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A survey on Information and Communication Technologies for Industry 4.0: state of the art, taxonomies, perspectives, and challenges

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***Abstract*—A new industrial revolution is undergoing, based on a number of technological paradigms. The will to foster and guide this phenomenon has been summarized in the expression "Industry 4.0" (I4.0). Initiatives under this term share the vision that many key technologies underlying Cyber-Physical Systems and Big Data Analytics are converging to a new distributed, highly automated, and highly dynamic *production network*, and that this process needs regulatory and cultural advancements to effectively and timely develop. In this work, we focus on the technological aspect only, highlighting the unprecedented complexity of I4.0 emerging from the scientific literature. While previous works have focused on one or up to four related enablers, we consider ten technological enablers, including besides the most cited Big Data, Internet of Things, and Cloud Computing, also others more rarely considered as Fog and Mobile Computing, Artificial Intelligence, Human-Computer Interaction, Robotics, down to the often overlooked, very recent, or taken for granted Open-Source Software, Blockchain, and the Internet. For each we explore the main characteristics in relation to I4.0 and its interdependencies with other enablers. Finally we provide a detailed analysis of challenges in leveraging each of the enablers in I4.0, evidencing possible roadblocks to be overcome and pointing at possible future directions of research. Our goal is to provide a reference for the experts in some of the technological fields involved, for a reconnaissance of integration and hybridization possibilities with other fields in the endeavor of I4.0, as well as for the laymen, for a high-level grasp of the variety (and often deep history) of the scientific research backing I4.0.**

***Index Terms*—Industry 4.0, Big Data, Internet of Things (IoT), Cloud Computing, Mobile Computing, Artificial Intelligence, Human-Computer Interaction, Robotics, Open-Source Software, Blockchain, Internet, Manufacturing.**

I. THE RISE OF INDUSTRY 4.0

It is commonly agreed that three different stages of industrialization happened since 18th century: the first (from the end of 18th to the start of 20th century), depending on water and steam power, and represented by the invention of the *mechanical loom* in 1784 [1]; the second (from the end of 19th century to early seventies), based on mass production and division of labor and soon depending on electrical energy, summarized by the deployment of the *assembly line* in 1870 [1]; the third (from early seventies to the present day), depending on electronics and on IT, and represented by the *programmable logic controller (PLC)* in 1969 [1].

Table I: Chronological list of governmental initiatives aimed at *Industry 4.0* for top 10 economies based on GDP and other European countries.

Expression	Country	Year	Ref.
Industrie 4.0	Germany	2011	[2]
Manufacturing Academy of Denmark (MADE)	Denmark	2013	[3]
Industria Conectada 4.0	Spain	2014	[4]
Future of Manufacturing	UK	2014	[5]
Made in China 2025	China	2015	[6]
Plattform Industrie 4.0	Austria	2015	[7]
Society 5.0	Japan	2016	[8]
Smart Industry	Sweden	2016	[9]
Piano Industria 4.0	Italy	2016	[10]
Made Different	Belgium	2016	[11]
Smart Industry	Netherlands	2017	[12]
Manufacturing USA	USA	2017	[13]
Industrie du Futur	France	2017	[14]
Průmysl 4.0	Czech Republic	2017	[15]
Indústria 4.0	Portugal	2017	[16]

After the introduction of mechanization, electricity, and digitalization, the current ongoing (or still potential) transition towards an ICT-backed automated and interconnected industry has been dubbed "Industry 4.0" and can be seen as the fourth stage of industrialization. This fourth industrial revolution is based mainly on *Cyber-Physical Systems* or CPS (integration of computing, communication, and control), and *Big Data Analytics* (techniques to extract value from challenging amounts of data), and heavily depends on the Internet-of-Things paradigm (characterized by the pervasive presence of a variety of interconnected objects such as mobile phones, sensors, and actuators) and associated technologies.

In Figure 1 a schematic timeline of industrial revolutions is depicted, where for Industry 4.0 the main ICT enablers—as emerged from this work—are also shown.

The appearance of the term "Industry 4.0" (or **I4.0**) is tracked back to November 2011, in an article by the German government defining its high-tech strategy, defined "Industrie 4.0", for 2020 [2]. Since 2011, similar governmental initiatives have been also put forward by other countries [3–16] : a chronological list of the varying project names and respective

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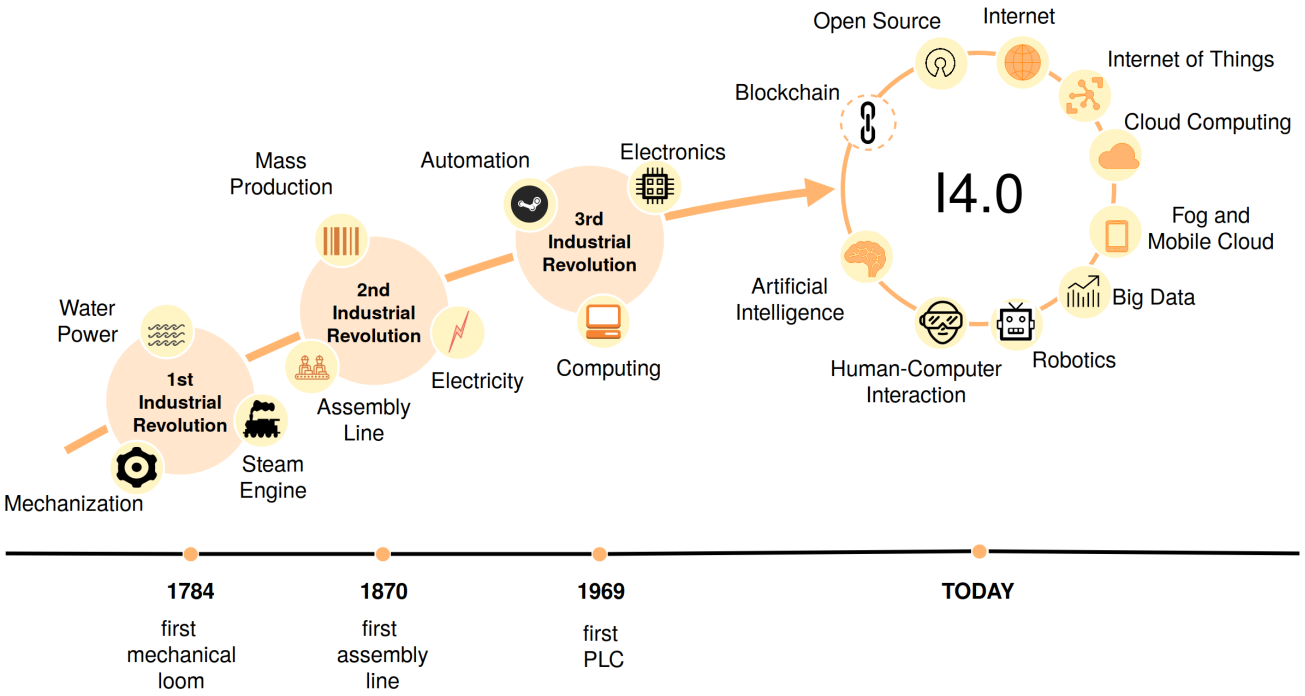

Figure 1: Main enablers for the different industrial revolutions, up to I4.0. The *Blockchain* enabler is still in course of exploration and adoption, therefore is reported for completeness, in dashed line.

country is reported in Table I[1] for the top 10 world economies based on GDP (*source: International Monetary Fund*) and other European countries.

In its broader meaning, the concept of Industry 4.0 can be seen as a governmental explicit commitment to foster, guide, and properly develop a set of technologies and the cultural and legal framework necessary to harness their full potential. Notwithstanding their long-term sustainability issues, ICTs are expected to have great potentials in playing key roles to support global economical, social, and environmental sustainability, that also strictly concern sustainable industrialization [17]. Besides the technologies involved, there are in fact also development plans including aspects of enterprise management and work organization, regulatory frameworks, and dissemination and training.

The key concept behind I4.0 is *integration*, seen along three different axes: (i) *horizontal integration*, that regards cooperation between enterprises along a value chain; (ii) *vertical integration*, that refers to extensive automation inside the single enterprise; finally, (iii) *end-to-end integration*, that envisions connections across the value chains (realizing the value network) between possibly every couple of digitally enabled participants (machine-to-machine, human-to-machine, human-to-human) [2]. More specifically, in the view of I4.0 the interconnected CPSs are expected to enable the transition from a linear "value chain" to an automated and highly dynamic "value network" including production systems, infrastructures, and customers, ideally completing the automation of the whole production process [18]. From this vision descends that the entities that communicate in this fully integrated network must be *smart objects*, able to interact with each other, autonomously, to reach an orchestrated goal [19, 20].

According to Weyer et al. [21], there are three central paradigms that explain the vision of I4.0: (i) *the smart product*—products are able to require production resources and orchestrate the production process for its completion; (ii) *the smart machine*—machines become cyber-physical production systems, where traditional production hierarchies are replaced by decentralized, flexible, modular, and self-organizing production networks); (iii) *the augmented operator*—the I4.0 vision does not aim at implementing workerless production facilities, but acknowledge the centrality of the human operator: leveraging technological support, human operator is the most flexible entity in the production system who can be faced with a wide range of different jobs, from specification and monitoring to verification of production strategies.

A number of expressions that partially overlap with I4.0 have been coined in the last few years, predating I4.0 definition and providing main ideas to its inception. Many of these expressions contain the word *Internet* or result from a combination of a qualifier among *agile*, *cloud*, *collaborative*, *smart*, *smarter* and a subject among *manufacturing*, *factories*, *production systems*, etc. These concepts have been collected from the scientific literature and Table II summarizes them pointing to related references. Focusing on the years from the official appearance of the term "Industry 4.0", Figure 2, shows the different levels of popularity of I4.0 and its related expressions in the

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[1] The *Make in India* initiative (launched in 2014), while focusing on several areas of improvement for the growth of India manufacturing, is not included in the table since it does *not* adopt an Industry 4.0 vision.

Table II: Alphabetical list of expressions strictly related or significantly overlapping with *Industry 4.0*.

Expression	References
Agile Manufacturing	[23–25]
Cloud Manufacturing	[26, 27, 24, 28]
Collaborative Manufacturing	[29, 30]
Cyber-Physical Production System	[31, 32, 2]
Digital Manufacturing	[33, 2]
Factory of the Future	[29, 18]
Industrial Internet	[34, 35]
Industrial Internet of Things	[19, 28]
Internet of Everything	[36, 37]
Mass Customization	[20, 38, 30]
Smart Factory	[26, 20, 2]
Smarter Planet	[39]

scientific literature.[2] In more details, *Mass Customization* and *Cloud Manufacturing* are the most popular expressions among those considered, being cited in the title of more than 200 scientific publications. Interestingly, as shown by the figure, the expression "Industry 4.0" is gaining popularity in the scientific literature dramatically faster than the other ones taken into account (appearing in the title of more than 1400 papers as for the end of 2017). Rather than providing a detailed definition for each of the expressions in Table II, we will highlight their scope when describing the related aspects in I4.0.

Possibly due to its relative novelty, scientific literature on Industry 4.0 has not yet been covered by extensive surveys. On the one hand this is understandable, given the impressive ramp-up of publications compared with similar concepts and keywords shown in Figure 2. On the other hand, given the extreme multidisciplinary nature of I4.0, this lack is a grave issue. Indeed by missing the big picture of the many technologies involved, the innovating practitioner and the researcher risk to (i) oversee issues and limitations that are implied by integration in scenarios from "nearby-but-separate" research field, or (ii) to reinvent the wheel for solutions elsewhere well known, or (iii) miss the opportunity of new applications into other fields of solutions and expertise from their specialty.

