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Review

Scanning the Industry 4.0: A Literature Review on Technologies for Manufacturing Systems

V. Alcácer [a,c,*], V. Cruz-Machado [a,b]

[a] Department of Mechanical and Industrial Engineering, Faculty of Science and Technology, Universidade Nova de Lisboa, Lisboa, Portugal
[b] UNIDEMI, Department of Industrial and Mechanical Engineering, Faculty of Science and Technology, Universidade Nova de Lisboa, Lisboa, Portugal
[c] Department of Mechanical Engineering, ESTSetúbal, Instituto Politécnico de Setúbal, Setúbal, Portugal

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ABSTRACT

Industry 4.0 leads to the digitalization era. Everything is digital; business models, environments, production systems, machines, operators, products and services. It's all interconnected inside the digital scene with the corresponding virtual representation. The physical flows will be mapped on digital platforms in a continuous manner. On a higher level of automation, many systems and software are enabling factory communications with the latest trends of information and communication technologies leading to the state-of-the-art factory, not only inside but also outside factory, achieving all elements of the value chain on a real-time engagement. Everything is smart. This disruptive impact on manufacturing companies will allow the smart manufacturing ecosystem paradigm. Industry 4.0 is the turning point to the end of the conventional centralized applications. The Industry 4.0 environment is scanned on this paper, describing the so-called enabling technologies and systems over the manufacturing environment.
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Contents

* Corresponding author at: Department of Mechanical Engineering, ESTSetúbal, Instituto Politécnico de Setúbal, Setúbal, Portugal.
E-mail address: vitor.alcacer@estsetubal.ips.pt (V. Alcácer).
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1. Introduction

Global recession over the last years changed the overview on the industrial sector, now looking at the real value-added that it creates. Companies that followed the trend to relocate activities by looking for low cost labor, are now committed to recover their competitiveness.

German manufacturing strategy played a key role on this shifting, launching initiatives to maintaining and promoting its importance as a "forerunner" in the industrial sector [1]. The buzz word "Industry 4.0" has been presented and with it big promises arose to face the latest challenges in manufacturing systems. The impeller Industry 4.0 (I4.0) is enabling and reinforcing this trend using its technologies, changing the way of living, creating new business models and new ways of manufacturing, renewing the industry for the so-called digital transformation.

In 2011, the German government have brought into the world a new heading called *Industrie 4.0* (I4.0), assumed as the fourth industrial revolution [2–6]. I4.0 aim is to work with a higher level of automatization achieving a higher level of operational productivity and efficiency [3,7], connecting the physical to the virtual world [8–9]. It will bring computerization and inter-connection into the traditional industry [3]. According to several authors [3,5–6], I4.0 can be assumed as Cyber-Physical Systems (CPS) production, based on heterogeneous data and knowledge integration and it can be summed up as an interoperable manufacturing process, integrated, adapted, optimized, service-oriented which is correlated with algorithms, Big Data (BD) and high technologies such as the Internet of Things (IoT) and Services (IoS), Industrial Automation, Cybersecurity (CS), Cloud Computing (CC) or Intelligent Robotics [3,7,9]. From the production approach, Martin and Schäffer [8] define I4.0 as the intelligent flow of the workpieces machine-by-machine in a factory, on a real-time communication between machines. On this environment, I4.0 will make manufacturing become smart and adaptive using flexible and collaborative systems to solve problems and make the best decisions [7]. It brings a good development for the industrial scenario focusing on creating smart products, smart processes and smart procedures [5]. Companies expected to increase the level of digitalization, working together in digital ecosystems with customers and suppliers [10].

Since I4.0 boom, the research community has experienced different approaches to I4.0 concept; however, the general society may be confused based on the lack of understanding on this area. There is a need for clarification of I4.0 related concepts and technologies.

This paper deals with the research of I4.0 in manufacturing environments on a literature review over the enabling technologies, focusing on the state-of-the-art and future trends. The approach of I4.0 for manufacturing systems in this paper is based on the Smart Factory (SF) concept. The SF concept makes use of components such as IoT, IoS, the systems integration and Cyber-Physical Production System (CPPS) that is formed by several linked CPS (CPS may use up until nine key enabling technologies, widely assumed by research community).

The paper is structured as follows: section 2 presents the Refence Architecture Model Industrie 4.0 (RAMI4.0) as the guidance for the I4.0 technologies implementation, section 3 presents key enabling technologies of I4.0, section 4 reviews the Smart Factory (SF) concept of the I4.0 structured with its components, and the final remarks are in section 5 which introduces the summary and gives future outlooks.

2. Reference Model of I4.0

Several German associations and institutions cooperated on the creation of the reference model for I4.0. This 3D model in Fig. 1 is the development of a shared language and a structured framework [11–12] that describes the fundamental bases of I4.0. It is intended to assist on the I4.0 technologies implementation [13].

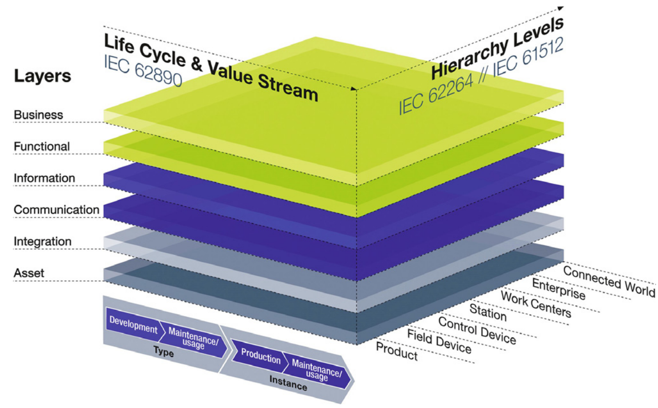


Fig. 1. Reference Model RAMI4.0 [136].

The Reference Architecture Model Industrie 4.0 (RAMI4.0) should enable to identify the existing standards and among it, identify and close the gaps, loopholes and identify the overlaps [14].

On the left horizontal axis from the IEC 62,890 standard, facilities and product lifecycle with the correspondent value stream are showed [15]. RAMI4.0 clearly describes the difference between instance and type. When the design and prototyping is completed, the type becomes an instance, ready for production [14].

The hierarchy levels from the IEC 62264 standard are showed in the right axis, representing the different grouped entities by functional properties, defined to represent all hierarchical levels of the enterprise, from the "Product" (e.g., a workpiece) to the "Connect World" level. The "Connect World" is the last stage of the I4.0 development enterprise environment using IoT and IoS to connect enterprises, customers and suppliers [13–14]. The hierarchy levels are discussed further inside the SF in section 4 through the Fig. 25.

The layers on the vertical axis represent a reminder to integrate all aspects on the enterprise digitalization [11]. The functional layers of the organized vertical axis describe:

- "Asset Layer" represents reality, for instance, physical components including linear axes, robots, conveyor belts, PLC's, metal parts, documents, archives also persons that form a part of connection to the virtual world via the "Integration Layer" [12,14–15]. Also, non-physical objects such as software or ideas;
- "Integration Layer" provides processed information for the digitization of the assets. Elements connect to Information Technologies (IT) such as sensors, Radio Frequency IDentification (RFID) readers, integration of Human-Machine Interface (HMI) and computer-aided controls the technical processes [12,14]. Persons via HMI also participate on this layer. In the virtual domain, each significant event is mirrored through the enabler [12];
- "Communication Layer" with the function of communication standardization. It makes use of uniform data format and predefined protocols, providing services for the "Integration Layer" [12,14–15];
- "Information Layer" to process and integrate consistently the different available data into useful information [14]. Also receives and transforms events to match the data which are available for the next layer [15];
- "Functional Layer" to enable formal descriptions of functions. It creates an horizontal integration platform of several functions that can be with remote access, resulting of the necessity of data

integrity. It supports the business procedures [15]. It generates the logic of the rules and decision (in some cases can be achieved on lower layers);
- "Business Layer" enables mapping of the business model and links between different business models. It ensures, within the value stream, the integrity of the functions [14–15].

It's possible to map all crucial aspects of I4.0, allowing the classification according to the model, of objects such as machines. This model allows the step-by-step migration from the actual to the future manufacturing environments [13].

The I4.0 essential technological elements are compiled at the first time as RAMI4.0 and it is registered in Germany in the DIN SPEC 91345 standard [14].

3. The Key Technologies of I4.0

I4.0 is characterized on manufacturing and services by highly developed automation and digitalization processes, electronics and IT [3]. From the production and service management perspective, I4.0 focus on establish intelligent and communicative systems such as Machine-to-Machine and Human-Machine Interaction, dealing with the data flow from intelligent and distributed system interaction [16]. Among other features, I4.0 promotes autonomous interoperability, agility, flexibility, decision-making, efficiency or cost reductions [17].

The I4.0 implementation should be interdisciplinary in a closely between different key areas. Several authors [5,18–19] described nine pillars (also called the building blocks) of the I4.0 framework as follows in the subsections. A fundamental key point to achieve the integration of I4.0 framework is the human contribution that will be improved with the development of professional skills of the stakeholders.

3.1. The Industrial Internet of Things

On the IT, the IoT is the connection of two words i.e. "internet" and "things". "Internet" as the network of the networks. A global system serving users worldwide with interconnected computer networks using Standard Internet Protocol suit (TCP/IP). As individually distinguishable by the real world, the "things" can be anything like an object or a person [20]. Today, IoT is widely used for instance, in transportation, healthcare or utilities [21]. Thing-to-Thing, Thing-to-Human and Human-to-Human form a network inside IoT, connected to the internet. Individually identifiable objects exchange information inside this network. [22–23].

IoT has been increase with the advancement of mobile devices. IoT can be achieved with connected RFID, Wireless Sensor Networks (WSN), middleware, CC, IoT application software and Software Defined Networking (SDN) as the key enabling technologies [23]. Fig. 2 presents the associated technologies in IoT.

One simple definition of IoT described by Sezer et al. [21] is: "*IoT allows people and things to be connected anytime, anyplace, with anything and anyone, ideally using any path/network and any service*". In other words, Bortolini et al. [24] defined IoT as an ubiquitous presence for a common purpose of various things or objects interacting and cooperating each other, digitalizing all physical systems. For different aims, the digitalized information can be used to adjust production patterns, with the use of a virtual copy of the physical world and using sensor data [7]. The entire production systems such as machinery and related resources can be the "things" managed and virtualized by I4.0 [4,7]. In addition, the IoT nature as to be decentralized and heterogeneous [25].

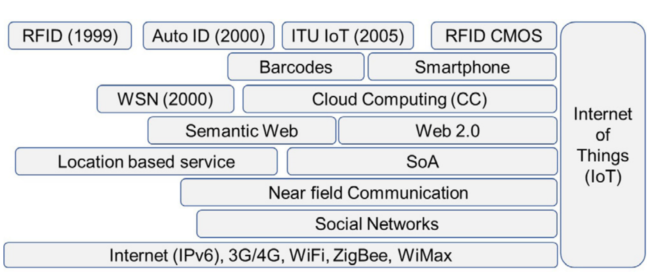


Fig. 2. Technologies Associated with IoT [25].

Regarding to IoT design architecture, Trappey et al. [26] established a logical framework by layers to classify IoT technology and used to characterize and identify CPS. According to several authors [25,27–28], IoT architecture most common layering in a typical network, includes four main layers as represented in the Fig. 3 as follows:

1) "Sensing Layer" to sense the "things" status with a unique identity and to integrate, e.g., actuators, sensors, RFID tags as several types of "things";
2) "Network Layer" to support the transferred information through wired or wireless network from the "Sensing Layer" to "Service Layer", being the support's infrastructure. This layer determines and maps "things" automatically in the network enabling to connect all "things" for sharing and exchange data;
3) "Service Layer" makes use of a middleware technology supporting services and applications, required by the users or applications. The interoperability among the heterogeneous devices is ensured by this layer, performing useful services, e.g., information search engines and communication, data storage, exchanging and management of data as well as the ontology database;
4) "Interface Layer" to make the interconnection and management of the "things" easier and to display information allowing a clear and comprehensible interaction of the user with the system.

