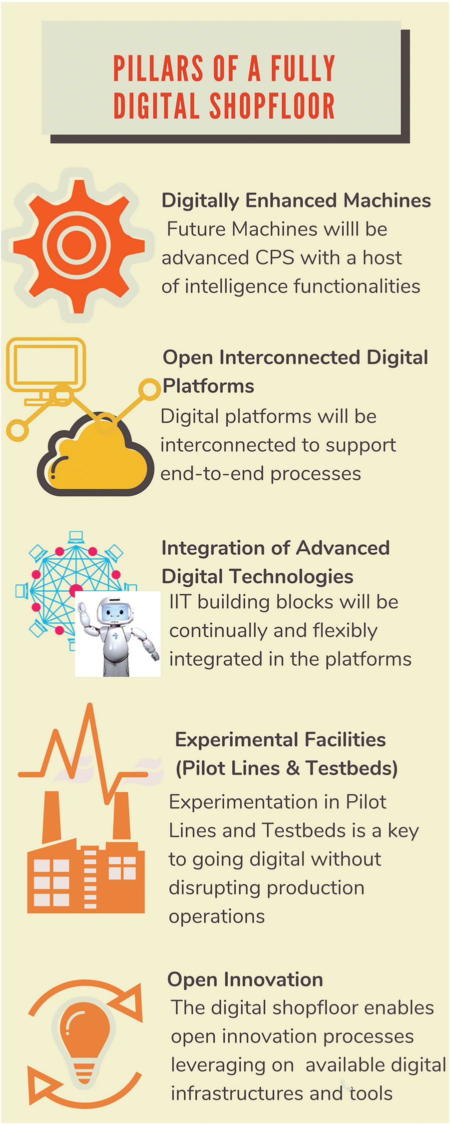
- **Open:** The solutions of the digital shopfloor should be openly accessible through Open APIs (Application Programming Interfaces), which will facilitate their expansion with more features and functionalities.
- **Cost-Effective:** The digital shopfloor will be extremely cost effective in its configuration and operations, based on its flexible, dynamic, reconfigurable and composable nature. In particular, the autonomy of the digital shopfloor solutions will eliminate costs associated with human-mediated error-prone processes, while their composability will lower development and deployment costs.
- **Human-Centric (Human-in-the-Loop):** A fully digital shopfloor shall address human factors end-to-end, including product design aspects, employees' training, proper visualization of production processes, as well as safety of human-in-the-loop processes.
- **Continuous Improvement:** The digital driven production processes will be characterized by a continuous improvement discipline, which will occur at various timescales, including machine, process and end-to-end production levels.

In the scope of the digital shopfloor, products and production processes can be fully virtualized and managed in the digital world (e.g., through their digital twin counterparts). This implies that digital information about the products and the production processes will be collected and managed end-to-end, towards a continuous improvement discipline.

The vision of the digital shopfloor requires development and integration activities across the following complementary pillars:

- **Digitally enhanced manufacturing equipment:** Industry 4.0 hinges on the interconnection of machines and equipment in the cyber world as CPS systems. Currently, legacy machines are augmented based on internet of things protocols in order to become part of Industry 4.0 deployments. At the same time, new machines come with digital interfaces and acts as CPS systems. In the medium and long term, machines will be digitally enhanced in order to provide embedded intelligence functionalities, such as the ability to detect and remedy defects, to identify maintenance parameters and to schedule maintenance activities and more. Such intelligence functionalities will endow machines with flexibility, reconfigurability, adaptability and proactivity properties, which are key enablers of the fully digital shopfloor.

- **Open digital platforms for automation and service engineering:** In the digital shopfloor, digitally enhanced machinery must be interconnected in order to support factory wide processes. To this end, various digital manufacturing platforms shall be integrated based on composable



functionalities. This is also important given that factories and manufacturing chain tend to deploy multiple rather than a single digital automation platform. Hence, the composition of multiple functionalities from different platforms is required in order to support end-to-end production processes as part of the digital shopfloor.

- **Interoperable digital components and technologies:** The digital shopfloor will be able to seamlessly integrate advanced digital and CPS technologies such as sensors, data analytics and AI algorithms. The digital shopfloor will be flexibly and continually upgradable with the best-of-breed of digital technologies for manufacturing as the latter become available. This is a key prerequisite for upgrading the intelligence of the plant floor, with minimum disruption in production operations.
- **Experimentation facilities including pilot lines and testbed**s: The transition to a fully digital shopfloor requires heavy and continuous testing efforts, as well as auditing against standards. Extensive testing is therefore required without disrupting existing operations as a means of guaranteeing smooth migration. To this end, there is a need for experimental facilities and pilot lines where digital manufacturing developments can be tested and validated prior to their deployment in production. This is the reason why some of the subsequent chapters of the book refer to existing experimental facilities and testbeds, as key elements of Industry 4.0 and digital manufacturing platforms ecosystems building efforts.
- **Open Innovation Processes**: One of the overarching objectives of Industry 4.0 is to enable increased flexibility in digital automation deployments, not only in order to boost new production models (such as mass customization), but also in order to ease innovation in digital automation. To this end, open innovation processes should be established over the interconnected digital platforms, leveraging on IT innovation vehicles such as Application Programming Interfaces (APIs) and the experimental facilities outlined above. The latter could serve as a sandbox for innovation.

The road to the fully digital shopfloor is very challenging as a result of the need to develop, establish, validate and combine the above-listed pillars. However, there is already evidence of the benefits of digital technologies in the shopfloor and across the supply chain. Later chapters of this book present this evidence, along with some of the key digital manufacturing platforms that demonstrate the benefits of digital manufacturing platforms and of the related digitally transformed production processes.

1.5 Conclusion

This chapter has introduced Industry 4.0 in general and digital automation platforms in particular, which are at the core of the book. Our introduction to Industry 4.0 has underlined some of the proven and most prominent use cases that are being implemented as part of early deployments. Special emphasis has been given in use cases associated with flexible automation, worker training and safety, predictive maintenance, quality management, digital simulations and more. Basic knowledge about these use cases is a key prerequisite for understanding the automation use cases and applications that are presented in subsequent chapters of the book.

The chapter has also presented the most widely used digital technologies in the scope of Industry 4.0. Emphasis has been put on illustrating the relevance of each technology to Industry 4.0 use cases, but also on presenting how their evolution will impact deployment and adoption of CPS manufacturing systems. This discussion of digital technologies is also a prerequisite for understanding the details of the digital solutions that are presented in subsequent chapters. This is particularly important, given that no chapter of the book presents in detail digital technologies. Rather the emphasis of the book is on presenting advanced manufacturing solutions based on digital automation platforms that leverage the above-listed digital technologies.

Despite early deployments and the emergence of various digital automation platforms, the Industry 4.0 vision is still in the early stages. In the medium- and long-term, different technologies and platforms will be integrated towards a fully digital shopfloor, which supports the digital transformation of industrial processes end-to-end. The vision of a fully digital shopfloor entails the interoperability and interconnection of multiple digitally enhanced machines in-line with the needs of end-to-end automation processes within the factory. As part of this book, we present several automation approaches and functionalities, including field control, data analytics and digital simulations. In the future digital shopfloor, these functionalities will co-exist and seamlessly interoperate in order to enable fully autonomous, intelligent and resource efficient factories. With this wider vision in mind, readers could focus on the more fine-grained descriptions of platforms and technologies presented in subsequent chapters.

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