The works we found in the scientific literature related to I4.0 have provided partial coverage, often on the same few aspects (mostly Big Data and IoT); of the ones comparable in depth of analysis with our work we have reported the most relevant in Table III in chronological order, summarizing the aspects of I4.0 they cover. While [40–44] focus each on a specific aspect, thus cannot capture the technological complexity of I4.0, others [45–47] offer a relatively broader scope, including three to four main technological aspects. The literature review by Oztemel and Gursev [48] identifies the basic components of I4.0 focusing on intelligent manufacturing. The survey by Liu et al. [47] is placed somehow midway between vertical surveys and more broad ones, as it focuses on *smart warehouses* and the involved technologies (data collection, localization, human activity recognition, and multi-robot collaboration). In our work we cover all these aspects in the context of their wider fields: Industrial Wireless Networks and data collection in *Internet of Things*, human activity recognition and Augmented Reality in *Human-Computer Interaction*, and Robotics, Big Data, Cloud and Mobile Computing each in a dedicated section.

Other surveys of interest provide non-strictly-technological views, that are out of the scope of this work (and thus are not reported in Table III): business models [42] and socio-technical issues and management [49].

The wider-focusing assessment of literature we found is provided by Liao et al. [50], carried with a formalized bibliometric approach. From a quantitative analysis of literature on I4.0, the authors derive the shares of different types of publications addressing I4.0 (among journals, conferences, white papers, book chapters and books), the most represented terms and topics associated with I4.0 (namely, in decreasing order of frequency: Cyber Physical Systems, Smart Factories, Industrial Revolutions, Internet of Things, Production Systems, Manufacturing Systems, Smart Manufacturing, Production Processes, Cyber Physical Production Systems, Industrial Internet), and similar text-mining based analysis. We refer to [50] for further interesting inferences on bibliometric data on I4.0, while—due to the nature and objectives of that work—we highlight its lack of discussion of the topics surfaced by the analysis, of the interrelation among them, as well as the limited number and depth of analysis of the cited technological aspects.

To fill this gap in the literature, in this paper we focus on the technological aspects, more specifically on the vast set of Information and Communication Technologies implied by I4.0, to shed light on their extension and impact. For each main technology we briefly describe it to the depth necessary to appreciate its contribution to I4.0 (with up-to-date references for further details), then we contextualize to I4.0 the applications, features, and issues. This way we provide for specialists in some of the interested fields also an overview of the others, fostering the cross-disciplinary interactions at the basis of I4.0. After having introduced the most relevant enablers, we discuss the most interesting application scenarios of I4.0 derived from the case studies and experiences stemming out from the literature. Finally, we highlight and discuss the challenges and future directions of ICT enablers in the light of I4.0.

The structure of the paper is as follows: Section II introduces the main ICT enablers supporting the I4.0 vision (namely, Digital Communication Infrastructure, Internet of Things, Cloud Computing, Fog and Mobile Computing, Big Data, Robotics, Human-Computer Interaction, Artificial Intelligence, Blockchain, and Open Source Software) together with the recurring challenges to I4.0 they imply; in Section III we discuss the most interesting case studies and experiences derived from the scientific literature; in Section IV we analyze the main challenges and future directions in I4.0; Finally Section V draws the main conclusions.

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[2] Statistics about the scientific literature were extracted adopting Google Scholar [22]. Although inferred results might be not 100% accurate, they provide useful insights about literature trends. 2017 was the last year with complete statistics at time of writing.

Table III: Literature surveys about ICT aspects related to I4.0.

Reference	**Year**	**Aspects Covered**
Liu et al. [47]	2018	Smart warehouses, Human-Computer Interaction, Robotics
Xu and Duan [44]	2018	Big Data
Fraga-Lamas et al. [43]	2018	Augmented Reality
Lu [46]	2017	Big Data, IoT, Cloud Computing, Mobile Computing
Preuveneers and Ilie-Zudor [45]	2017	IoT, Big Data, Cloud Computing, Human-Computer Interaction
Li et al. [41]	2017	Industrial Wireless Networks
Liao et al. [50]	2017	Bibliographic analysis

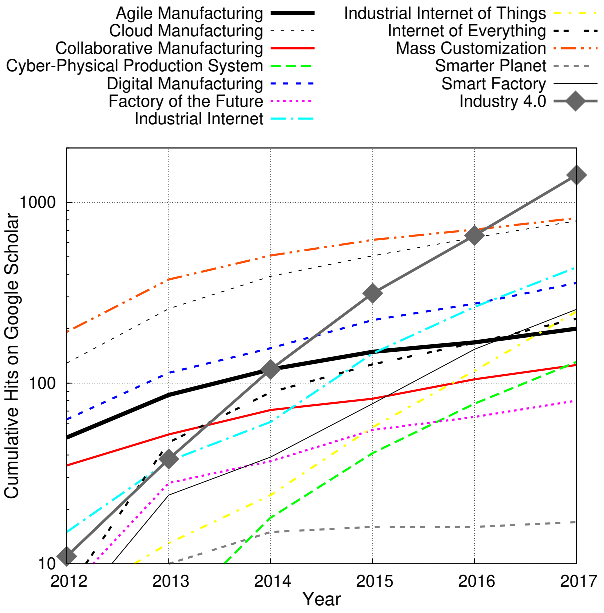

Figure 2: Popularity of I4.0 in the scientific literature compared to related expressions in Table II (number of publications per year). “Industry 4.0” is gaining popularity dramatically faster than the other considered expressions. Data Source: *Google Scholar* (exact match in title). The time window spans from the official appearance of the term “Industry 4.0” to the last year with complete statistics available at time of writing.

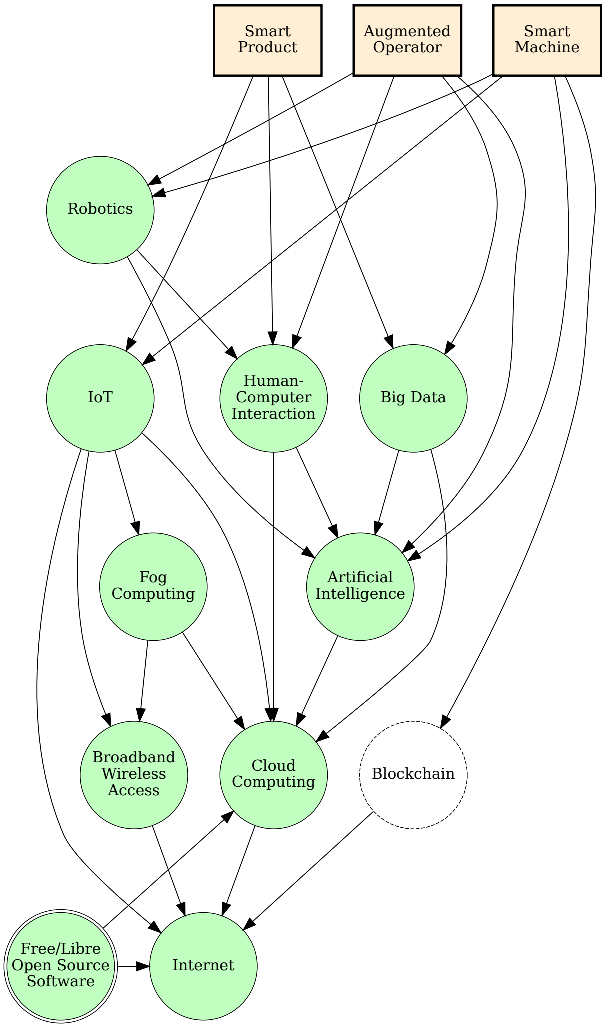

Figure 3: Central paradigms (squared) and enablers (circled) of Industry 4.0. Arrows represent the *“Uses” relationship*. The enabler *Free/Libre Open Source Software* is used by all others, thus the arrows pointing to it are not shown for readability sake. The enabler *Blockchain* is reported in dashed line as it is not included in technologies with strong literature evidence, and is discussed in Section IV-G.

II. INDUSTRY 4.0: ICT ENABLERS

The technical aspects of I4.0 that both contributed to the birth of the concept, and will support its actual implementation, all belong to the Information and Communication Technologies. In Table IV these enablers are listed, along with the section they are described in, and the main references for deepening their knowledge. It is evident that, albeit being well-established fields with specific characteristics and concerns, most of them are closely interrelated (mainly due to the history of their evolution). In our analysis, we found that their convergence is further stressed by the nature of I4.0 itself. We have made explicit the strongest dependencies in Figure 3, where we also showed the dependencies existing between the central I4.0 paradigms as described in the previous section (namely: augmented operator, smart product, and smart machine) and their enabling information-and-communication technologies. As the figure shows, the central paradigms found their properties in several technological enablers.

The *Smart Product*, in order to become an *active participant* in the production process [21, 51], must be able to communicate its presence, characteristics, and requirements to the surrounding machines or humans: the IoT (Section II-B) provides the means for such needs. In turn, IoT depends on Cloud Computing (Section II-C) and its variants for non-trivial computation, and on the ubiquitous Digital Communication Infrastructure (Section II-A) for efficient and economically feasible global information transfer.

Another key aspect of Smart Products in I4.0 is their nature of continuous source of data about themselves, the environment they are immersed in, and the (advanced) interaction with the

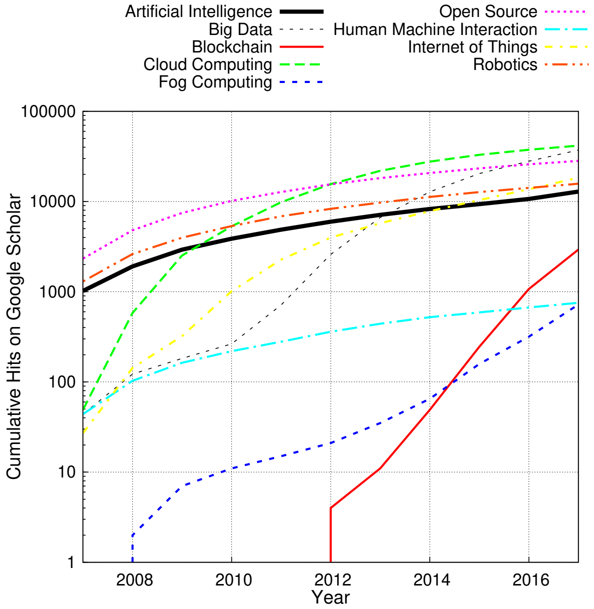

Figure 4: Popularity of ICT enablers related to I4.0 in the scientific literature in the last decade (number of publications per year). Data source: *Google Scholar* (exact match in title).

user [52]. These properties find their technological enablers in Big Data infrastructures (Section II-D) and Human-Computer Interaction (Section II-F), both in turn relying on Cloud Computing and Artificial Intelligence (Section II-G).

The *Smart Machine* is able to self-organize to meet the production necessities as derived from the Smart Product and the production environment, realizing *ad-hoc* production networks with other machines [21]. A notable component of this dynamic production network regards the generation, storage, and distribution of energy: the smart grids and their envisioned interconnected evolution [53]. The main technical enabler for the Smart Machine is found in Robotics (Section II-E), and same as in the case of the Smart Product, the necessary communication means are provided by IoT. Additionally, the means for advanced reasoning and autonomic behavior are provided by Artificial Intelligence. A leap forward in Machine-to-Machine communication and autonomic behavior is envisioned through the use of Blockchain (Section IV-G), providing provably untampered record of events and automatic execution of transactions without trusted entities. The Blockchain technologies in turn rely on the global Digital Communication Infrastructure for efficient long-range communications.