Differing from IoT based users, regarding to industrial environments needing real-time data availability and high reliability [29], the Industrial Internet of Things (IIoT) is the connection of industrial products such as components and/or machines to the internet. For instance, linking the collected sensing data in a factory with IoT platform, IIoT increases production efficiency with the BD analysis [22].

A typical IIoT is showed in Fig. 4, with wire and wireless connections, increasing value with additional monitoring, analysis and optimization.

As a natural evolution of IoT, the IoS can be seen as the connectivity and interaction of the things creating valuable services and is one of the fundamental basis of the SF. IoS is discussed further in section 4.

3.2. Cloud Computing

Cloud Computing (CC) is an alternative technology for companies who intent to invest in IT outsourcing resources [30]. Assante et al. [31] characterized CC for Small and Medium Enterprises (SMEs) as a resource pooling with rapid elasticity and measured service, on-demand self-service and broad network access. The adoption of CC has several advantages related to cost reduction, e.g., the direct and indirect costs on the removal of IT infrastructure in the organization, the resource rationalization service by the dynamically scalable users consuming only the computing resources they actually use or portability when using any type of device connected to the internet such as mobile phones or tablets accessing from any world location [30]. By this, the cloud can have

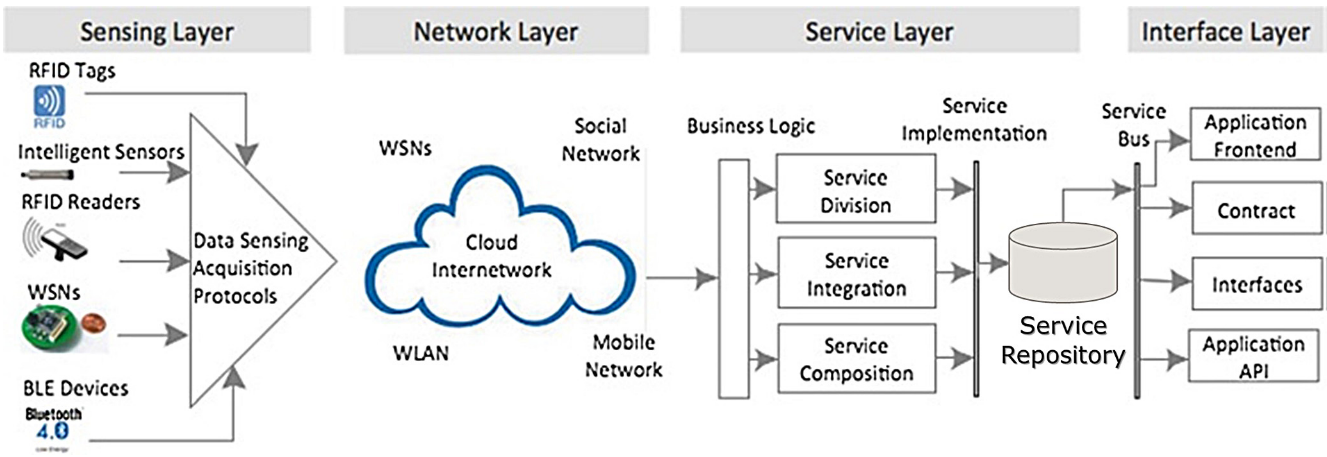


Fig. 3. Generic Service-oriented Architecture (SoA) for IoT [25].

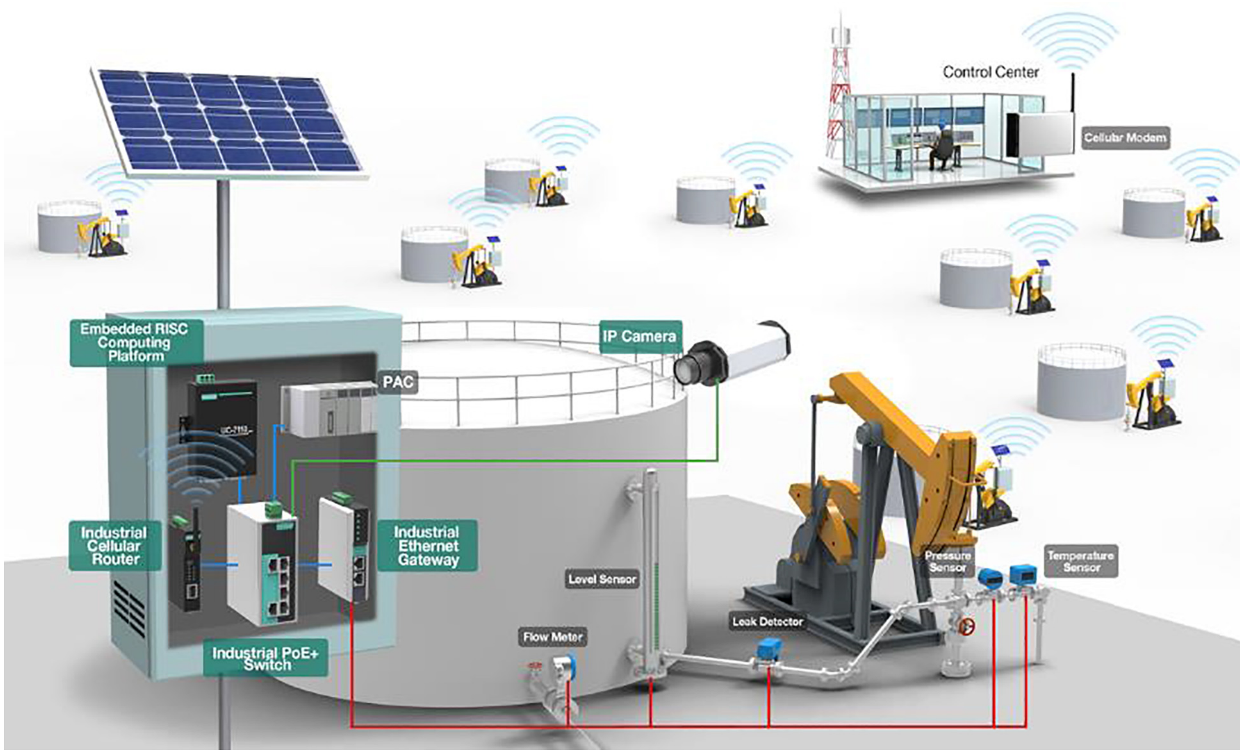


Fig. 4. Typical IIoT network [137].

any of the four types of access: public (usually on a data center location, managed by vendors and available for all public [32]), private (same organization location and offering special benefits [32]), hybrid (combination of public and private clouds [32]) and community (shared by multi organizations and supported by a specific sharing of interests and concerns community [33]). Everything is treated as a service in CC. These services define a layered system or types of service models structured for CC as in Fig. 5 and the management overview is shown in Fig. 6, as follows [31,33–34]:

- Infrastructure as a Service (IaaS) is where cloud service providers supply users with fundamental computing resources, with virtual infrastructures, e.g., virtual servers, networks or storage and where users into the cloud can deploy and run arbitrary software, which can include, for instance, operating systems applications;
- Platform as a Service (PaaS) is where users develop and run applications using programming languages on the cloud infrastructures. Therefore, it can be achieved scalability, high speed server and storage. Users can build, run and deploy their own applications with the use of remote IT platforms. On this layer, there is no concern on the resource's availability and maintenance [35];
- Software as a Service (SaaS) is where applications reside and runs in a cloud infrastructure [34]. Accessible from various client devices through an interface such as a web browser and programs. The focus is to eliminate the service applications on local devices of individual user, achieving an high efficiency and performance for the users. This category enables software applications such as Computer-Aided-Design (CAD) software and Enterprise Resource Planning (ERP) software, with a lower total cost of ownership [35].

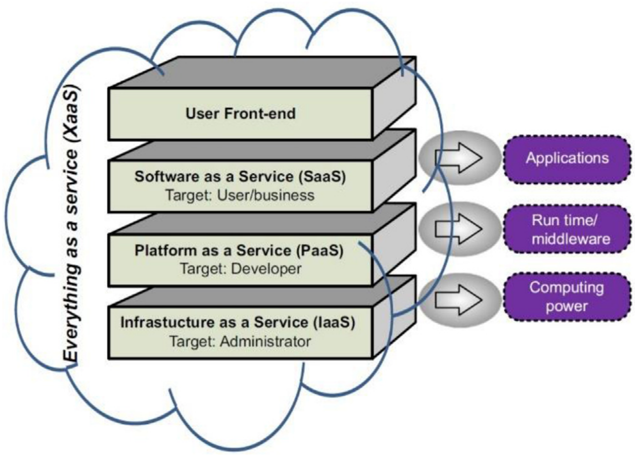


Fig. 5. Everything as a Service on CC [33].

All underlying Everything as a Service (XaaS) layers allows direct interactions with the user interface layer at the top.

On manufacturing environments, Cloud Manufacturing (CMfg) concept was proposed to make use of CC technology, in order to improve the current manufacturing systems [36]. Cloud-related manufacturing has two approaches:

1) CC in manufacturing industry as a manufacturing version of CC - using cloud applications in manufacturing industry directly, web-based manufacturing applications or computer-aided are examples of possible deployments in the CC system. These applications are implemented at two service levels of CC system, matching SaaS and PaaS levels [37];
2) CMfg systems as an entire new type of cloud service, based on Service-oriented Architecture (SoA) in the cloud environment that provides manufacturing capabilities [36]. It reflects the IaaS level on CC system [37].

With the combination of advanced technologies, it arises a new computing and service-oriented manufacturing mode as CMfg [38]. A solution such as CMfg enables users to request services from all stages of a product lifecycle ranging from design, manufacturing, management and so on [38–39]. By this meaning, the main characteristics of CMfg is the service-oriented approach [40] and its trend on shifting manufacturing approach from production-oriented to service-oriented [33,41]. A brief CMfg model is shown in Fig. 7, consisting on three categories of stakeholders: providers, operators and consumers, with their cooperation to maintain sustainable operation of a CMfg system [42–43]:

- Providers – own and provide the abilities and the manufacturing resources [43]. Within the entire product lifecycle, for sharing purposes, providers publish manufacturing resources to the CMfg platform and also receive manufacturing tasks from the cloud platform. Everything is transformed into services, under the exclusive management of the operator [42];
- Operator/s - to operate CMfg platform and to deliver services to providers, consumers and even third parties [43]. In an on-demand manner, consumers from the cloud platform can achieve high-quality and sustainable manufacturing services. Providers have permission to publish their resources and capabilities with the use of tools provided by the cloud platform [42];
- Consumers - to subscribe the manufacturing computing services availability in a CMfg service platform [43]. Under the exclusive management of the operator, consumers, including enterprises consumers and individual consumers, submit their

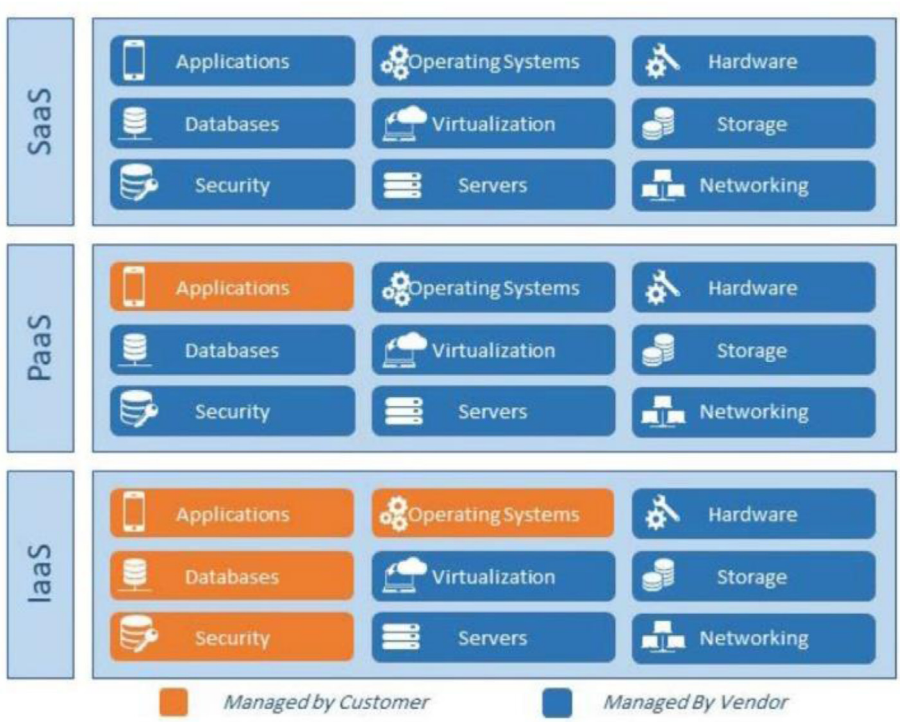


Fig. 6. Management overview in CC models [32].