In the above-depicted context, the role played by the human operator is still critical, but it needs to be re-thought, taking advantage of the tools that make operators become *Augmented Operators*. Trends show that the interaction between the operators and the working environment cannot be overlooked: indeed, progresses in fields such as Human-Computer interaction (Section II-F) and robotics (Section II-E) allow to design cooperative working environments where humans may interact by leveraging Virtual/Augmented reality technologies with enabled CPSs empowered by AI (Section II-G).

Each enabler is discussed in details in the following sections, first providing the basics and then summarizing its main application scenarios concerning I4.0. Figure 4 reports the popularity in the scientific literature of the enablers taken into account for what concerns the last decade.[3] Although all the enablers considered in this section provide strong contribution to I4.0—as witnessed by the scientific literature—it is worth noting that some of them are technological paradigms emerged to provide solutions (e.g., Blockchain or Cloud and Fog Computing); others represent wide research fields, focusing on classes of problems (e.g, Artificial Intelligence, Robotics, and Big Data). Some of them (e.g., Robotics, the Internet, and Cloud Computing) also have a longer history and provide more basilar functionality to others, that are of relatively recent adoption (e.g., Internet of Things as well as Big Data). Such variety reflects also on the nature of challenges that each the enabler faces in the framework of I4.0 (analyzed in Section IV.

A. *Internet – Digital communications infrastructure*

The Internet, as the infrastructure allowing global addressing and communication, is essential to Industry 4.0 in practically all its aspects. A summary of main references for the Internet regarding different aspects in Industry 4.0 is reported in Table V. Over time the Internet has evolved towards providing an universal communication service, as the “Next Generation Network” envisioned by ITU-T [54]. Because of the critical role played by the Internet, I4.0 inherits its challenges and issues related to security, availability, infrastructural costs, performance. The impact of technological, economical, and political decisions that regard this infrastructure can be huge, and of growing importance with I4.0. For what specifically concerns industrial applications, digital communications have undergone at least three phases of evolution [55]: initially (’80s and early ’90s) the *fieldbus systems* where used to connect sensors, actuators and controllers; around 2000 this changed with the introduction of Ethernet-based networks (cheaper and fast spreading technology derived from IT sector); finally close to 2010 wireless networks have started to find application in industrial automation, although limited by the much stricter reliability requirements. Both the two last phases paved the way for the Internet of Things (IoT). Similarly, the spread of mobile personal communications and wireless LAN technologies has radically lowered the cost and effort that is needed to connect a (mobile) terminal to the Internet, again providing a foundation for the IoT and I4.0.

Despite its current ease of use, the Internet is arguably the most complex system ever build by humanity, resulting from the cooperation of a great number of independent actors and elements and made possible thanks to a strongly modular and decentralized approach. Therefore we refer to Leiner et al. [56] for a historical perspective on the Internet, and in the following we will consider only its basic aspects that are functional to introducing the opportunities, challenges, and risks involved in the context of I4.0.

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[3] We focus on the last ten years in order to catch the evolution of the popularity of the enablers since their early publication ramp up. It is worth noting that most of the considered enablers (with the exception of Open Source, Robotics, and Artificial Intelligence that are wide research fields) result in less than 100 publication items in 2012 proving the young nature of these technologies.

Role of Internet in I4.0

Although the role of the Internet as well as its impact could be given for granted (as being implicitly required or transparently leveraged by other enablers), the Internet is the most critical enabler of I4.0. *The overall I4.0 paradigm thoroughly relies on the Internet infrastructure, to the extent that without the Internet as we know it, there would be no such thing as I4.0.*

From the one hand, the Internet acts as the glue making the interaction among distributed entities (both humans and machines) possible. In fact, objects, products, and operators become "smart" thanks to integration: smartness is provided/achieved by context awareness, including the sharing of information (in real time) through the digital communication infrastructure, or by leveraging computational power and memory storage in remote economically efficient (Cloud) datacenters, again accessed through the Internet.

Moreover, the overall I4.0 paradigm has been built upon the Internet infrastructure. Without the support of the Internet, the I4.0 vision would lack a number of fundamental building blocks. Indeed, all the enablers discussed in this work—as also shown in Figure 3—proved to intimately depend on the broadband digital communication infrastructure provided by Internet. For instance (just to mention some aspects), IoT without the IP gluing layer would be little more than sensing and actuating devices in local networks; the Cloud paradigm would not be feasible without (high-performance) global interconnections; current visions, designs and implementations for Big Data analytics and artificial intelligence would also not be possible, while Human-Computer interaction and even robotics would be dramatically different without the Internet.

More than 20 years ago the IPv6 was designed and standardized to overcome several limitations of the former IPv4 protocol, above all to face the then-forthcoming addresses exhaustion. However, its adoption has been anything than smooth, requiring the availability and stability of solutions (from applications to network components) across the Internet infrastructure, as well as the adoption of these solutions by stakeholders [74]. The prominent rise of I4.0 is expected to further fuel the migration to IPv6 because of the need of identifying and addressing billions CPSs.

Table IV: Technological I4.0 enablers and main related references.

Enabler	Section	Main References
Internet	II-A	DeNardis [57]
Internet of Things	II-B	ITU [58], Atzori et al. [59, 36]
Cloud Computing	II-C	Mell et al. [60], Armbrust et al. [61]
Fog and Mobile Cloud	II-C	Bonomi et al. [62], Fernando et al. [63]
Big Data	II-D	Chen et al. [64], Gantz and Reinsel [65]
Robotics	II-E	Siciliano and Khatib [66]
Human-Computer Interaction	II-F	Card et al. [67]
Artificial Intelligence	II-G	Cohen and Feigenbaum [68]
Open Source	II-H	Feller and Fitzgerald [69]

Table V: Main aspects of interest in *Internet and digital communication infrastructures* related to I4.0.

Aspect	Main References
Network Neutrality	Wu [70], Antonopoulos et al. [71]
Topology Discovery	Donnet and Friedman [72]
Internet Censorship	Leberknight et al. [73]
IPv4-to-IPv6 transition	Nikkhah and Guérin [74]
DNSSEC Adoption	Herzberg and Shulman [75]
BGP flaws	Goldberg [76]
Resilience to faults and attacks	Neumayer et al. [77]

As a result, without the opportunities enabled by the Internet, the I4.0 paradigm would not differ from the scenario produced by the 3rd industrial revolution, where a wide range of automation tools and devices, enabled by electronics and computing progress, would be forced to act as standalone pieces, thus widely limiting the opportunities provided by integration and interaction. Without fear of contradiction, we could state that no one among the peculiar I4.0 characteristic applications would be feasible without the Internet.

On the other hand, the criticality of the Internet also reflects a number of issues (e.g., network neutrality, privacy, evolution of the protocols, fault detection and mitigation, attacks, etc.) that are migrated as they are to the dramatically critical I4.0 framework. These and other aspects are discussed in depth in Sections IV-A.

B. *Internet of Things*

Likely the strongest inspiration for I4.0, the "Internet of Things" (IoT) is a concept closely related to ubiquitous computing, dating back to the end of '80s, although the first reported usage of the term is 1999 by Kevin Ashton, related to the use of Radio Frequency Identification (RFID) tags for logistics [78]. A more general vision of IoT is presented by ITU as the move from *anytime, anyplace connectivity for anyone*, forward to *connectivity for anything* [58], initially with focus on digital identification and machine-to-machine (M2M) communications [59]. This can be considered the seed of I4.0 as the focus moved from humans communicating with humans, to eventually machines interacting with machines, on a global scale.

The objects conforming to the IoT have a wide range of understandings and connotations, including RFID [79] and Wireless Sensor Networks (WSNs) [80] and all share strict requirements in terms of power consumption, being powered by batteries or through energy harvesting.

A significant boost from the inception of IoT has been the ongoing deployment of IPv6 protocol (see Section II-A), purposely designed with a list of properties that were lacking in the widely deployed version (IPv4) and are highly appealing for IoT: a virtually endless supply of unique addresses ($667 \cdot 10^{21}$ per square meter on Earth), security at network level, extensibility, and support for mobile terminals, with undergoing further developments aimed at low-power communications [81]. On the

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other hand, existing non-trivial challenges toward IPv6 address allocation (heterogeneity of nodes and network technologies, extreme constraints and miniaturization, and multi-homing) also reflects to IoT [82].

More in general, besides the IP protocol a *second generation of IoT* [36] has seen the adoption or adaptation of standards and approaches of web applications to M2M communication, as solutions for global addressability and standardization of interfaces. Finally, the latest evolution of IoT (*third generation*) extends interoperability on the content level (with focus on semantic characterization and standardization as well as information-centric networking), on ubiquitous access to resources (e.g., computation, storage, networking, energy) thanks to Cloud Computing [83], aiming at the autonomous social behavior of interconnected things. In order to deal with such complex and heterogeneous scenario, we organize IoT-related topics according to a widely accepted [84] layered logical framework:

- At the basis of the logical framework lies the *perception layer*, composed of sensors and actuators;
- on top of it, the *transmission layer* provides the means for conveying sensed information to the upper layers, and commands to the perception one;
- on top of transmission, the *computation layer* deals with incoming data, for processing it and taking decisions to be offered to the upper layer (cloud computing and big data analytics are involved at this layer);
- finally the topmost, the *application layer*, is the actual user of the IoT infrastructure for some high-level goal (e.g. home automation, healthcare, transport, manufacturing, etc.).

Most of the research from the *second generation* of IoT has focused on the *transmission layer* and its communication protocols. Although designing and implementing a *low-power*, *highly reliable*, and *Internet-enabled* communication stack is a commonly agreed requirement, IoT definition still appears somehow fuzzy for some aspects.

Since 2003, several standardization bodies at IEEE and IETF started putting together a framework to the communication protocols of the emerging systems. The standard with the largest impact is IEEE802.15.4, defining a low-power Physical layer (upon which most IoT technologies have been built) and a MAC layer, which has been the foundation of ZigBee 1.0 and and later versions. To address the reliability issues due to the single-channel nature of this MAC protocol, alternatives using *channel hopping* were developed, such as TSMP (Time Synchronized Mesh Protocol) that became the *de-facto standard* for reliable low-power wireless in industrial applications—whose basic principles also represented the foundations for the WirelessHART standard—before time-synchronized channel hopping was integrated into the IEEE802.15.4 protocol.

In contrast with close-range Local Area Networks, protocols for Low Power Wide Area networks (LPWA) focus on long range with low power consumption and low cost (neglecting higher data rate, lower latency and higher reliability). Several standardization bodies have published physical and MAC layer protocol standards addressing this scenario, and a number of proprietary protocols have been proposed as well. In this regard we mention IEEE802.11 **LRLP** (Long Range Low Power), ETSI **LTN** (Low Throughput Networks), 3GPP **eMTC** (enhanced Machine-Type Communications) and **NB-IoT** (NarrowBand IoT), IETF **6LPWA/LP-WAN**, Weightless SIG **Weightless-W/N/P**, **LoRaWAN** by LoRa Alliance, and **DASH7** by DASH7 Alliance. We point to Raza et al. [85] for a comparative analysis of such standards.

A number of IETF working groups facilitated the integration of low-power wireless networks into the Internet, providing standards such as 6LoWPAN as a convergence layer, ROLL RPL as a routing protocol, and CoAP for the application layer. **6LoWPAN** (developed by an IETF working group in 2007) is the specification for mapping services required by the IPv6 over Low power WPANs to maintain an IPv6 network even in presence of Low power Wireless Personal Area Networks (WPANs) with characteristics different from former link layer technologies in terms of limited packet size, various address lengths, and low bandwidth. This standard also provides header compression to reduce the transmission overhead, fragmentation to meet the IPv6 requirement in terms of Maximum Transmission Unit.

RPL (Routing Protocol for Low Power and Lossy Network) is a link-independent routing protocol based on IPv6, created to support minimal routing requirements through building a robust topology over lossy links, supporting both simple and complex traffic models.

Finally, **CoAP** (Constrained Application Protocol) defines a web transfer protocol based on REpresentational State Transfer (REST) on top of HTTP functionalities thus enabling tiny devices with low power, computation and communication capabilities to utilize RESTful interactions. Other application-layer protocols have enjoyed adoption or have been proposed for IoT: we cite **MQTT** (Messagge Queue Telemetry Transport), **AMQP** (Advanced Message Queuing Protocol), and also the re-purposing of **XMPP** (eXtensible Messaging and Presence Protocol), an instant messaging standard.

We refer to the publications by Palattella et al. [86], Al-Fuqaha et al. [87], and Sheng et al. [88] for a detailed discussion on communication standards as well as related challenges and opportunities.

Beyond the mentioned protocols, all of the visions described above build on technologies that have experienced research, development, and commercial success in their own applications. These technologies—being grouped and collectively implicitly considered under the IoT term—enable new, more complex, usage scenarios. The involved enablers (namely, digital communications infrastructure, for the *transmission layer*, and Cloud Computing and Big Data, for the *computing layer*) are analyzed in detail in the relevant sections for their contribution to I4.0 and related issues (see Section II-A for the digital communication infrastructure, Section II-C for Cloud Computing, and Section II-D for Big Data).

Role of IoT in I4.0

A summary of main references for the Internet of Things regarding different aspects in Industry 4.0 is reported in Table VI.

The most recent vision of IoT, when applied to manufacturing processes and industry in general, greatly overlaps with

Table VI: Main aspects of interest in *Internet of Things* related to I4.0.

Aspect	Main References
IIoT	i-SCOOP [89], McKnight [90], Higberg and Larsson [91], Wang et al. [92]
OT	Kim et al. [93], Liang et al. [94], Galloway and Hancke [95], Felser [96], Li et al. [97]

I4.0. This in fact can be considered as a step beyond IoT, adding reference architectures with manufacturing and logistic details [78], or conversely as considering an already heavily automated manufacturing process and adding IoT technologies, with a number of new opportunities (and challenges) as a consequence [20].

The specific application of IoT to the vision of I4.0 is the so-called **"Industrial IoT"** (IIoT), defined as "machines, computers, and people enabling intelligent industrial operations, using advanced data analytics for transformational business outcomes" [89]. At a basic level, IIoT can be summarized as sensor-equipped industrial machines connected through Internet technologies with other machines for e.g., monitoring, analysis, and management. The implementation of this vision has deep consequences in technology, business organization, and markets, and comes with a list of risks and drawbacks together with the promised opportunities and benefits.

For what concerns the pros, IIoT carries a number of benefits [90, 91, 98], such as: (i) *closed-loop design* (analyzing real-world usage data, designers are able to understand how products are being used and thus they can design better-performing products); (ii) *increased consumer value* (being able to share valuable information, products provide the end user with a better experience); (iii) *predictive maintenance* (thanks to the ability to gather data, IIoT enables fault prediction and thus maintenance before failures occur, avoiding machine downtime); (iv) *new service lines* (manufacturers have the ability to obtain new revenue services, offering remote monitoring services, and better enabling remote software updates and improvements); (v) *reduced labor cost* (technology improvements lead to save unnecessary expenses, also allowing to improve work environment for employees). Wang et al. [92] proposed a layered architecture for IIoT—comprising sensing entities RESTful services hosted by cloud servers (to improve integration and accessibility) and user applications—where sensing, processing, and communication optimizations can reduce energy consumption.

Indeed—albeit to a smaller extent—automation and digitalization were already part of the third industrial revolution , and are thus extensively present in current industry under the terms SCADA (Supervisory Control And Data Acquisition) [99, 100] and *operational technology* (OT). As a consequence, industrial communication systems are currently based on a variety of legacy architectures and protocols such as HART [93], Foundation FIELDBUS, CAN and Profibus, and their recent wireless versions [94]. These communication stacks are diverse, often highly industry-specific, with interoperability issues. Their requirements were centered around robustness and reliability, and also often tightly bounded latency and jitter.

It is worth noting that, in addition to the technologies mentioned above, since the early 2000s industrial networks are also starting to display a greater reliance on Ethernet [95], with modified or integrated variants like EtherCAT [96]. In the last decades, in the IT world the ubiquity and interoperability of the TCP/IP communication stack (commonly adopting Ethernet protocols Data Link and Physical layers) have fueled the IoT paradigm. This has included the adoption and extension of wireless LAN (Wi-Fi) from the original Small-Office-Home-Office scenario also in industrial scenarios [97].

Regarding its *Industrial* application, the shift of IoT towards IIoT requires the integration and eventually seamless merging of OT and ICT in a cyber-physical—production—system. Indeed, a growing integration between industrial and enterprise networks has been observed, despite the functional differences between the two (in terms of e.g., implementation, architecture, failure severity, real-time requirements, determinism, data size, traffic characteristics, temporal consistency requirements, ruggedness, etc.) [95]. The new requirements in low-latency network communications have pushed for the research and publication of new standards for Link layer and Network layer, as the IEEE 802.1 time sensitive networking (TSN), and the IETF deterministic networking (DetNet), respectively [101]. This also led to a situation where engineers involved in the design and maintenance networks have to be familiar with both traditional enterprise concerns (e.g., network security in terms for example of malware [102]), as well as traditional industrial concerns (such as determinism and response time).

The result of the fusion between OT and ICT can already be found in industrial applications characterized as *smart* with respect to the previous ones: smart factory applications, smart warehousing, smart metering and monitoring, smart maintenance and equipment management. Moreover, as the resulting digital-transformation scenario is today characterized by the explosive growth of devices and data, and lack or unsuitability of standards, IIoT is expected to accelerate the convergence of Cloud, legacy ICT and OT security [103, 104].

As the vision of Industry 4.0 includes global communications, the Industrial Internet of Things will extensively adopt not only Internet technologies, but also the Internet itself as a global communication infrastructure, thus enjoying its cost-effective services and also being affected by its numerous challenges and issues.

C. Cloud and Fog Computing

"Cloud Computing" (or simply "Cloud") is a paradigm that enables "Utility Computing", i.e. the leasing of computing resources (computational power, storage, and the related networking resources) in real time, with minimal interaction with the provider. This way, Cloud simplifies operation, as it does not require a careful dimensioning and forecast of needed resources, allowing pay-per-use billing on a short-term basis, without upfront commitment by the user. Moreover, cloud customers take advantage of the appearance of infinite computing resources on demand, and are able to leverage—or deliver to their own clients—*everything as-a-service*: the

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Table VII: Main aspects of interest in *Cloud* related to I4.0.

Aspect	Main References
Cloud Manufacturing	Thames and Schaefer [28]
Field device control	Kehoe et al. [112]
Process Control	Givehchi et al. [113], Goldschmidt et al. [25]
Enterprise Management and Manufacturing Execution	Colombo et al. [29], de Souza et al. [114], Chofreh et al. [115], Xu [23]

most common services are characterized as Infrastructure, Platform, or Software as-a-Service (IaaS, PaaS, and SaaS, respectively) [105], with further variations such as Function-as-a-Service (also dubbed “Serverless Computing” [106]). In addition, thanks to the extensive adoption of virtualization technologies, Cloud Computing increases resource utilization, allowing to implement economies of scale [61] and keep costs low. Ultimately, the main drivers behind the adoption of Cloud Computing are found to be economics and simplification [107–109].

Over the years, several shortcomings of the Cloud Computing paradigm have become apparent, mostly related with the communication between the end device and the datacenter hosting the cloud services: latency, bandwidth, cost, and availability of the connection all contribute to limit a number of uses for Cloud Computing, preventing the use of its full potential.

Different terms and expression have been coined for the solutions proposed for this category of issues, namely “Fog Computing” [110], “Mobile Cloud” [63], “Edge computing”, and recently in the all-encompassing expression “Fog and Mobile Edge Computing (FMEC)”[4]. The common characteristics of these more recent proposals is the use of cloud resources closer to the user (e.g., in a mini-cloud at 1-hop from terminal, or to local peer terminals) to solve the issue with high latency or with the inconvenience (cost, restrictions to mobility, reliability) of the connection to cloud services.

Another issue with Cloud is more essential to its nature: it provides its as-a-service facilities with appealing prices by masking the real infrastructure, sparing the cloud customer to manage the details of operations related to the cloud resources, and offering economies-of-scale grade prices. While these are exactly the desired properties of Cloud Computing, the opacity of infrastructure can become a limit when performance and multi-cloud setups are required: we refer to [111] for an analysis of issues and techniques in Cloud status and performance monitoring.

Role of Cloud Computing in I4.0

A summary of main references for Cloud Computing regarding different aspects in Industry 4.0 is reported in Table VII.

Cloud Computing is indirectly implied in several enablers of I4.0, specially Big Data, but also for IoT and Visual/Virtual Computing. In addition to this, it is considered as an inspiring metaphor in **“Cloud manufacturing”** [28], envisioned as a networked manufacturing model based on on-demand access to a shared collection of distributed manufacturing resources (instead of just computing/storage as in classic Cloud Computing). The goal is to form production lines that are temporary, reconfigurable, and distributed, and are able to optimally allocate resources in response to customer-generated demand, with the ultimate aim of reducing product life cycle costs, and time-to-market delays, while providing a user-tailored product. It is evident that such goals are significantly overlapping with the ones of I4.0 itself (see [28] for an analysis of the differences).

Although the concept of Cloud Manufacturing reflects the definition of Cloud Computing, most of the resources in the former need to be operated manually by humans [27]. A significant difference is that in Cloud Computing humans are ideally kept out of the operations at all, differently than in Cloud Manufacturing where humans are key participants to the process. In this view, Cloud Computing is but one convenient technology enabling the service-oriented architecture that is at the basis of the Cloud Manufacturing paradigm [26].

Considering a more direct involvement of Cloud Computing in I4.0, different possibilities have been presented to leverage Cloud flexibility for the goals of dynamism and efficiency of I4.0. Table VIII summarizes paradigms and service models adopted in the surveyed literature in the context of I4.0. As shown in the table, while Iaas, PaaS, and SaaS are recurring terms in the context of I4.0 [116, 118, 119, 24, 25, 28, 121], a set of new paradigms has stemmed out, such as *Control-aaS* [113, 25], *Industrial Automation-aaS* [118], PLC-aaS [113, 25], and *Machinery-aaS* [113]. Indeed, most of works focusing on the adoption of Cloud for industrial automation aim at **implementing through the cloud groups of services** from the layered automation architecture in Figure 5. This approach modifies the overall architecture structure from strictly hierarchical to a more flat service-oriented one (see [119] for a web service-oriented architecture for industrial automation). This migration is fueled by a trend emerging in the last decade: the extension of functionalities embedded in field devices has endowed them with more *intelligence* and more flexibility; indeed, communication among field devices has seen the improving and spread of standards and protocols [122], fostering interoperability and decoupling (hence, the possibility of migrating functions to the cloud, as shown in [31]).