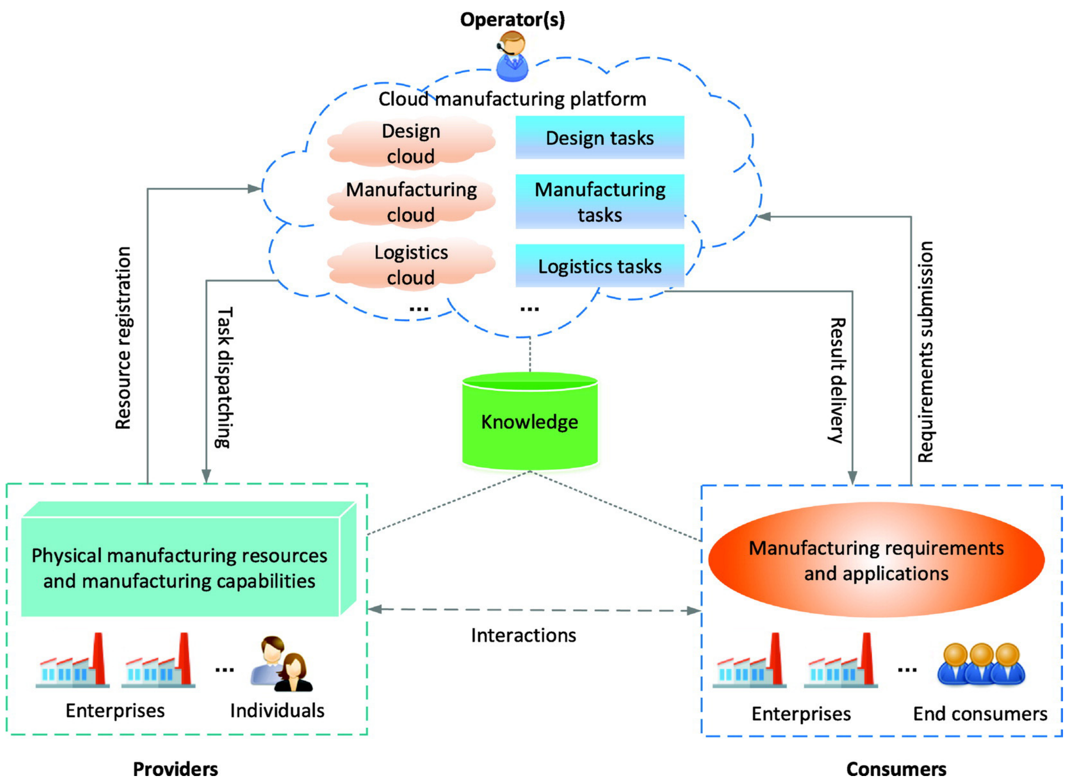


Fig. 7. CMfg model [42].

requirement tasks to the CMfg platform, e.g., design, manufacturing, test or simulation tasks and also receive the execution results of their orders [42].

CMfg is a manufacturing paradigm based on Knowledge. In the running process, the knowledge plays as the central role [44], e.g., models, standards, protocols, rules and algorithms as knowledge, indispensable in many process and activities within entire lifecycle services as service generation, service management and service applications [42].

The concept of CMfg makes use of CC, BD, IoT, CPS, the networked manufacturing, service-oriented manufacturing, virtual manufacturing and virtual enterprise [45–46]. Cooperation can be enabled and supported by CMfg, sharing and management of manufacturing resources such as fabrication capabilities, equipment, applications, software tools, know-how, etc., of companies [47–48] and these companies can be included into the cloud, becoming accessible to potential consumers, in a pay-as-you-go manner [39]. CMfg enables the recommendation and execution, intelligent mapping and search of a service [33]. CMfg can provide in a form of service scalable, flexible and cost-effective solutions with lower maintenance costs and supports. Manufacturing tasks can be obtained also as services into the CMfg service platform [41]. Cloud data center owns the computational resources and the different organizations, e.g., manufacturing enterprises, owns the manufacturing resources [45]. There is no need for manufacturers and users to invest in high-tech computers, computer licenses or worrying about software updates or upgrades [48]. Mai et al. [46] in Fig. 8 discussed a CMfg platform integrating resources and services related to 3D printing, including, e.g., design, 3D printers, assembly, simulation, models, software, etc. It is important to consider model library management and the online-device integration on the construction of the 3D printing service CMfg platform, due to the close relation between 3D printing and 3D models.

Usually with a short budget for the initial investment, lack of experience and related technical support, SMEs are seeking novel technologies such as cloud technologies. According to Wang et al. [49], SMEs needs high level of safety and security regarding their customer's requirements, i.e., all data and results as to be maintain within the boundaries of the own company. These facts indicate that public or community cloud services probably are not suitable in this scenario. To fulfill this need, Wang et al. [49] proposed a CMfg system tailored to meet the requirements of SMEs, considering a hybrid cloud structure. Within this, the sensitive data stays inside a private cloud, with integrated and managed hardware and software. Moreover, the data interoperability presence of the public and private clouds is identified on the multiple levels in the CMfg.

3.3. Big Data

Huge amount of generated data from different types, can come from interconnected heterogeneous objects [24]. This huge amount of structured, semi-structured and unstructured data can describe Big Data (BD). In order to obtain the correspondent value, these data would need too much time and money to be store and to be analyzed [50]. Bringing value opportunities to industries in the era of Internet of Everything can be achieving with the connection of more physical devices to the internet and with the use of a generation of novel technologies.

Data collection or storage characterize BD, but the core characteristic of BD is the data analysis and without it, BD has no much value [51]. Systematic guidance can be provided by BD for related production activities within entire product lifecycle [52], achieving cost-efficient running of the process and fault-free [53], and help managers on decision-making and/or to solve problems related to operation [52]. The use of BD provides a business advantage through the opportunity of generated of value-added [54].

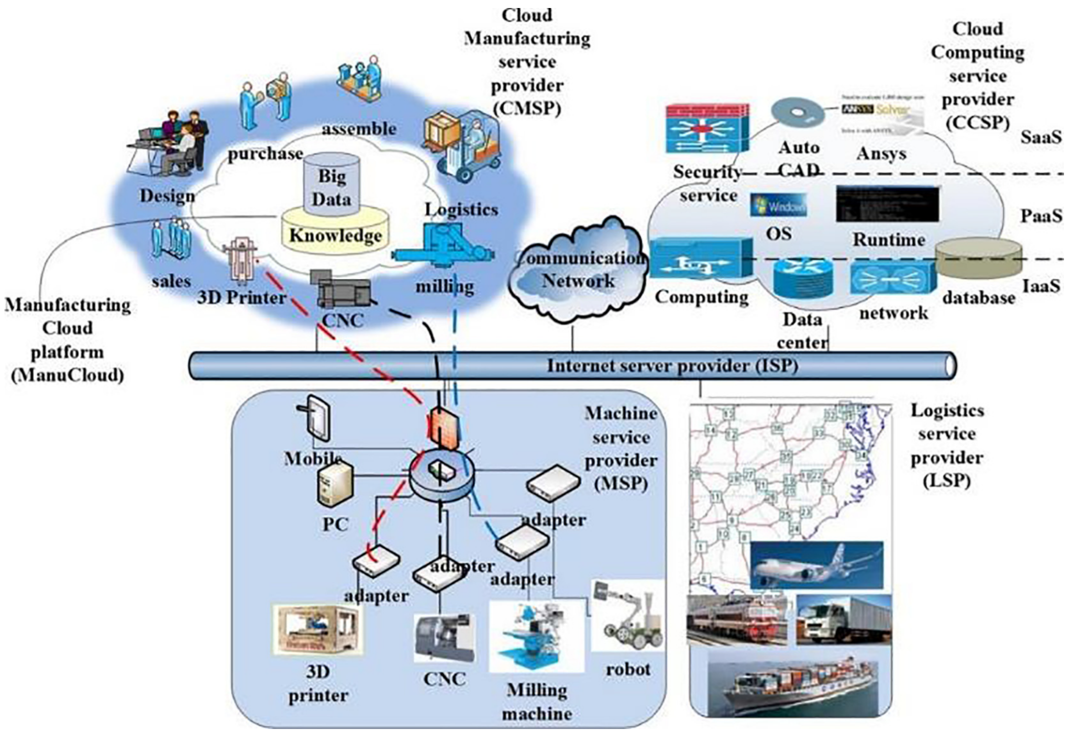


Fig. 8. Various services in CMfg [46].

Cemernek et al. [55] presented BD definition of the TechAmerica Foundation, as "*a "term" describing large volumes of high velocity, complex and variable data requiring advanced techniques and techniques to enable the capture, storage, distribution, management and analysis of the information*". BD demands a cost-effective, innovative forms of information processing for enhanced insights. According to the researched definitions of BD, differing from the traditional data processing [21], the first suggestion to characterize BD was related in terms of Volume, Variety, and Velocity, also named as the Three V's. These was the three dimensions that emerged as a common framework of challenges in data management [56]. To

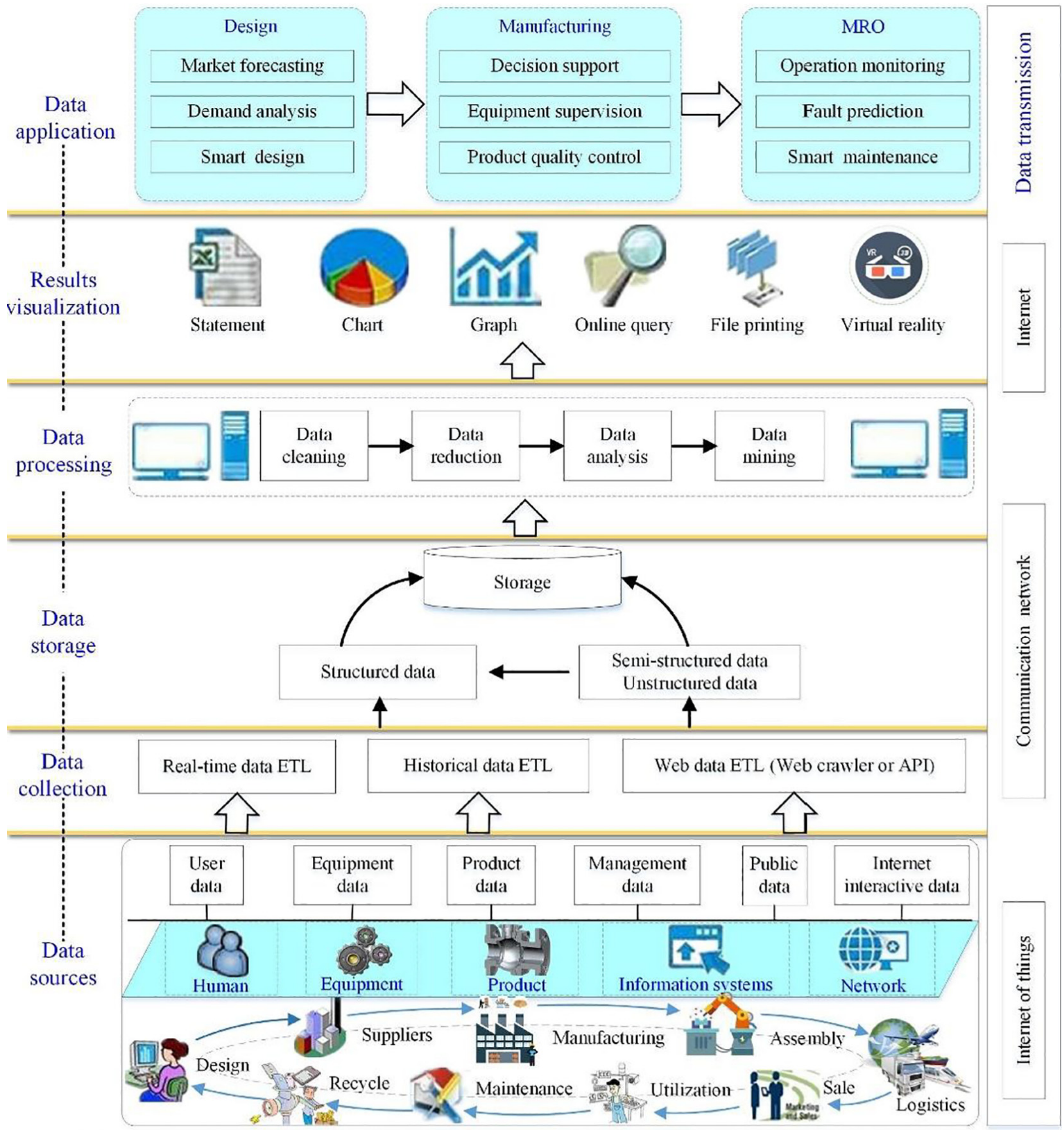
process continuously large amounts of unstructured heterogeneous data collected in formats such as video, audio, text, or others [51], additionally, other dimensions have also been attempted to assign for a better characterization such as: Veracity, Vision, Volatility, Verification, Validation, Variability and Value [56]. According to several authors [21,51,56–57], the description of the dimensions as follows:

- Volume – great data volume size consuming large storage or consist of enormous number of collections. BD sizes are mentioned in multiple terabytes and petabytes;
- Variety – various types of data, generated from a large sources and formats variety, and multi-dimensional data fields contents. It refers to the structural heterogeneity in a dataset;
- Velocity – rapid production. Generation, analysis, delivery, and data creation measured by its frequency. It refers to the data generation rate and the speed for analyzing and acting upon;
- Veracity – represents the unreliability in some data sources. Some data requires BD analysis to gain reliable prediction;
- Vision – only a purposeful process should send data generation. The likelihood of data generation process is addressed in this dimension;
- Volatility – a limited useful life can characterize data generated. The data lifecycle concept is addressed by this dimension. It ensures the replenishment of the outdated data with new data;
- Verification – conformity of the data generated by a specification set. It ensures the conformity of the engineering measurements;
- Validation – the vision conformity of the data generated. Behind the process, the transparency of assumptions and connections are ensured;
- Variability – data flow rates measured by its variation. Variability and Complexity was added as two additional dimensions of BD;
- Value – through extraction and transformation, defines how far BD generates economically worthy insights and benefits. Value as a defining BD attribute.

On manufacturing domain and at the BD process comprehension, it is the engineering aspects that give value to the BD analysis using its dimensions [51]. These dimensions are dependent from each other, related with the relativity of BD volumes applied to all dimensions [56].

To explore data, advanced data analysis is required. Using CC through the advanced analytics, methods and tools, off-line and real-time data are analyzed and mined, e.g., machine learning, forecasting models, among others. Knowledge is extracted from the huge data number enabling manufacturers on understanding the product lifecycle various stages [50]. Moreover, the advanced analytics of BD can be used as a facilitator, identifying and overcoming bottlenecks created by IoT generated data [58].

The mutation opportunity from today's manufacturing paradigm to smart manufacturing is offered by BD [59]. Therefore, BD can help manufacturers on more rational, informed and responsive decision-making way. Manufacturing competitiveness in the global market is enhanced by these BD characteristics. Various stages in data lifecycle where manufacturing data is exploited are depicted in Fig. 9 consisting on the complete manufacturing data journey.



ETL: Extract-Transform-Load **API**: Application Programming Interface **MRO**: Maintenance, Repair & Operations

Fig. 9. Manufacturing data lifecycle [59].

According to Mourtzis et al. [58], in a framework structured by levels of a manufacturing enterprise, the lower level generates data directly from machine tools and operators. For an enterprise, this data is very important, providing precious information when used and analyzed enabling adaptivity and flexibility on the higher levels of the enterprise.

BD analytics is an essential key to digital manufacturing, playing as an enabler for technologies. Moreover, the scope of mass customization focusing on the needs of individualized markets, use BD analytics as foundation [58].

As mentioned above, IoT data converges to BD in order to analyze it and take conclusions from collected datasets. In other words, IoT data will be a part of BD [21] and BD cannot be explored further without the IoT [57]. Furthermore, CC and BD are considered as a coin with its two faces: BD is seen as the absorbent application of CC, while CC provides the IT infrastructure of BD [57].

3.4. Simulation

For the successful implementation of the digital manufacturing [60], an indispensable and powerful tool, the computer simulation, is becoming a technology to better understand the dynamics of business systems [61]. Manufacturing industry current challenges can be approached by this technology [62], dealing with the complexity of the systems, with elements of uncertain problems that cannot be resolved with usual mathematical models [63]. On a customized product manufacturing environment, the value of simulation is remarkable and evident. Simulation allows experiments for the validation of products, processes or systems design and configuration [60]. Simulation modeling helps on cost reduction, decrease development cycles and increase product quality [61]. In order to analyze their operations and support decision-making, manufacturers have been using modeling and simulation [64]. Simulation technologies already proved its effectiveness in the approach of several practical real-world problems in manufacturing sector [65]. Mourtzis et al. [60] presented on their research, the domain areas of simulation as shown in Fig. 10 with the focus on simulation methods and tools. Simulation is defined as an operation imitation, over time, of a system or a real-world process. It uses a system's artificial history and its observation, drawing inferences over the operational features of the representation of the real system.

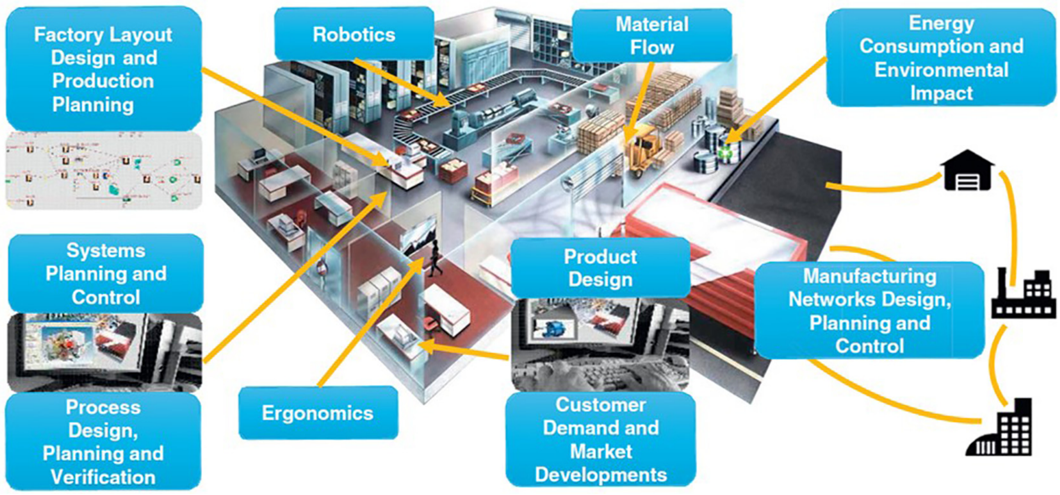


Fig. 10. Domains on simulation research of contemporary manufacturing [60].

Simulation modeling is the method that makes use of a real models or imagined system models or imagined process models. It helps on a better estimating and understanding the modeled systems or process through its behavioural analysis [61]. A model is an entity (generally a simplified abstraction) used to represent other entity with a particular defined purpose [66]. Simulation modeling allows to gain insights into complex systems by the development of complex and versatile products and make possible to test new concepts or systems, resource policies and new operating before its real implementation, allowing to gather information and knowledge with no interference on the actual running system [60]. The Fig. 11 shows types of simulation models discussed by Mourtzis et al. [60] regarding to the classification, dimensions, and differences.

Choose and develop the best suitable type of simulation model to represent the real system is a multiparameter decision, e.g., static models for modelling a structure without activity and dynamic models for investigating the behaviour of a system evolving through time [67].

Simulation have been playing a spotlight role in design evaluation (referred to as off-line) and operational process performance (referred to as on-line) during a manufacturing system [65,67].

Its usual the existence of making long-term decisions on the design process [67] in, e.g., facility layouts, system capacity configurations, material handling systems, flexible manufacturing systems and cellular manufacturing systems [65]. Simulation runtime in off-line is not significant on the simulation process, offering the advantages to study and analyze the what-if scenarios [67].

On the operational process of the manufacturing system, e.g., manufacturing operations planning and scheduling, real-time control, operation policies and maintenance operations [65], the decision-making is short-term, making the simulation runtime a very important aspect. On-line simulation relates the number of entities belonging to the production system, the number of its generated events, the activities complexity and simulation time horizon. If the IT system is integrated with the on-line simulation, for instance, it's possible to own the capacity to estimate the future shop floor behaviour and to emulate and/or determinate the manufacturing system logic control [67].

Optimal or near-optimal system design is the goal for decision makers. This optimization is possible due a systematically search on a wide decision space without restrictions or pre-specified requirements. This simulation optimization tool will search for the optimal design within a given system, according to the com-

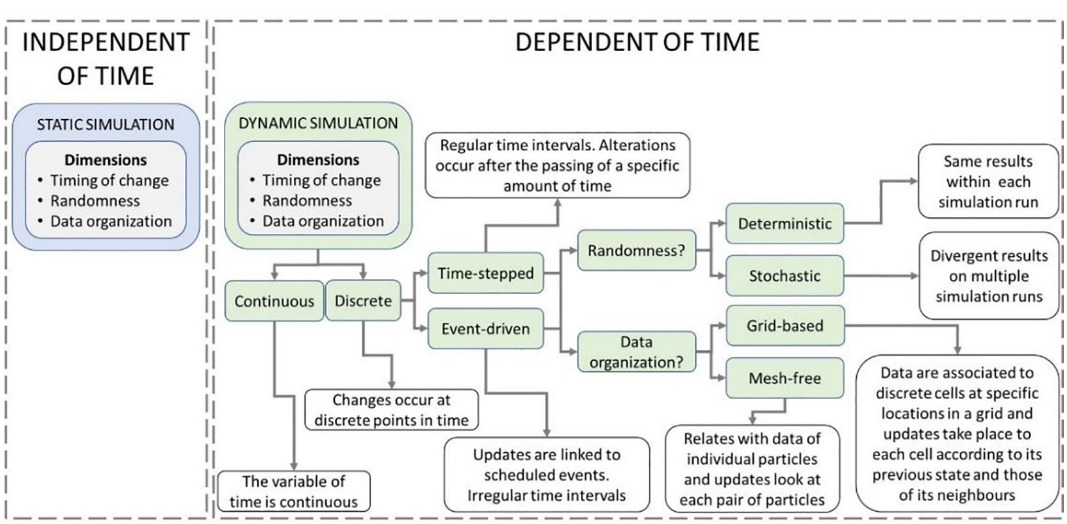


Fig. 11. Types of simulation. Based on [60].

puter simulation model. On dynamic and uncertain environments, this tool has the potential on optimizing control decisions and on supporting real-time decision-making. This can be possible when the required computational efficiency is reached [68]. Compared to conventional simulation, real-time simulation, on-line, can analyze the behaviour of user and system in milliseconds, allowing the user to develop and produce "virtually" a prototype for the product or service [69]. According to Cedeño et al. [69], a real-time simulation is when a computer runs at the same rate as the physical system, so the simulation model needs to be feed with real-time data that can be reached using IoT.

A high-fidelity simulation of a manufacturing factory is defined as Virtual Factory (VF). An industrial collaboration environment focusing on Virtual Reality (VR) representation of a factory [70] or an emulation facility [71] can be considered a VF. The VF vision considers validated real factories simulation models to generate data and to be worked in formats of real conditions in a real factory [64].

The new simulation modeling paradigm is based on the concept of Digital Twin (DT) [61]. An ultra-high-fidelity simulation is provided by the DT concept and it plays an important role in I4.0. It extends simulation to all product lifecycle phases, combining real-life data with simulation models for better performances in productivity and maintenance based on realistic data [61].