Regarding manufacturing and industrial automation, several applications of Cloud Computing are considered in [118], in reference to the *automation hierarchy* depicted in Fig. 5. In such hierarchy, the lower layers (Field level and lower-half Control level) are bound by real-time critical requirements, and are harder to move towards a cloud architecture. There are no strict physical requirements on the upper layers such as upper-half (non-real-time) Control, Manufacturing, and Enterprise layers. E.g., plant management, enterprise resource planning, can in principle be implemented as services hosted in a cloud.

Common to all levels there are the requirements related

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[4] It is the title of an IEEE International Conference, on Fog and Mobile Edge Computing (FMEC) https://ieeexplore.ieee.org/xpl/conhome.jsp?punumber=1820344 .

Table VIII: Cloud paradigms and service models adopted in the context of I4.0 and related scenarios. “Generic” groups all cases not falling in the other columns. “-aaS” suffix stands for “as-a-Service”.

Reference	**Year**	**Generic**	**IaaS**	**PaaS**	**SaaS**	**Storage-aaS**	**Control-aaS**	**Fog**	**Industrial automation -aaS**	**PLC-aaS**	**Machinery-aaS**
Mezgár [116]	2011		✓	✓	✓	✓					
Xu [23]	2012	✓									
Bonomi et al. [62]	2012							✓			
Putnik et al. [117]	2013	✓									
Givehchi et al. [118]	2013		✓	✓	✓				✓		✓
Givehchi et al. [113]	2014						✓			✓	
Chofreh et al. [115]	2014	✓									
Colombo et al. [29]	2014	✓									
Langmann and Meyer [119]	2014		✓	✓	✓						
Zhan et al. [24]	2015		✓	✓	✓						
Gazis et al. [120]	2015							✓			
Goldschmidt et al. [25]	2015			✓			✓			✓	
Hao and Helo [27]	2015					✓					
Schlechtendahl et al. [31]	2015	✓									
Pizoń and Lipski [121]	2016				✓			✓			
Thames and Schaefer [28]	2016		✓	✓	✓						
Almada-Lobo [32]	2016	✓									

to security at large, including Intellectual Property protection. Given these requirements, for supporting **Enterprise Management** and **Manufacturing Execution**, ERP and other high-level management software can be easily implemented as SaaS (and indeed this is an established and studied trend [115]). This approach has been researched in Europe by several past projects, the most relevant being: *SOCRADES* [114] (investigating web services and SOA for automation levels below the management one); *IMC-AESOP* [29] (researching SOA-based solutions for DCS/SCADA systems, with cloud implementations).

In addition to M2M communications, Cloud Computing is the ideal facility to provide communications and integration services, allowing collaboration among users, field technicians, experts, supervisors, managers [27]. Other examples of applications of Cloud Computing for the Enterprise Management and Manufacturing Execution Level are considered by Xu [23].

Regarding the **Process Control level**, in Givehchi et al. [113] an experimental analysis of virtualized PLCs is performed, finding latency worsening of 3 $msec$ (compatible with soft real-time requirements), although the considered cloud deployment is with on-premises hardware, with no remote off-premises interactions, with network delays as small as $7 \mu sec$). A very in-depth analysis and proposal is presented by Goldschmidt et al. [25], where a Control-as-a-Service architecture is designed to fully benefit from multi-tenancy, elasticity, and cost effectiveness of Cloud. The authors highlight how hard-real-time control requirements can not, with current technologies, be fulfilled with a cloud-based approach, and focus on non-real-time or soft-real-time tasks. Finally, for the **Field level** the adoption of Cloud is surveyed in [112], with specific focus on robotics (also see Section II-E).

Indeed the analyzed motivations for adoption of Cloud Computing (management of uncertainty in sensing, models, and control, and high performance computing to solve optimization problems in quasi-real-time) are not limited to robots but can be generalized to field-level of manufacturing plants. More in general, at the Field level the restrictions on latency requirements call for Fog Computing solutions [121], where computing, storage, and communication resources are available near (in terms of latency) the field devices, also more easily fulfilling the requirements in terms of jitter, bandwidth, energy, and cost of the communication.

An application of Cloud Computing that involves all levels of the automation hierarchy is for the scheduling of virtual and physical resources. Depending on the kind of cloud service that is leveraged (SaaS, PaaS, or IaaS), the promises of the Cloud paradigm can be achieved by means of intelligent dynamic allocation of physical and virtual resources. This process is computationally high demanding and will require cloud resources itself, moreover its complexity is expected to dramatically grow in the context of I4.0: this is currently an open issue, requiring its own part of future research [24].

The overall picture emerging from the state-of-art is that Cloud Computing is a fundamental enabler for I4.0 as a paradigmatic model, as a component of industrial automation architecture (for data collection, distribution, and storage, and control computing), and indirectly as an infrastructure for high-level functions (data analysis). Moreover it is the technology of choice for achieving (logical) decentralization of manufacturing execution and planning systems [32], and for allowing seamless introduction of human intellectual work where and when needed (e.g., crowdsourcing difficult tasks [112]). The future of I4.0 is therefore tightly bound to the research on Cloud Computing and its evolution.

D. Big Data

The expression "Big Data" has a much discussed scope and definition. Over time its focus has moved from datasets characteristics in relation to the *current* technologies (datasets which could not be captured, managed, and processed by general computers within an acceptable scope, according to Apache Hadoop definition) to the technologies designed to economically extract *value* from *very large volumes* of a *wide variety* of data, by enabling the *high-velocity* capture, discovery, and/or analysis [65]. A concise characterization is the "Multi-Vs", that captures the largest and most cited common set of properties associated with Big Data: (i) *Volume* (data scale increases); (ii) *Velocity* (collection and analysis are subject to time bounds); (iii) *Variety* (data is composed of various types, i.e. structured data, unstructured, and semi-structured); (iv) *Veracity* (data has varying degrees of trustworthiness, according to provenance, management, and processing); (v) *Value* (the whole architecture is aimed at—economical—value extraction.

This "5-Vs" characterization highlights the strong context-dependent nature of Big Data, that are so defined necessarily with reference to specific applications (Value) and technical constraints (Volume, Velocity, Variety, Veracity). These peculiar requirements, challenging—by definition of Big Data—the available technologies, have spun significant innovation over data management techniques and tools in the last two decades, also leveraging Cloud Computing as an enabler for the new distributed paradigms: we refer to [123] for an overall technological analysis of the evolution of Big Data.

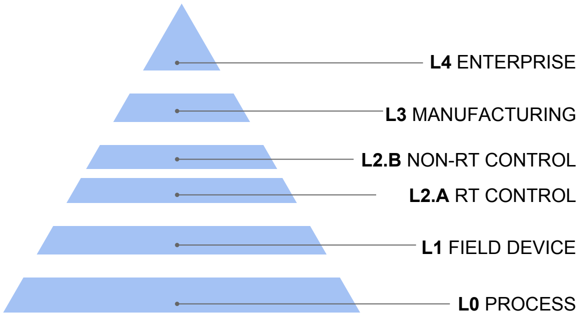

Figure 5: Automation hierarchy (inspired by [31]).

Table IX: Main aspects of interest in *Big Data* related to I4.0.

Aspect	Main References
Product-related data	Li et al. [124]
Enterprise data	Gantz and Reinsel [65]
Precision Control	Stojanovic et al. [125]

Role of Big Data in I4.0
Big Data and related concepts are directly implied in I4.0 in several ways. A summary of main references for Big Data regarding different aspects in Industry 4.0 is reported in Table IX.

The most "traditional" source of Big Data, that historically led the big-data applications and pushed for the necessary tools, is **Online Social Network data**. Initially aimed at targeted advertising and market analysis, in the context of I4.0 this data is more directly used to tune the manufacturing value chain, in an automated fashion. From a point of view, whole I4.0 can be seen as an effort to foster such timely feedback from in-the-wild data collection back into the design-production-delivery cycle. Therefore this source of Big Data—with related technologies—is expected to be a enabler also in I4.0.

A new source of Big Data, more specific of the I4.0 evolution, pertains to **Product-related data**: sensors embedded in smart products, or tracking the product will collect information about the usage and health status information, specific of both the customer and the smart product. The analysis of such data will fuel innovative and customer-centric post-sale services, as well as provide feedback for better product design and marketing. The applications of Big Data on product data, from product inception to its recycling, is rich and complex: all the phases of product life cycle present their own categories of input data to be processed with Big Data tools and produce output data for decision making (we refer to [124] for a detailed analysis).

Another already present source of Big Data that will increase its importance in I4.0 is **enterprise data**. Enterprises already produce and manage high volumes of data: besides internal accounting, employee data, internal communications, there are also data custody requirements from regulations. In Gantz and Reinsel [65] there is already a call for quick focus on business intelligence and related data mining to effectively face global competition and the foreseen spread of highly responsive decision-making based on data. In I4.0 this is only expected to ramp up, due to focus on extensive exploitation of the stream of data, enriched with more data sources and with metadata on the process itself. This will add to *external data* (i.e. from outside the enterprise), coming from sold products, customers, and from suppliers/partners, calling for more and more application and evolution of Big Data technologies. In fact, enterprises are forced to exploit green initiatives to deal with high energy

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consumption related to big data generation, collection, as well as transmission, storage which may also lead to energy and resource inefficiencies [126, 127].

In the production cycle further increase of data will come from the advancing of technologies. In fact **precision control**, one of the components of I4.0, generates the kind of data streams that challenge current technologies (and likely will continue pushing the border of what is Big Data as new technologies become widely available) [125].

Another source of Big Data in the context of I4.0 is the **Continuous Process Improvement practice**, that requires collection of detailed information about the whole production process, in order to identify and eliminate non-essential and non-value-added steps, and reduce process variability (to increase predictability and discover new improvement possibilities). This improvement practices will be automated in the form of (plant/product) health status detection, prognostics, and remediation [128], that also will generate Big Data to be managed with the related techniques. This is carried on to further heights considering that for efficient Intelligent Maintenance Systems, a production system should (i) be self-aware and self-maintaining at component-level granularity and (ii) feed its fault detection and prognosis algorithms with history of components behavior (even of replaced ones) [129]. This likely will keep engaging the high *Volume* management capabilities of Big Data.

Finally, **Cyber-physical Production Systems (CPPS)** are domain-specific Cyber-Physical Systems (CPS), therefore previous research and applications leveraging the Big Data paradigm for CPS are fully relevant in the scope of I4.0 as well: we refer to Atat et al. [130] for a survey on the role of Big Data in the different aspects of CPS, and related challenges.

E. Robotics

Robots are making a considerable impact on human life, from industrial manufacturing to healthcare and transportation [66]. Systems are commonly considered in the area of robotics whether they are able to perform the three functions defining a robot: (i) acting on environmental stimuli in combination with (ii) sensing and (iii) logical reasoning. Robots—being capable of carrying out a complex series of actions automatically—have been one of the elements defining the third industrial revolution. *Evolutionary robotics* is a technique for the automatic creation of autonomous robots that leverages the tools of neural networks, genetic algorithms, and dynamic systems [131]. It is inspired by the Darwinian principle of selective reproduction of the fittest and views robots as autonomous artificial organisms. According to this view, robots develop their own skills in close interaction with the environment (without human intervention). The resulting robots share with simple biological systems the characteristics of robustness, simplicity, small size, flexibility, and modularity.

Role of Robotics in I4.0

A summary of works related to Robotics in I4.0 is reported in Table X.

Table X: Main aspects of interest in *Robotics* related to I4.0.

Aspect	Main References
eRobotics	Rossmann [132], Cichon et al. [133]
Cloud Robotics	Kehoe et al. [112], Wan et al. [134]
3d Printing	Zhang et al. [135], Tam et al. [136]

With current state of the art in industrial robotics ranging from additive manufacturing to inspection, security and maintenance of plants [137, 135], robotics is contributing to modernize most of the classical production lines and their corresponding work methodologies [138].

Driven by market opportunities, evolutionary developments is driving towards the development and the adoption of safe robots which interact directly with humans as well as improved techniques for sensing and path planning, alongside non-traditional applications such as self-driving cars and semi-autonomous drones [139]. Recently, also robotics-enabled additive manufacturing developments have made meaningful progress, as robotic integration allows to achieve a structurally-informed method of fabrication that provides designers with an opportunity to explore a fuller design space that considers both geometry and performance [136, 135].

Thanks to availability of cost-effective (and in most part self-assembled) *3D printers* under open-source and open-hardware licensing, additive manufacturing for low volume productions and prototyping has become widespread for hobbyists (often associated in *FabLabs*) and SMEs [140].

eRobotics aims at providing comprehensive software support to address applications related to robotics and automation. It helps to cope with inherent complexity (facilitating the development and cutting costs for advanced robotics and mechatronics), thus to achieve the best advancements in the development of robots in their respective fields of use [132].

Joining multiple process simulation components "Virtual Testbeds" can be provided, making available a comprehensive tool chain and thus enabling holistic development. The modularity of different building blocks (combined to a fully integrated system)—like sensors or actuators—leads to a continuous development cycle [133]. The concepts of simulation-based control and Simulation-based Support add new functionalities especially regarding real robot interfaces: simulation-based control aims at filling the gap between simulation and real hardware, while simulation-based Support focuses on intuitive user interfaces and simulation in the loop to support the users by means of augmented reality [133].

The development of cloud computing and big-data analytics gave birth to *cloud robotics*, a paradigm leveraging automation systems and robots that rely on either data or code from a network to support operation. The framework of cloud robotics assumes that not all sensing, computation, and memory is integrated into a single standalone system and allows to design (multi-)robot systems with improved energy efficiency, high real-time performance, and low cost [112]. Indeed, cloud robotics aims at transferring the high complexity of the computing process to the cloud platform through communication technology. This paradigm—backed by advances in cloud computing as well in as big data analysis, open source, robot

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Table XI: Main aspects of interest in *Human-Computer Interaction* related to I4.0.

Aspect	Main References
Virtual Reality	Seth et al. [143], Bougaa et al. [144], Orlosky et al. [145]
Augmented Reality	Paelke [146], Kao et al. [147], Shafiq et al. [148, 149], Orlosky et al. [145]

cooperative learning, and network connectivity—reduces the computational load on individual robots, allowing to improve functionalities as well as reduce cost [134].

For what concerns the network facilities supporting the communication between robots and controllers, as well as among robots, a variety of communication protocols specifically designed for industrial control applications has been proposed (e.g., Fieldbus, Control Area Network, WorldFIP, DeviceNet). Proposals based on Ethernet also exist, aiming at leveraging its higher data rate and extension with both fiber-optic cabling and, lately, with Wi-Fi wireless transmission. These industrial Ethernet protocols provide determinism and real-time control. Recent solutions use standard Ethernet (i.e., non real-time) aiming at controlling robotic cells control by using the standard Ethernet (non-RT) while maintaining safety and quality of production [141].

F. Human-Computer Interaction

Interaction (with or without computer) is an information-transfer process. Card et al. [67] proposed in 1986 the Model Human Processor [67], that is a simplified view of the human processing involved in interacting with computer systems. It comprises three subsystems: the perceptual system, the motor system, and the cognitive system, and includes principles of operation describing the behavior of the system under certain conditions [142].

In the interaction with a computer, the human input is the data output by the computer and vice versa. Input in humans occurs through the senses (mainly vision, hearing and touch) while output through the motor controls of the effectors (primarily fingers, voice, eyes, head and body position). Different ways in which users communicate with the system exist (e.g., batch input, direct manipulation, virtual reality, etc) [142]. While in the early days, batch processing was common, nowadays the fact that there are many different types of data that may be entered into and obtained from a system as well as there are many different users, reflects into the different approaches to be implemented.

Role of Human-Computer interaction in I4.0

A summary of works related to Human-Computer interaction in I4.0 is reported in Table XI.

Current trends in I4.0 show that the human interaction in CPSs cannot be eliminated but, on the contrary, it should be supported and emphasized. The I4.0 vision acknowledges the **centrality of the human operator**: rather than implementing production facilities without human workers, it aims at augmenting workers' capability, reshaping their role in production cycles [21]. Indeed, achieving high productivity as well as higher and higher manufacturing flexibility has become a primary goal to cope with rapidly changing production needs due to demand uncertainties generated by market [150]. In this context, human operators are considered the most flexible entity in the production system as they can cover a wide range of different jobs, from specification and monitoring to verification of production strategies.

I4.0 aims at providing a cooperative work environment, not only for enterprises but also for individuals, enabling collaboration among the entire manufacturing ecosystem. Collaboration and cooperation among users in networked enterprises is of the utmost importance [116], and the interactions between humans and machines are even emphasized when dealing with CPSs [117].

Defining the interface between human operators and machines and properly **identifying the required level of automation** in semi-automated systems has proven to be crucial, both to system performance and costs. Indeed, the scientific literature reported how industry automation investments may lead to suboptimal results when considered as a "black or white" decision, as in most of the cases the distinct choice among human or machine is unnecessary. With this aim, methodologies have been investigated and evaluated to systematically define the level of automation for each industry [151, 150]. Consequently, the human factor should be taken into consideration when engineering systems involving both human and machine [91]. In more details, studies suggest that interaction between humans and machines should be considered as changeable, rather than creating a situation where either machines work without input from operators or vice versa: such approach helps address situations where automation does not always work as intended, requiring human intervention for correcting disturbances or system failures [151]. Since in complex automated systems operators not only conduct physical tasks but also perform a series of *cognitive tasks* (such as supervision, control, and decision making), the automation of these cognitive activities has gained more and more significance, as it can decrease operators' mental workload and improve their performance. An increased level of cognitive automation, together with an improved management of information flows, can provide better support to operators, thereby enhancing manufacturing flexibility [150]. This calls for the tools provided by Artificial Intelligence (see Section II-G) for implementing cognitive automation. In addition, the application of numerical control technologies as well as ongoing digitization generate huge amounts of information that are potentially helpful for supporting operators. From the need to process—often in real-time— such flows of information, the field of research of Big Data and related tools comes into play (see Section II-D).

According to the considerations above, focusing on the performance of people is utmost to improve the quality of manufacturing processes and products. Human resources are often considered as one type of manufacturing capability, including employees, skills and knowledge required to complete a specific job. Hence, the integration of humans with software and hardware is one of the fundamental requirements to satisfy this new development needs in the industry [27]. In this light, enhanced human-computer interactions, or more broadly, **enhanced human-machine interfaces** are enablers of distributed manufacturing [152] together with collaboration software. User interfaces of CPSs involved in the production automation in particular, need to be well designed and taking into consideration the industrial application requirements [153].

Dix et al. [142] identified a number of different interaction styles, such as: (i) *command line interface (CLI)*, providing a means of expressing instructions to the computer directly, using function keys, single characters, abbreviations or whole-word commands; (ii) *menus*, where a set of available options is displayed on the screen; (iii) *natural language*, with systems that can be built to understand (restricted) subsets of a language; (iv) *question/answer and query dialog*, where the user is asked a series of questions and so is led through the interaction step by step; (v) *form-fills and spreadsheets*, that can be used for both data entry and data retrieval applications; (vi) *WIMP interface*, with windows, icons, menus and pointers, which is the default interface style for the majority of computer systems today; (vii) *point-and-click interface*, that is closely related to the WIMP-style, but restricted to only pointing and clicking action to access information; (viii) *three-dimensional interfaces*, either consisting in interfaces where ordinary WIMP elements are given a 3D appearance or based on interfaces with 3D workspaces. The reported diversity of interaction styles reflects the fact that different types of data have to be manipulated, as well as the availability of input and output devices is fueled and dictated by technology evolution.

The most complex 3D workspace is **Virtual Reality** (VR), defined as "a high-end user interface that involves real-time simulation and interaction through multiple sensorial channels (e.g., vision, sound, touch, smell, taste)" [154]. VR enables users to become immersed in a computer-generated scene and interact using natural human motions [143], thus providing utmost contributions to I4.0 vision in terms of new technologies, worker-factory relationship, modular infrastructure, and production efficiency [144]. According to Burdea Grigore and Coiffet [154], the quality of a VR user experience can be evaluated through three aspects: (i) *immersion*, (i.e. the feeling of being in a virtual scene through fully or partially real-world occulting devices); (ii) *interaction* (i.e. the set of actions/reactions interfaces and interaction techniques for the users to communicate with each other and with the system); (iii) *imagination* (i.e. the interpretation of the parameters that result from a VR experience). **Augmented Reality** (AR) consists in the enhancement of real world experience through important additional information that is generated by the computer in real time, such to upgrade human senses [27]. An augmented reality system is made up of sensors, the AR software, and an appropriate display where users can observe the real world as composed of virtual objects (rather than being composed of all artificial objects as happens in VR frameworks) [146, 147]. Data processing (such as historical analysis and prediction) can be performed on *virtual twins* of the monitored entity, that are in a non-trivial relation with their physical counterpart. In an industrial domain, smart decision can be made based on intelligent virtual objects and systems, representing real-life machines, components, and materials [148, 149]. For instance, AR enables registered annotations and 2D or 3D virtual objects to be interactively integrated into a real environment in real-time, such to aid the interpretation of information in a spatial context. All these approaches are able to provide an *invisible interface*, trough which users are connected with the virtual environment as they would with the real world. Under the guidance of such systems, users can perform real-world tasks.

VR and AR have begun to take advantage of the high-speed capabilities of wireless network and data-streaming technologies. However, limitations like bandwidth and latency still prevent users from achieving high fidelity telepresence and collaborative virtual and augmented reality applications. The advent of 5G networks is expected to mitigate these issues [145].

Research and development will greatly benefit from I4.0 leveraging virtual environments also for testing algorithms, settings, and models of both the products to be manufactured and the manufacturing equipment manipulating them [112]. This makes VR an ideal tool for simulating tasks that require frequent and intuitive manual interaction such as assembly. Technologies such as mobile projectors also provide novel design opportunities for systems in industrial manufacturing, implementing, for instance projection-based AR assembly assistance system that supports users in the production process by projecting picking and assembly information into the physical workspace [155].

Since assembly environments are today capable of simulating visual realism to a very high level, simulating realistic interaction represents the next big challenge for the virtual prototyping community [155]. Indeed, Haptic technologies—providing both force and tactile feedback, i.e. object hardness, weight, and inertia, as well as surface contact geometry, smoothness, slippage and temperature—are evolving and offer a revolutionary approach to realistic interaction in virtual environments. Research has shown that the addition of haptics to virtual environments can result in improved task efficiency times [155].