Technologies based on simulation are the core role in the digital factory approach, allowing experiments and validation upon different manufacturing system patterns, processes and products [72].

3.5. Augmented Reality

New challenges are coming with Augmented Reality (AR) usage in everyday [73]. Increase human performances is the aim of AR, supplying the needed information to a given specific task [74]. This novel technology provides powerful tools, acting as an HMI [75]. AR technology can be found on a wide range of sectors, e.g., entertainments, marketing, tourism, surgery, logistics, manufacturing, maintenance, etc. [76]. As a growing evolving technology, recently, AR usage is spreading to different manufacturing fields [77]. The use of AR on manufacturing processes regarding to simulation, assistance and guidance has been proven to be an efficient technology helping on problems [78]. AR technology increase reality operator's perception by making use of artificial information about the environment, where the real world is fulfilled by its objects [79–80]. As long as it interacts with human senses, AR can make use of any kind of hardware [74]. Using AR can help on closing some gaps, e.g., between product development and manufacturing operation, due to the ability to reproduce and reuse digital information and knowledge at the same time that supports assembly operations [78]. Fig. 12 shows the most relevant tasks related to industrial environments and manufacturing fields where the AR brings value.

The principle of AR is the combination of two scenarios: 1) digitally processed reality with 2) digitally added artificial objects that could be 2D flat objects, or by other definitions that only considers 3D objects within the scene [73]. The authors [79–80] defined AR system features as: 1) the ability on combining real and virtual objects on a real environment, 2) the ability on align each other the real and the virtual objects, and 3) the ability on running interactively, in 3D, and on real-time.

Making use of conventional hardware, the use of AR has a big advantage that can be minimal or even zero purchase expense. Some cases, the see-through glasses component can be more expensive [73]. On industrial environment, other key advantage was pointed by Blanco-Novoa et al. [81] about the assets: AR provides dynamic real-time information, so it can suppress most of the paperwork.

The AR system software might be selected based on environment's considerations, which obviosity differ among them, e.g., on the military environment the proper use is zero-connectivity to ensure CS, differing from commercial environment that requires providing remote assistance's connectivity [74].

The essential parts of an AR system make use of electronic devices to directly or indirectly view a real-world combination with virtual elements. According to Fraga-Lamas et al. [75], these elements can be:

- Image capture element – web camera is sufficient [73];
- Display – for projection of the virtual information on the images acquired by the image capture element. Basically, three device types with optical options can be used [80,82]: 1) hand-held (video and optical), 2) head-worn (video, optical, and retinal), and 3) spatial (projector and hologram);
- Processing unit – to generate virtual information to be projected;
- Activating elements – to trigger the display of virtual information, e.g., sensors, QR markers, GPS positions, images, etc.

In order the user to visualize information, these AR devices use types of optics as follows [82]:

- Video – merged worlds (real and virtual) into the same digital view;

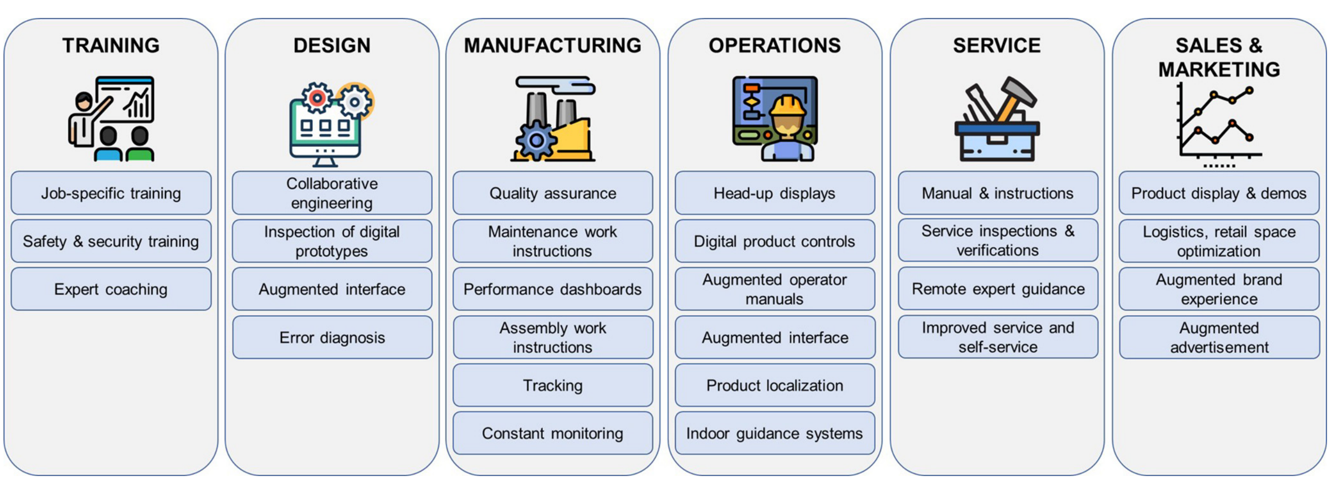


Fig. 12. Value of industrial AR across I4.0. Based on [75,77].

Fig. 13. Conceptualization of using the AR-QDA application on a full productive line [83].

Fig. 14. Step-by-step assembly procedure [76].

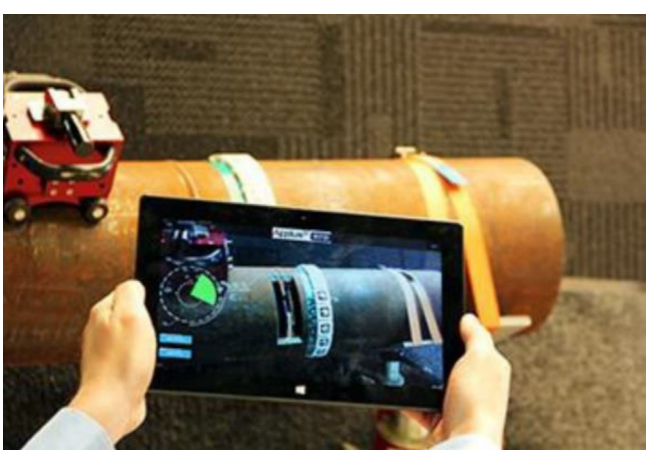


Fig. 15. AR in non-destructive testing on pipelines [84].

- Optical – real world with virtual objects overlaid directly on the view;
- Retinal – direct projection of virtual objects onto the retina with the use of low-power laser light;
- Hologram – real world mix with virtual objects using a photometric emulsion;
- Projection – projection of virtual objects directly on real-world objects with the use of a digital projector.

Related to the quality of products, Segovia et al. [83] proposed an AR system solution to production monitoring, based on Statistical Process Control (SPC) and Six Sigma methodology. It uses AR in real time reports to assist quality data reporting by monitoring Cpk indexes to support the decision-making process. The AR system was linked to a Computer-Aided-Quality (CAQ) to receive data. The CAQ used was Quality Data Analysis (QDA) software that allows the user to verify quality goals. The used measurement device was wireless connected to QDA software. The QDA software generated reports and exported them automatically in a file to the AR application. The mobile device used to run the AR application was a tablet. Fig. 13 shows the AR technology with the inside of the facilities and the displayed Key Performance Indicators (KPI) of each workstation. According to Segovia et al. [83], one of the biggest benefits of this tool is the reduction on audit times.

Maintenance is one of the most promising fields of AR. It enhances human performances in technical maintenance tasks execution as also supports on maintenance decision-making [76]. One example of AR in maintenance is shown in Fig. 14 on a step-by-step assembly procedure of a consumer device, using Hand-Held Display (HHD) to carry out maintenance tasks. The AR application has text description of the task on the bottom, right and left arrows to go forward and backward on the procedure.

Other example in the use of AR technology is on the diagnostics field. A meaningful example is shown in Fig. 15, also with the use of an HHD. The defects inspection and mapping on the pipe was made with a 3D image. The defects position is indicated on the pipe and it can be seen a clearer image of the nature and scale of defects. At the end, the operator can detect, locate and mark defects using a tablet and a marker [84].

3.6. Additive Manufacturing

Products and services innovations needs hard and long research work and development that I4.0 with the novel technologies such as simulation via virtual reality are enabling it. However, on the next step, there is a manufacturing process with its related costs that can be a barrier to competitiveness. Additionally, at the end, there is a dilation of product or service lead time for markets.

The Additive Manufacturing (AM) paradigm is being increasingly developed and it brings into real industry, high feasible applications [85]. Jian et al. [86] discussed the potential of AM on the replacement of many conventional manufacturing processes. AM is an enabling technology helping on new products, new business

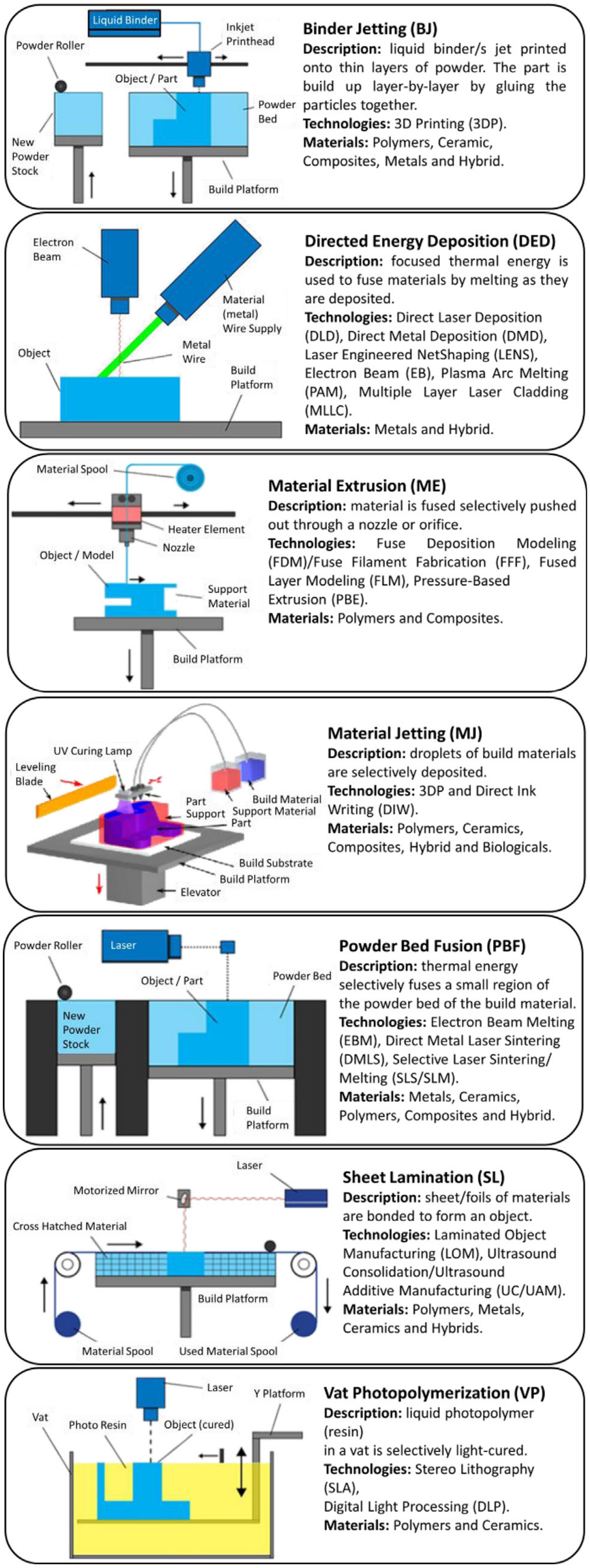


Fig. 16. Categorized AM processes. Based on [88–89,138–139].

models and new supply chains. A set of technologies that enables "3D printing" of physical objects form the collective term AM [87]. Products such as one-of-a-kind, can be manufactured without the conventional surpluses, so it is a big advantage. AM technologies can be referred also with other synonyms such as rapid prototyping, solid freeform manufacturing, layer manufacturing, digital manufacturing or 3D printing [88]. With AM it's possible to create prototypes to allow value chain elements independence, and therefore, achieving time reduction on design and manufacturing process.