Newer approaches promote mobile devices and wearables as a mean of communication among the shop floor operators and other departments, to quickly notify unexpected production-line failures. As a result, according to the industry 4.0 vision, production line machinery is more and more equipped with monitoring software, so as to flag the technicians before a maintenance task is required [156]. Indeed, AR is often adopted to visualize real-time information on wearable devices backed by cloud infrastructures to achieve real-time communication [27].

Mobile devices, such as smartphones, tablets, and smart-glasses are expected to be the most important tools when dealing with CPSs [157]. These tools are helping redesign traditional industrial user interfaces, characterized by their unimodal interactions—where e.g., systems receive commands that have been mechanically input by keyboard, mouse, or touch screen and show the reply on a screen. In these legacy systems, auditive channel usually plays a subordinate role, e.g., being used to alert the user with a working signal when errors happen. Indeed, voice control has a lot of advantages for mobile application interactions (e.g. when the operator's visual attention and his haptic capabilities are fully occupied).

Controlling devices with natural gestures (that can be either image- or device-based) is a valid alternative to speech recognition, in that it is particularly intuitive and immediate. The so-called *iPhonization* is an impressive example for how natural forms of interaction can help to realize intuitive device operation [157].

According to the I4.0 vision, employees will be equipped with a **personal assistant** (possibly in the form of their mobile device), in order to retrieve information from production systems, contact colleagues, and perform support functions. Support can be provided on-site and taking into account work environments (e.g., considering location, task, person). Current workplace can be detected leveraging advanced indoor positioning systems [158] as well as integrated cameras and object recognition, and then analyzed. The natural interaction occurs on the basis of multitouch, dialogue-driven voice control, and gesture recognition. Such personal-assistant based approach is expected to provide an efficient, effective, and satisfactory use of available technologies to coherently prepare and visualize a substantial amount of information, by means of either augmented reality or virtual reality [157].

G. *Artificial Intelligence*

Artificial Intelligence (AI) consists in the simulation through computer systems of human intelligence processes such as *learning* (i.e. the acquisition of information and rules for using it), *reasoning* (i.e. the adoption of rules to reach conclusions), and *self correction*. The term "Artificial Intelligence" was coined in 1956, and is adopted today as an umbrella term that encompasses heterogeneous intertwisted branches such as Robotics, Big Data Analytics, Machine Learning, Machine Vision, and Natural Language processing [68]. Because of their specific impact on I4.0, note that we deal with Big Data (see Section II-D) and Robotics (see Section II-E) in dedicated sections.

The high levels of flexibility and self-organization desired by the overall production network to provide competitiveness in global markets, reflects to challenging requirements in terms of **agility**— i.e., the ability to work in an environment of continuous and unanticipated changes—demanded to AI systems. Indeed, agility impacts the entire manufacturing organization, including product design, customer relations, and logistics, as well as production.

In this regards, *Multi-Agent Systems* (MAS) offer a way to relax the constraints of centralized, planned, sequential control. MAS is a very active area of research with commercial as well as industrial applications and can be applied in I4.0 for realizing agent-based and holonic manufacturing systems. MAS technology is an advanced manufacturing scheme where the involved resources are defined as intelligent agents negotiating with each other to implement dynamic reconfiguration to achieve flexibility. In more particulars, holonic manufacturing is based on the concept of holonic systems, where subparts are simultaneously self-contained wholes and depending parts [159]. For additional details we refer to the review provided by Adeyeri et al. [160] providing a picture of published articles on agents' usage at manufacturing enterprise level for reconfigurable manufacturing system.

Table XII: Main aspects of interest in *Artificial Intelligence* related to I4.0.

Aspect	Main References
Computer Vision	Toro et al. [165], Posada et al. [166], Pérez et al. [167], Monostori [168]
Cyber-Physical equivalence	Stork [169]

Machine learning is the science of getting a computer to act without programming and encompasses three types of algorithms: supervised, unsupervised, and reinforcement learning [161]. *Deep learning* refers to a subset of Machine Learning that is characterized by multi-layered ("deep") architectures, and can be thought of as the automation of predictive analytics [162]. *Pattern recognition* is also a branch of Machine Learning focusing on identifying patterns in data. *Machine vision* (or Computer Vision) captures and analyzes visual information leveraging cameras, analog-to-digital conversion, and digital signal processing and aims at creating a model of the real world from images [163]. *Natural language processing* (NLP) is an area of research and application that explores how computers can be used to understand and manipulate natural language text or speech [164].

Role of Artificial Intelligence in I4.0

A summary of main references for Artificial Intelligence regarding different aspects in Industry 4.0 is reported in Table XII. AI, backed by emerging information technologies (such as IoT, Big Data, and Cloud Computing) helps implement the smart factory envisioned by Industry 4.0 [170]. Interconnected CPSs and smart machines are at the basis of the I4.0 vision. The applications generated in this industrial environment are heavily benefited from tools aimed at supporting decision through the analysis, the filtration, and the interpretation of huge amounts of information from different types of sources [171].

According to the proposed architectures, smart machines, conveyers, and products communicate and negotiate with each other to reconfigure themselves to achieve flexible production. Indeed, systems implementing the I4.0 vision are in charge of deciding and triggering actions, as well as controlling each other independently. Within smart factories, the industrial network collects massive data from smart objects and transfers them to the cloud, thus enabling system-wide feedback and coordination based on data analytics to optimize system performance (see Section II-D).

Therefore, AI perfectly fits with challenges arisen in typical I4.0 scenarios as it is required the use of knowledge-based and intelligent information approaches [172, 165]. Techniques from Machine Learning have already been used in manufacturing for more than twenty years (*Intelligent Manufacturing*) where the newest results in these fields are significantly contributing to recent advancements [173, 159].

To achieve the I4.0 vision, it is also necessary to capture, analyze, and interact with both the real and the virtual production worlds with a high level of precision. **Computer Vision** is defined as the entire field of acquiring, analyzing, and synthesizing visual data by means of computers. Its application plays an important role in achieving Industry 4.0 solutions.

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Indeed, Computer Vision is an important enabling technology that sensibly enhances the final outcomes, acting as a unifying element in many applications and a facilitator and integrator of other technologies [166]. Different vision techniques are used for inspection and quality control processes as well as for robot guidance (e.g., photogrammetry, stereo vision, structured light, time of flight and laser triangulation). Passive techniques, such as stereo vision and photogrammetry only require ambient lighting to solve the problem by looking for the same point in multiple images and computing the intersection of the projection lines; active vision techniques instead, project a visible or infrared pattern onto the scene and estimate the depth information e.g., from the returning time, the deformation of the pattern or trigonometric calculations [167]. The choice of the vision system to use depends upon the parts that need to be located or measured. Vision systems are already widely adopted in industry, mainly for inspection and quality control processes, and are increasingly used to improve the safety of workers [167]. Computer Vision is also largely adopted for robot guidance, as robots need machine vision to identify and locate working parts, to move around the working space and avoid obstacles, to work collaboratively with humans, to improve their positioning accuracy, etc. [167, 168]. Depending upon the specific goal, vision systems can be scene-related (when the camera is mounted on a mobile robot and applied for mapping, localization and obstacle detection) or object-related (when the camera is attached to the end-effector of the robot manipulator and new images can be acquired by changing the point of view of the camera) [167].

For what concerns Computer Vision in the framework of I4.0, **cyber-physical equivalence** (CPE) (where a virtual representation of the cyber-physical production system is fully synchronized with the physical one in aspects such as geometry, function, and behavior) represents a challenging and promising research field, aiming at implementing solutions for e.g. using fast-enough 3D-capture devices to acquire moving objects or articulated machinery and then streaming this 3D information into a virtual environment to facilitate planning tasks [169].

H. Free/Libre Open Source Software

An often overlooked enabler of I4.0 is Open Source Software, also "Free/Libre Open Source Sofware" (FLOSS), i.e. software distributed under a license that permits redistribution in source code form, modification, and usage with almost no restriction. By considering FLOSS as an enabler for Industry 4.0 we include the ecosystem based on the development paradigms, communities, and tools involved with such category of software, besides the software itself.

Many (and not completely overlapping) definitions of FLOSS can be found, so we refer to [69] for an analysis of its defining properties and a framework for analyzing the related development approach. Besides the specific definition, and the dozens common FLOSS licenses, the key feature is the possibility to modify the software, improving it or adapting it to new usage context, with the possibility of sharing the modifications. A consequence is that such software can be obtained and (re-)distributed with no additional licensing/royalties costs, although other implicit costs in its operation (etc. planning, learning, technical support) are usually present as in proprietary software. FLOSS characterizing properties have fostered development methods much different from proprietary software [174, 69], and they (along with associated business models) have proved extremely effective in promoting applied research, innovation, fairer competition, and faster progress in several fields. This phenomenon has been thoroughly studied for its impact on research and industry: see [175] for an early survey of studies, and [176] for a massive survey and analysis of popularity of FLOSS and motivations in terms of performance, security, reliability, scalability, total cost of ownership; the overall better quality of open-source software and its help in adopting best practices such as software reuse has been also empirically confirmed [177]. It is worth noting that, as the FLOSS development models typically are highly geographically distributed, this category of software relies heavily on the Internet to be produced and maintained.

Table XIII: Main aspects of interest in *Free-Libre Open Source Software* related to I4.0.

Aspect	Main References
Internet protocols	Wheeler [176], Oshri et al. [178]
IoT	Uckelmann et al. [179]
Robotics	Han et al. [180]
Additive manufacturing	Wittbrodt et al. [181]
Cloud Computing	Kehoe et al. [112]
Blockchain	Porru et al. [182]

Role of Open Source software in I4.0
A summary of main references for Free/Open Source Software regarding different aspects in Industry 4.0 is reported in Table XIII.

For virtually all the enablers of I4.0 considered in this paper, the contribution of Open Source Software in terms of operating systems, protocol implementations, middleware, applications is easily verifiable by checking the—generalist and specialized—Linux distributions and public software repositories[5]. The Internet can be considered an application context in which FLOSS has shown a specific evident success [176]. Regarding the web, that arguably has been the "killer application" for the Internet and the origin of the web-based technologies fueling the *second-generation IoT* (see Section II-B), FLOSS has a deep impact from both the server side and the client side. To put into context such statement, consider that 64% of active web sites are run on two examples of FLOSS HTTP servers (namely Apache and nginx), and the GNU/Linux operating system runs more than 66% of the web server hosts; regarding the client side, the operating system kernel Linux is at the basis of the Android mobile operating system, accounting for 86% of

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[5] More than 300 up-to-date Linux and BSD *distributions* (specialized or customized variants of the operating system) are tracked by Distrowatch (https://distrowatch.com), and public repositories such as SourceForge (https://sourceforge.net), GitHub (https://github.org), GitLab (https://gitlab.org), etc. collectively claim to host millions of open-source projects.

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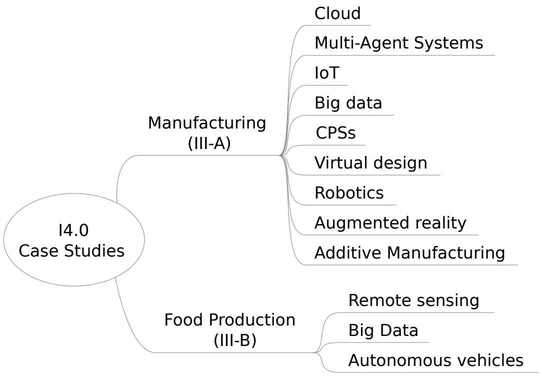

Figure 6: Case Studies and Experiences in applying I4.0 principles.

the global market share of mobile devices[6]. Still regarding web client Oshri et al. [178] use the history of the so-called *browser wars* to provide an in-depth business analysis of how open source lead the establishment of the *de facto* web standards.