As follows in Fig. 16, AM processes are classified into seven categories according to the standard of the International Organization for Standardization (ISO)/American Society for Testing and Materials (ASTM) 52900:2015 (ASTM standard F2792).

AM technology is defined by Kim [85] as a process of creating a 3D object-based on the deposition of materials on layer-by-layer or drop-by-drop under a computer-controlled system. Some potential benefits of AM can be summarized as follows [89]:

- Manufactured parts directly from CAD data files (final or near final parts with minimal to no additional processing);
- Greater customization without extra tooling or manufacturing cost;
- Manufacturing of complex geometries (some geometries cannot be achieved on conventional processes, otherwise, it is achieved by splitting it into several parts);
- Manufacturing of hollow parts (achieving less weight) or lattice structures;
- Maximization of the material utilization for the "zero waste" approach;
- Smaller operational foot-print towards manufacturing a large variety of parts;
- On-demand manufacturing and excellent scalability.

According to Shin et al. [90], AM workflow includes the geometry design, computational tools and interfaces development, material design, process modeling and control tools, and it was also discussed the AM applications fields such as nano-scale (bio-fabrication), micro-scale (electronics), macro-scale (personal products, automotive), and large-scale (architecture and construction, aerospace and defense).

For the next generation of AM processes, Chang et al. [91] discussed novel processes such as micro/nano scale 3D printing, bio-printing (AM of biomaterials), and 4D printing (combination of AM with smart materials (stimulus-responsive that change their shape or functional properties)) to fabricate within high resolution a complex 3D features, in multi-materials, or multi-functionalities.

On a near future, AM technology will expand eventually to super-advanced technology areas and substitute current technologies [85].

3.7. Horizontal and Vertical Systems Integration

Engineering, production, marketing, suppliers, and supply chain operations, everything connected must create a collaborative scenario of systems integration, according to the information flow and considering the levels of automation [18]. In general, the systems integration of I4.0 has two approaches: horizontal and vertical integrations [10,92]. Real-time data sharing is enabled by these two types of integration [16].

Horizontal integration is the inter-company integration [92] and is the foundation for a close and high-level collaboration between several companies, using information systems to enrich product lifecycle [16], creating an inter-connected ecosystem within the same value creation network [10,92]. It is necessary an independent platform to achieve interoperability on the development of these systems, based on industrial standards, enabling exchanging data or information [92].

Vertical integration is a networked manufacturing system [93], the intra-company integration [92] and is the foundation for exchanging information and collaboration among the different levels of the enterprise's hierarchy such as corporate planning, production scheduling or management [10,93]. Vertical integration "digitizes" all the process within entire organization, considering all data from the manufacturing processes, e.g., quality management, process efficiency or operations planning that are available on real-time. By this, in a high level and flexible way, providing the small lot sizes production and customized products, the vertical integration enables the transformation to SF [16]. It's important to refer that standards must be the bases of the vertical integration [92].

According to several authors [16,93–96], the paradigm of I4.0 in manufacturing systems has another dimension between horizontal and vertical integration considering the entire product lifecycle. This kind of integration is based on vertical and horizontal integrations [93]. In a vision of holistic digital engineering, as the natural flow of a persistent and interactive digital model, the scope of the end-to-end digital integration is on closing gaps between product design and manufacturing and the customer [94], e.g., from the acquisition of raw material for the manufacturing system, product use and its end-of-life. The phase of end-of-life product contains reusing, remanufacturing, recovery and disposal, recycling, and the transport between all phases [95]. Fig. 17 shows the relationship between the three types of integration on a manufacturing system, considering vertical integration as the corporation(s), horizontal integration between corporations, and end-to-end integration linking design, production and logistics as an example.

3.8. Autonomous Robots

Manufacturing paradigm is shifting rapidly production from mass towards customized production, requiring robots, for instance, as a reconfigurable automation technology. The impact on the production systems of the manufacturing companies is that this trend leads to the production adaptation for a wider product variation, focusing ideally on batch size one. Nowadays, to reach the flexibility demanded level, robots are essential on production systems [97]. Towards that, abilities on computing, communication, control, autonomy and sociality are achieved terms when combining microprocessors and Artificial Intelligence (AI) with products, services, and machines to make them become smarter. Robots with AI, adaptive and flexible, can facilitate different products manufacturing and consequently providing decreasing production costs [16]. In addition, a robot also can be seen as one of the forms of AI [98].

Processes such as product development, manufacturing and assembling phases, are processes that adaptive robots are very useful on manufacturing systems [16]. It is important to refer that fully autonomous robots make their own decisions to perform tacks on a constantly changeable environments without operator's interaction [99]. Fig. 18 shows an overview, not strict, on the autonomous robot characterizations, considering industrial and non-industrial environments.

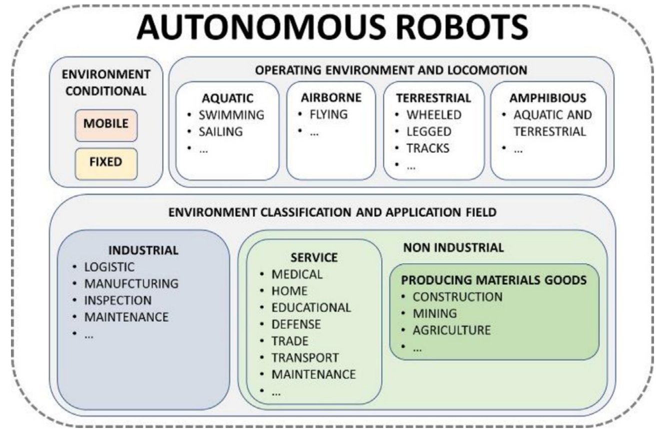


Fig. 18. Characterization scheme for autonomous robots. Based on [99,140].

Dirty or hazardous industrial applications on unstructured environments can be improved by an Autonomous Industrial Robot (AIR) or multiple in a close collaboration. Hassan et al. [100] presented a multiple autonomous robot's collaboration approach in Fig. 19, consisting on robots with different capabilities performing grit-blasting and spray painting.

According to Hassan et al. [100], with the deployment of multiple autonomous industrial robots working as a team, it's possible to have a larger range of manufacturing applications. Other approach in multi-robot systems can be seen in Fig. 20 during a

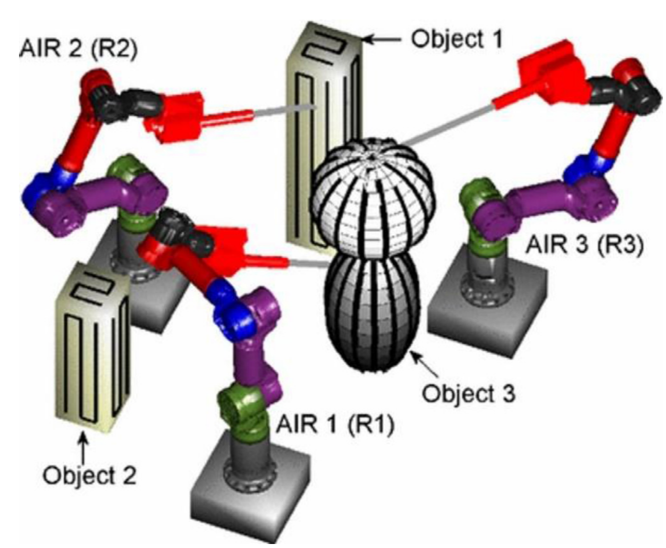


Fig. 19. Autonomous industrial robots performing grit-blasting or spray painting [100].

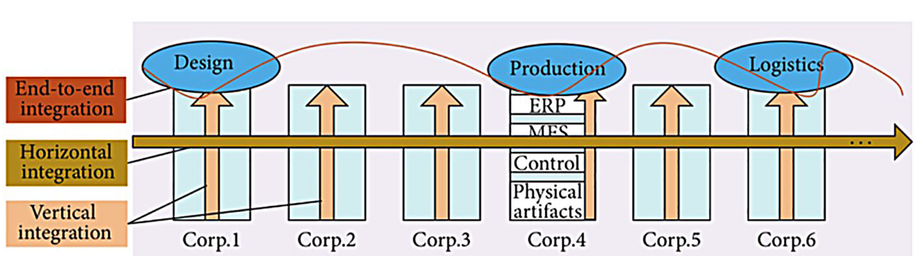


Fig. 17. Types of integrations in the manufacturing system [96].

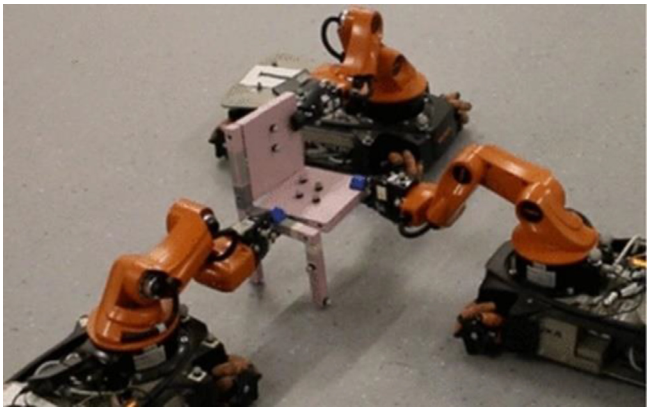


Fig. 20. Assembly configuration robots [101].

sequence of collaborative assembly operations, dealing with robot configurations to grasp assembly parts and build complex structures such as a chair [101].

Collaborative robots concept also introduces the proximity of robots with humans [102]. On the vision of SF, collaborative robots (cobots) and humans will work closely together. Cobots are a category of robots specially designed to interact directly and physically with humans, in a close cooperation [103–104]. This is possible due to the safety existing limits on speed and forces that automatically restarts the cobot allowing to guide the cobot by hand [103]. By this, for manufacturing companies, human-robot barrier is break down offering bigger affordability and flexibility on solutions [104].

3.9. Cybersecurity

Every year, increasingly, devices are connected to the global network: the internet. In a close future, the main source of data will be inanimate objects [105]. By this, IoT, virtual environments, remote access, stored data on cloud systems, etc., are many open opportunities that represents increasing new vulnerabilities leading to a compromised information for people and enterprises. The risk scenario becomes reality because the enterprise boundaries are unclear and are vanishing [106]. Kannus and Ilvonen [107] defined Cybersecurity (CS) as a new term on a high level of information security, and through the word “cyber” it spreads to apply also on industrial environments and IoT. CS is a technology laying on protecting, detecting and responding to attacks [108].

IoT has to be built based on safety communications on each point of the manufacturing process and safety interoperability has to be assured between facilities as basic elements of the supply chain value. I4.0 technologies must allow the creation of a safety cyber environment, benefiting on CS.

Direct attacks from evil persons and/or software can be hard jeopardies to Industrial Control Systems (ICS). These ICS of the industrial sectors are basically control such as Supervisory Control and Data Acquisition (SCADA), process control systems, distributed control systems, CPS or Programmable Logic Controllers (PLC) [109]. The increasing of connected devices means more possibilities of cyber-attacks. Benias and Markopoulos [110] discussed why industrial devices get hacked, the main reasons as follows:

- Devices running for too much time (weeks or months) without updating security or anti-virus tools;
- Considerable number of old controllers used in ICS networks, designed when CS was not a concern;
- CS threats can enter bypassing CS measures due to the existence of multiple pathways from several ICS networks;
- Quick spread of malware due to several ICS networks that still remains implemented as a flat network without physical or virtual isolation among other unrelated networks.

I4.0 creates valuable information that needs to be protected. Information and data security are critical for the industry success. It is important that data is available just for authorized persons. Integrity and information sources must be ascertained. I4.0 has raised two demands for CS in order to secure smart manufacturing systems: Security Architecture and Security by Design. Hence, attacks, threats and malware must be automatically detected with zero-installation by the systems [106]. Manufacturing operations can be shut down by a cyber-attack, therefore, companies have money losses, but the main issue are cyber-attacks targeting systems requiring safety operations and representing a serious risk for the safety of the operators [111]. Elhabashy et al. [112] discussed other approach on manufacturing environments regarding to some potential attacks such as modifying product designs (related to CAD files, tolerances), modifying manufacturing processes (Computer-Aided-Manufacturing (CAM) files, machine parameters, used tools, tool paths) or manipulating process/product data (inspection results, indicators of machine maintenance). These attacks can delay a product’s launch, cause the production of modified products, can ruin customer trust or increase warranty costs.

The cyber-attack could be internal and/or external source. According to Khalid et al. [113], in Fig. 21, a cyber-attack can come from an internal source such as an operator that physically access to a data port or an external source such as an outside communication channel or also a wireless transmission.

The ICS safety is time-sensitive so an automatic incident response is need it. For a variety of industrial attacks, Software-Defined Networks (SDN) and Network-Function Virtualization (NFV) can facilitate automatic incident response. The incident response in ICS can be achieved using a private-cloud architecture (cost-effective investment). SDN and NFV makes automatic incident response possible to rapidly detect and temporarily replace the failing systems with virtual implementations of those systems. SDN and NFV are technologies to improve the following aspects: 1) network visibility, 2) network capabilities (enables network traffic flows with better management), and 3) network functions deployment and control using software, instead of specific hardware middleboxes [108]. However, the combination of SDN with NFV shows a capable approach in new defense solutions in depth for ICS [114].

The concept of defense-in-depth, as showed in Fig. 22, was discussed by Jasen et al. [115], according to the international standard IEC/ISA-62433 with the incorporation of three measures as technological, organizational, and human-centered, as multilayer approach for security ICS. Security controls at system level, network and plant must exist on this concept.

Updating the implemented security controls continuously is obligatory, keeping the protection up-to-date [115], such as follows on:

- Device level - with the installation of new security patches;
- Network level - with the firewall signatures of new threats updated;
- Plant/factory level - with the analysis and monitoring of the actual log sources.

4. The Smart Factory of the I4.0

According to several authors [2,4–8,116], the framework of the I4.0 is the development of the Smart Factory (SF). In conceptual terms, the SF is the heart of I4.0 [117]. CPS, IoT and IoS were assumed as the main components of I4.0 [1].

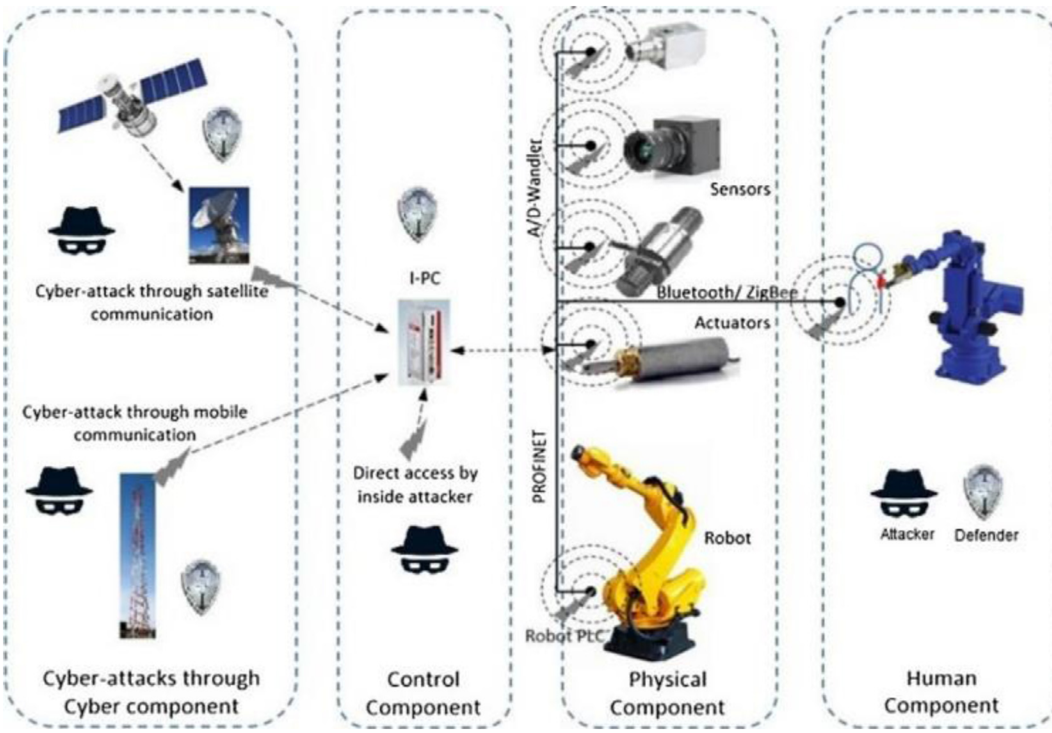


Fig. 21. Cyber-attack routes in an industrial connected manufacturing and logical effect diagram for human-robot collaboration [113].

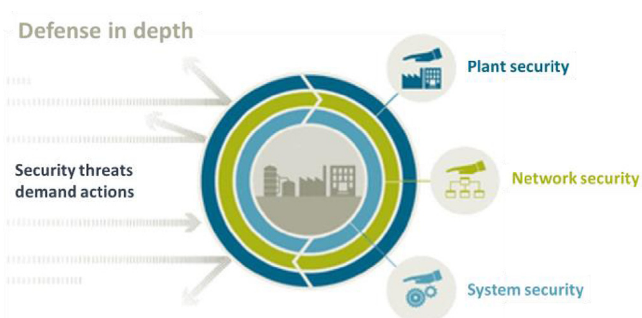


Fig. 22. Defense-in-depth [115].

These components have very closely linked each other, enabling the SF and built on the concept of decentralized production system with a social network connecting persons, machines and resources [1]. Using cloud-based manufacturing in SF, both IoT and CPS technologies converges to IoS to create, publish and share the manufacturing processes, represented in services that could be supply by virtual enterprises [118].

Compared to humans living in two worlds such as the physical and the cyber world, SF will work on the physical and on the DT, in the cyberspace. The DT will collect generated data from manual inputs and sensor networks, will process data on cyberspace and take the corrective actions on real-time to handle the physical world [29].

Based on the manufacturing process digitalization, I4.0 is the development of a new generation of SF's [24]. According to several authors [2,4,8,10], in this new generation of SF, the main key technology is CPS. SF is the key feature of I4.0 and the core concept component, where vertical integration occurs, the horizontal integration occurs in the SF value network and across different SF's, enabling end-to-end engineering integration across the entire value chain [119]. Fig. 23 identifies the transformation technologies of the current industrial production in a SF framework.

4.1. Cyber-Physical Systems

Cyber-Physical Systems (CPS) has the potential to change our life with concepts that already emerged, e.g., robotic surgery, autonomous cars, intelligent buildings, smart manufacturing, smart electric grid, and implanted medical devices [120] (e.g., a pace maker in a smaller scale [121]). CPS represents the latest and significative developments of Information and Communication Technologies (ICT) and computer science [120].

CPS is the merger of "cyber" as electric and electronic systems with "physical" things. The "cyber component" allows the "physical component" (such as mechanical systems) to interact with the physical world by creating a virtual copy of it. This virtual copy will include the "physical component" of the CPS (i.e., a cyber-representation) through the digitalization of data and information. By this, CPS can be assumed as a range of transformative technologies to manage interconnected computational and physical capabilities [122]. CPS embraces smart elements or machines who has the augmented intelligence and ability to communicate each other to make part of planning, unique or non-repetitive tasks. These smart elements, for instance, can control the needs of workpieces, alter the manufacturing strategies for the optimal production, choose (if already exists) or find a new strategy all by themselves. These elements will build their own network [123]. In other words, the CPS core is the embedded system to process information about the physical environment. This embedded system will perform tasks that were processed by dedicated computers. CPS model can be described as a control unit with one or more microcontrollers, controlling sensors and actuators that interacts with the real world and processes the collected data [124–125]. A communication interface will enable this embedded system to exchange data with the cloud or with other embedded systems. CPS is associated with the IoT concept [126]. According to Humayed et al. [127], CPS mainly consists of three components such as: 1) communication; 2) computation and control and; 3) handling and monitoring. The CPS communication can be both wired or wireless

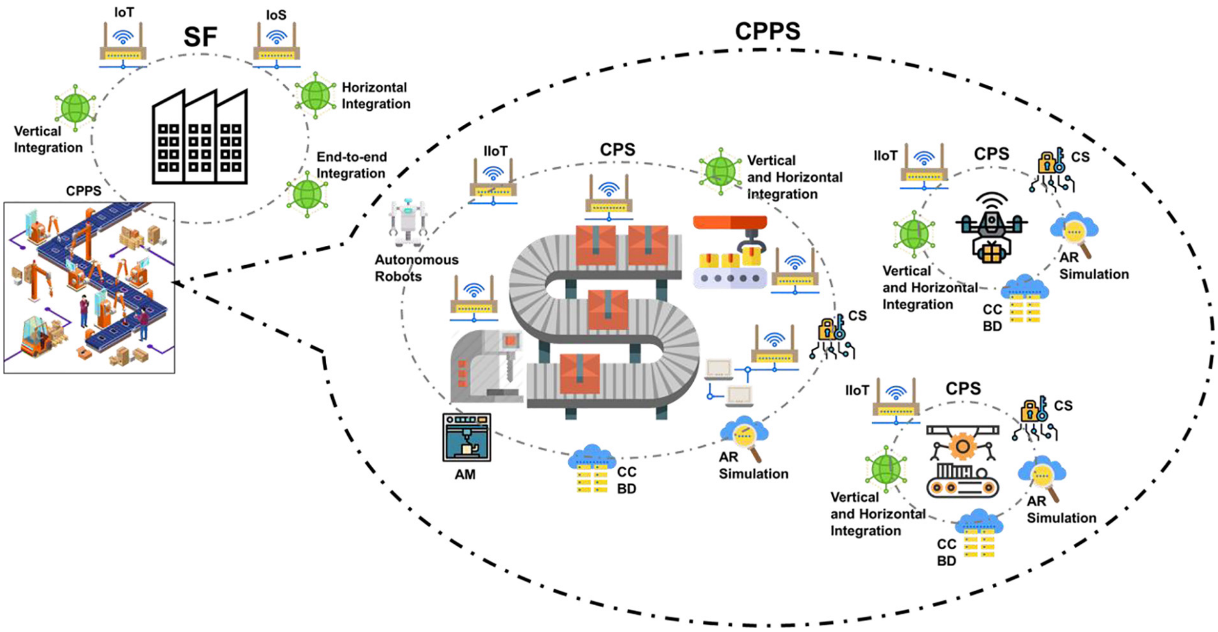


Fig. 23. Development of the SF for the I4.0 implementation.

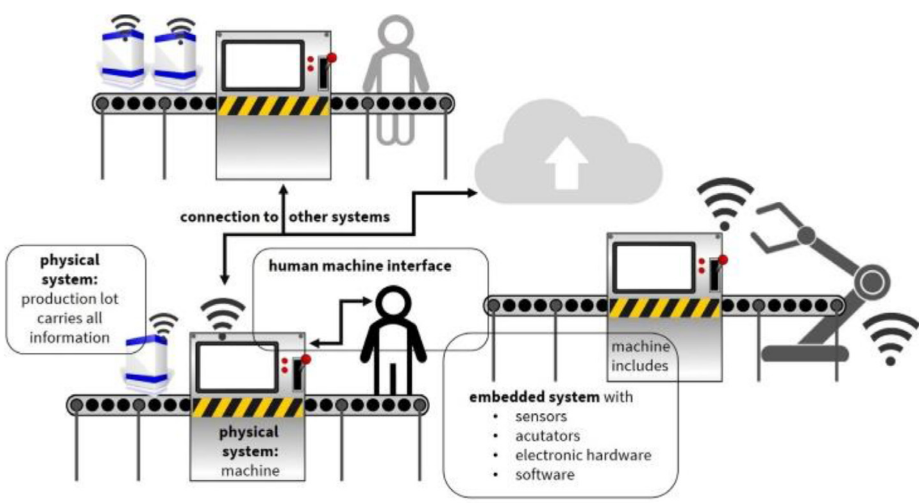


Fig. 24. Structure of a manufacturing CPS [128].

and connects CPS to a higher level such as control systems, or lower-levels such as physical world components. The intelligence is embedded on the computation and control component with the exchange of control commands and received measures. CPS is connected to the physical world by the handling and monitoring component, using actuators to handle physical components and using sensors to monitor them [127].

Referring a manufacturing system and according to Keil [128], Fig. 24 shows a schematic representation of a CPS, an embedded system integrated in physical systems such as production lots or machines. The sensors collect physical data and the electronic hardware and software will save and analyze it. The interaction between data processing and other physical or digital systems are the CPS bases. it's also possible to identify an HMI in this CPS schematics for supervision and exchange information.

Several CPS linked within digital networks form a Cyber-Physical Production System (CPPS) [128], based on sub-systems and autonomous and cooperative elements linked across all levels of production [120]. According to Rojas et al. [129], CPS are the building blocks for the SF, structured as CPPS. The collected data will be sent to BD and become accessible via CC. The CPPS interaction with the virtual world enables IoT in manufacturing [13,118]. As the system are getting intelligence regarding to the so-called smart objects, the IoT creates the connect environment with smart objects to the global internet. Several authors [3,6,10,19,58,94,113,121,124,130] discuss the level of cooperation and communication of CPPS in manufacturing.

The implementation of CPPS in the SF leads to a fundamental design principle as the real-time management in industrial production scenarios. CPPS will make the automation pyramid approach on a different manner. The traditional automation pyramid, as shows the Fig. 25, is partly break at the PLC's level. The field level and control remain including closest PLC's of the technical processes to improve critical control loops, and the highest levels of the hierarchy will be decentralized [131].

In the CPS-based Automation of the Fig. 25, the squares represent inputs/outputs devices, the lines represent service interactions and the blue, yellow, grey and black points represent the

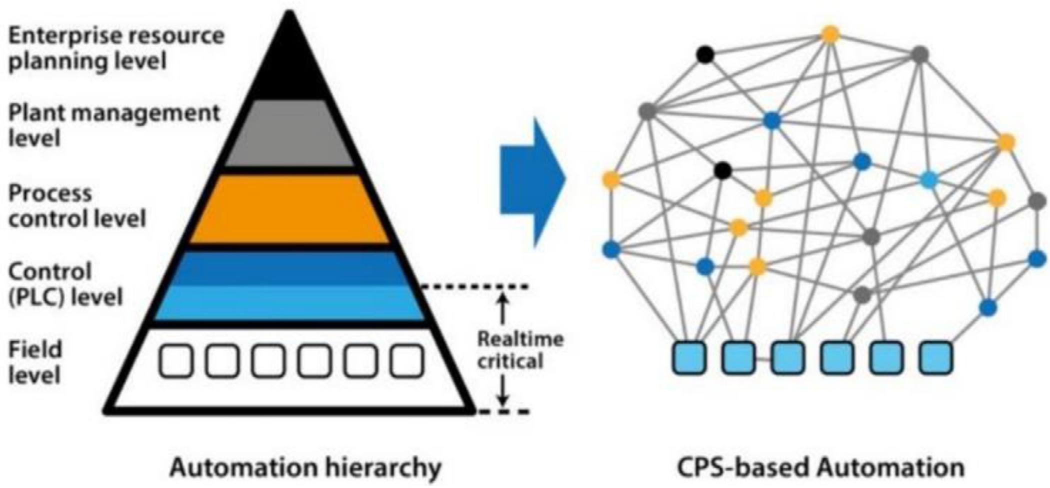


Fig. 25. Hierarchy decomposition of the traditional automation pyramid and the CPS approach [131].

corresponding functionalities of the five-layer architecture of the traditional automation pyramid [126].

Some researchers are developing a five C's structure for better analyzing I4.0. This five C's architecture can guide the development of I4.0 and it is dependent of CPS attributes. These five levels are: Connection Level (main attribute is self-configurable), Conversion Level (main attribute is early-aware), Cyber Level (main attribute is controllable), Cognition Level (main attribute is informational) and Configuration Level (main attribute is communicable) [116,132–133].

4.2. Internet of Services

Replacing physical things by services, the Internet of Services (IoS) is based on the concept that services are available through the internet so that private users and/or companies can create, combine and offer new kind of value-added services [1]. IoS can enable service vendors to offer their services on the internet. Thus, the manufacturing industry of product-oriented trend is rapidly shifting for service-oriented to enable gaining revenue through all lifecycle of a product service system. By this, high quality on products can be enable by SoA, and side-by-side, gives a strong competitive position for companies through the value-added services. IoS enables collecting product information, e.g., during its operation, for updates and for the development of new services, increasing the perceived product quality [29]. IoS is consider by Andulkar et al. [29] as the technology to monitor the product lifecycle.

5. Conclusions and Outlooks

As aforementioned, the foundations of the I4.0 are the advanced technologies of automation, and the ICT present across this review. Key challenge of I4.0 is to make the production systems more flexible and collaborative. For this purpose, the use of enabling technologies is the strategy that is behind of I4.0 paradigm. On an industrial context, each implemented technology in an individual manner will present a lower impact. On the other hand, when implemented together, it offers new possibilities to embrace the future. For instance, one of the I4.0 impact will be the elimination of monotonous work as well as physically demanding jobs.

IoT is an infinite world of possibilities on innovation and optimization, due to the combination of many advanced systems and technologies such as BD and analytics, AI, networks, clouds, intelligent objects, robotics, middleware, people, among others.

The development of a CMfg service integration platform is proposed by Mai et al. [46] as a promising concept. It is an online tool consisting on build a process with several sub-tasks with a series of modules sequentially connected each sub-task. This concept allows consumers to have customized products or even make products in the cloud. Even more, through CMfg, producers can create smart solutions to save costs and improve profits. A crucial note is the improvement of the safety and security regarding to online services that was mentioned at all examples. The development of CS technology deserves maximum efforts from all actors, since individual, professional users, and organizations that need to be safe and secured to face these rapid technological advances.

The Systems integration of I4.0 has two major characteristics relying on vertical and horizontal integration. The vertical integration of the manufacturing processes, breaks the traditional automation pyramid, focusing on distributed and collaborative architectures. The horizontal integration allows the creation of a new kind of value-added [129]. By this, there is an unavoidable surrounding of customers and suppliers that are involved just from the beginning of the product life cycle.

A challenging scenario with the deployment of I4.0 will be the extinction of the centralized applications used in common manufacturing environments, that leads to decentralized systems as one of the main I4.0 goals. By this meaning, distributed computing systems also plays a key role on I4.0 paradigm. It allows to save time on computing runtimes, allows working with more accurate details on smaller systems and for the overall system, and decreases the fail reaction time, e.g., if one computing system fails the others can continuing on computing.

Providing a guideline for the interdisciplinary I4.0 technologies, the RAMI4.0 was developed, describing the connection between IT, manufactures/plants and product lifecycle through a 3D space. The integration of RAMI4.0 and I4.0 component (component as, e.g., a production system, an individual machine or an assembly inside the machine) close the gap between standards and I4.0 technologies at the production level, leading to the emerge of CPPS [130].

Interoperability is one of the I4.0 design principles and can be found between BD and simulation as discussed by Shao and Jain [64]; BD on its analytics supports simulation by estimating the unknown input parameters and performing data calibration for simulation and its validation results. The return is the support of simulation for BD analytics on various roles. Data analytics application can summarize and report production trends (e.g., product

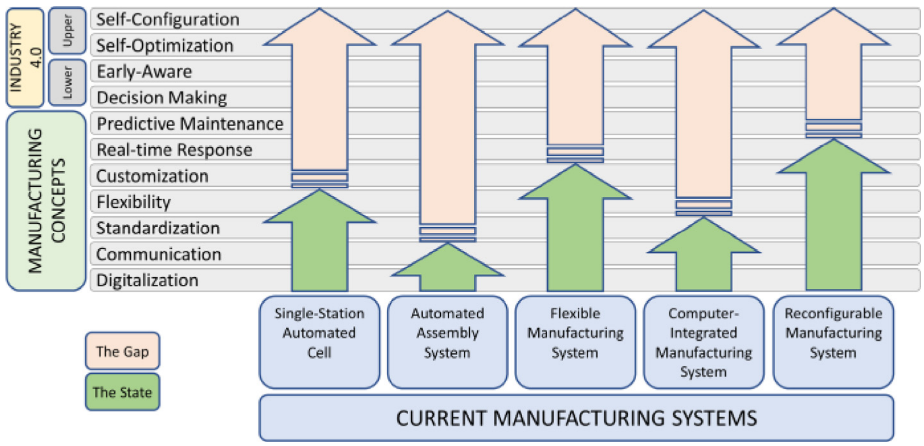


Fig. 26. Research gap between current manufacturing systems and I4.0. Adapted from [132].

variation cycle time or throughput average). Diagnostic data analysis can respond to what has happened and what is happening, identifying causes. Diagnostic analysis can take advantage using of manufacturing system' simulation model that emulates the current operation. Predictive analytics estimates performance based on planned inputs, e. g., product cycle time and throughput estimation for several products based on current policies. It will take advantage from simulation models to execute the what-if scenarios. Prescriptive analytics can respond to how can we make it happen and what will be the consequences. It uses simulation models to improve the production performance in future periods by emulating operations under paralleled realities and these plans can be improved with the arrangement of simulation and optimization models.

In the VF level, simulation can be seen as data generator allowing VF to generate for instance, streams of production data and resource utilization, and feed data to analytics applications. Can be seen also as supporting evaluation and validation giving an advantage to the real factory.

Simulation technology on I4.0, using VR, is an integral process to simulate all industrial processes, from planning, design, manufacturing, providing services, maintenance, try-outs or even quality controls. All processes can be simulated as modular [132]. It's possible to simulate and virtual verify a factory manufacturing process before being realized. After approved, all physicals can be done. For instance, if it is considering the combination within simulation and AM, after product simulation, the production of prototypes allows the time reduction on design and production process, by reducing the value-added dependencies. These time reductions are particularly relevant on customized markets.

Grieco et al. [4] presented an interesting case study in fashion manufacturing where a decision support system as a software is developed under the I4.0 concept, aiming the minimization of: 1) orders delivered later than due date, and 2) resource overload cases.

Many researchers discuss that the data is the raw material of the XXI century and the real world will be a huge information system. According to this, Lu [3] discussed one of the major challenges in I4.0 that will be the development of algorithms for dealing with data.

According to Salkin et al. [16], there is no specific I4.0 definition, and therefore, there is no definitive utilization of the enabling technologies to initiate the I4.0 transformation.

But the fact that this fourth revolution is been announced before it takes place, opens several opportunities for co-working environments between academic researchers and industrial practitioners, shaping on the manufacturing future [134].

5.1. Looking Forward

As mentioned by Rojas et al. [129], I4.0 is on its infancy and to make it a reality, several challenges and gaps must be addressed. By this, the roadmap for the I4.0 fulfillment is still not clear to date in both academia and industry [132]. Considering five fundamental manufacturing systems to conceive I4.0, Fig. 26 can represent the research gaps between the current manufacturing and the I4.0 requirements [132]. These five manufacturing systems are systems where is hard to achieve intelligent concepts, that are the goal of I4.0 development, neither I4.0 lower or upper levels. The closest to I4.0 is the Reconfigurable Manufacturing System.

5.2. Executing I4.0 in SMEs

Looking at European Union, SMEs represents the backbone of the economy and the key to competitivity. Inside this enterprise dimension, special approaches must be developed to introduce and apply I4.0 technologies [129]. The enabling technologies of I4.0 are the foundation for the integration of intelligent machines, humans, physical objects, production lines and processes to form a new kind of value chain across organizational boundaries, featuring intelligent, networked, and agile. By this, due to the increase level of complexity, manufacturing SMEs has doubts on the required financial effort for the transformation technologies and its impact on their business model [135].

The implementation of I4.0 in SMEs can be facilitated, for instance, on a SaaS approach, enabling technology acquisition for digital services with appealing investments. A clear example can be an SME integration on the supply chain of a product, allowing collaborative of project development, collaborative working on product's launch and time to market reduction, shared innovation, and consequently, minimizing the related risks.

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The authors declare no potential conflict of interests at all in this paper.

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