Regarding other enablers, research has also acknowledged the driving force of FLOSS, for the IoT specifically [179], for Robotics [180], Additive Manufacturing [181], Cloud Computing [112], and Big Data [183]. Notably, the very first blockchain implementation *Bitcoin* is open-source (like its dozens derivatives), and so are all the well-known blockchain technologies [182].

Inherent to the nature of FLOSS, the main benefits deriving from its adoption can be summarized in maximum interoperability, reuse, (public-) auditability, and possibility of community-based crowdsourcing of testing, development, and dissemination/advertising. All these properties fit extremely well in the paradigm of Industry 4.0. Moreover, for both open-source and proprietary software the lifecycle (design, development, maintenance, and decommissioning) has experienced similar trends to those inspiring Industry 4.0 (extensive automation and feedback loops): the spread of *Agile* approach to design and development [184], and *DevOps* life-cycle management paradigm [185], provided the conceptual, organizational, and technical tools to continuously sense the user/business needs and quickly respond to them. These tools in turn are mostly FLOSS and leverage Cloud infrastructures and services, again confirming the close interdependence of enablers inside I4.0.

III. INDUSTRY 4.0: CASE STUDIES AND EXPERIENCES

In this Section, guided by the contributions available in the scientific literature, we discuss the most relevant application scenarios of the I4.0 paradigm, with some related experiences.

In the following we purposely focus on those turning out to be the two domains mostly related to I4.0: *manufacturing* (see Section III-A) and *food production* (see Section III-B). This notwithstanding, the discussed ICT enablers clearly allow the extension of the I4.0 vision beyond the boundaries of economic sectors theory, from the industrial domain to a variety of additional ones (e.g., healthcare [186], hospitality and tourism [187]) that are traditionally considered among services. Therefore we will not include them in this section, to provide a more focused view, but we discuss them in Section IV.

A. Manufacturing

Manufacturing is a fundamental field of application of Industry 4.0 paradigm. In this field, extensive automation is one of the major indicators of the ongoing change, but it is not able to provide by itself competitive advantage. Thus, manufacturing-related activities (from design to shipment) are more and more carried out by intelligent technologies [188]. To address issues dictated by the rapidly changing environment, the manufacturing industry is therefore paying increasing attention to the agile, networked, service-oriented, green, social, and other manufacturing characteristics, and at integrating information as well as sharing resources among different industries and enterprises (e.g., for the demand of personalized customization) [189].

To obtain these goals, a number of I4.0 enablers have been considered for enhancing manufacturing and some applications have been experimented. Table XIV summarizes the most relevant examples related to cloud manufacturing and smart industry reported in the scientific literature. As these works refer to different subset of technologies, the table points to those considered by the reported literature.

In the following we describe the specific cases and applications, grouped according to the umbrella term (*smart factory, cloud manufacturing*) they have been presented with (often predating the spread of Industry 4.0 terminology).

Smart factory enhances other prior advanced schemes for manufacturing (e.g., flexible and agile manufacturing) that have been proposed to overcome the drawbacks of the traditional production lines [190]. Smart factory is achievable by extensively applying the existing enabling technologies (see Section II) while coping with the technical challenges, especially due to safety and security requirements (see Section IV for details). In this context, cloud-assisted wireless networks in the industrial domain are of the utmost importance to suitably support the smart factory and implement IoT and services [191]. Thanks to this kind of architectures, smart objects can communicate to implement *self-organization* as well as *system-wide coordination* leveraging the massive data uploaded to and processed by the cloud that has scalable storage space and powerful computing ability. Wang et al. [191] provided a general architecture for the smart factory, proposing a framework to integrate the industrial wireless network, cloud, and terminals with the smart shop-floor devices.

Cyber-physical Production Systems have been proposed as specialization of CPSs to manufacturing. In this regard, a general framework for adopting CPS in manufacturing has been defined by Lee et al. [192] and Lee [193], based on the so-called *5Cs architecture*. Its main levels and functions are: (i) *Connection*, to acquire data, e.g., from IoT machines, sensors, quality inspection processes, maintenance logs, and enterprise management systems; (ii) *Conversion*, where data are processed and converted to obtain meaningful information through signal processing, feature extraction, and commonly used prognostics and health management algorithms; (iii) *Cyber*, where all

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[6] https://www.statista.com/statistics/266136/global-market-share-held-by-smartphone-operating-systems/

information confluences and is processed and the performance of a single machine can be compared and rated, also considering historical information, to predict the future behavior of the machinery; (iv) *Cognition*, that generates a thorough knowledge of the system monitored and provides reasoning information to correlate the effect of different components within the system; (v) *Configuration*, acting as a resilience control system to apply corrective and preventive decisions made in the cognition level. Real-time access to monitoring information, related data integration, as well as predictive maintenance are fundamental challenging aspects which help to give better process control, optimize, and reduce overhead costs [194].

Cloud Manufacturing is a new manufacturing paradigm obtained combining technologies such as the IoT, Cloud, service-oriented technologies, and high performance computing [23]. Indeed, Cloud is transforming the business model of the manufacturing industry, helping it align product innovation with business strategy, and creating intelligent factory networks that encourage effective collaboration. This paradigm also encompasses other technology trends, according to specific use cases. Thanks to Cloud manufacturing, customers can request services ranging from product design, manufacturing, testing, management, and all other stages of a product life cycle.

In the following, the main examples stemming out from the scientific literature related to smart factory and cloud manufacturing are discussed. Saldivar et al. [195] investigated future methodologies and trends in smart manufacturing, design, and innovation, focusing on cloud, IoT, and CPS, as well as on the need of well-funded methodologies to integrate these technologies. Rüßmann et al. [196] described the building blocks of I4.0 with the related technology trends (namely, big-data analytics, autonomous robots, simulation, system integration, IIoT, Cybersecurity, Cloud Computing, Additive Manufacturing, and Augmented Reality), also analyzing their technical and economic benefits for manufacturing industry and referring to use case studies from Germany. Wang et al. [197] aimed at documenting the current status and the latest advancements of CPS in manufacturing, also identifying characteristics and requirements, as well as drivers (e.g., time-to-volume and time-to-market, reuse of equipment, reuse of materials, energy efficiency of production systems, self-organization and self-maintenance, online customers support) and barriers (e.g., the conservative approach of the industry, the absence of tailored software approaches, under-performing controllers and limited protocols, the need for equipment integration). Pisching et al. [198] presented the basic concepts and characteristics of service composition based on cloud manufacturing for I4.0, while Morgan and ODonnell [199] focused on identifying the capability of SOA to be implemented at different execution layers present in a manufacturing CPS. Adeyeri et al. [160] proposed a framework for reconfigurable agent-based manufacturing systems. Anderl [200] identifies integrated safety, security, privacy and knowledge protection as fundamental issues in integrating CPSs in the context of smart production systems.

Zhang et al. [201] discuss several typical applications of cloud manufacturing, such as manufacturing communities, virtual industry clusters, 3D printing, cloud service evaluation, and hybrid cloud manufacturing. Wang et al. [202] analyzed the developmental road considering the specific use case of customized furniture factory. Yen et al. [203] emphasize the role of cloud platforms in integrating CPS, for storage, sharing, and computing. Zhang et al. [205] introduced the conceptual model and operation mechanism of decentralized cyber-physical systems, allowing manufacturers to utilize a cloud-based agent approach to create an intelligent collaborative environment for product creation. Peres et al. [206] proposed a framework for the implementation of systems for a highly-flexible distributed data acquisition and analysis aimed at reducing the impact of failures.

The *SmartFactory*^{KL} initiative [190, 207] was established in 2005 in Germany by industrial and academic partners—representing various sectors of economy and research—to create and operate a demonstration and research test bed for future factory technologies. Its equipment basis is a hybrid production facility (designed to be highly modular) for the production of colored liquid soap. Several different wireless communications systems are employed in the demonstration facility. The platform enables research focusing on the use of innovative information and communication technologies in automated systems and on the resulting challenges in the design of such systems. Therefore it offers a research and development basis for numerous projects with various partners.

Regarding **other I4.0 enablers** applied to manufacturing, human-machine interface and IIoT have also been explored. An example is provided by BMW announcing the use of AR as a visual guideline in real-time for its workers [27, 208]. The application consists of a device (composed of glasses and headphones) enabling the operator to see and hear the exact instructions about how to repair a car, while at the same time the operator can ask for information about what tool is right for the next step of assembly or repair. Arnold et al. [209] performed a qualitative study, analyzing the influence of the IIoT on the business model of 69 manufacturing companies, reporting that the machine and plant engineering companies are mainly facing changing workforce qualifications, the electrical engineering and information and communication technology companies are concerned with the importance of novel key partner networks, and the automotive suppliers predominantly exploit IIoT-inherent benefits in terms of an increasing cost efficiency.

B. Food production

Food production processes and tools are seeing the same evolution described for the rest of human productive activities. Regarding agriculture, Walter et al. [210] suggested that it is undergoing a fourth revolution triggered by the increasing use of ICTs, that are proving to be the game changers, not only in developed countries but also in developing countries where e.g., mobile technologies are being adopted at a rapid pace. The drivers of the revolution in agriculture (also dubbed *Agriculture 4.0*) are the same of I4.0, and the underpinning principia are the same. Similar concepts have been proposed focusing on different products categories (vegetables or meat) and different

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Table XIV: Paper discussing Cloud Manufacturing / Smart factory and related enabling technologies.

Reference	Year	Cloud	Multi-Agent Systems	IoT	Big data	CPSs	Virtual design	Robotics	Augmented reality	Additive Manufacturing
Yen et al. [203]	2014	✓				✓				
Anderl [200]	2014					✓				
Zhang et al. [201]	2014	✓					✓			✓
Saldivar et al. [195]	2015	✓		✓	✓	✓	✓			
Adeyeri et al. [160]	2015		✓							
Rüßmann et al. [196]	2015	✓		✓	✓			✓	✓	✓
Pisching et al. [198]	2015	✓		✓		✓				
Lee et al. [204]	2015					✓				
Wang et al. [197]	2015	✓		✓	✓	✓				
Wang et al. [202]	2017	✓			✓	✓	✓			
Zhang et al. [205]	2017	✓	✓		✓	✓				

aspects of production (the very first steps of the food chain) and a number of names have been coined for them: *Smart Farming* [211], *Smart Agri Logistic*, *Smart Food Processing*, *Smart Food Awareness*.

As I4.0 and these concepts are focused on seamless integration and extensive automation of processes, it seems to us preposterous to have integration break at the artificial boundaries of economical sectors, and thus keep agriculture and farming out of the discussion on I4.0. Actually, considering the food production chain, the environment, farming, food processing, delivery, and consumption are all tied together in an economic network. Interconnected robots will have the same kind of disruptive impact whether they operate on a factory floor, or in a farm or an open country field (the planned availability of 5G coverage in rural areas and the use of drones [212] clearly show that a distinction between the Industry 4.0 paradigm and what we consider its *application* to a specific class of products (food) is moot.

In the following we describe such applications as case studies for the I4.0 paradigm, limited to the food chain.

Smart Farming consists in the use of smart, data-rich ICT-services and applications, in combination with advanced hardware (e.g. in tractors, greenhouses, etc.). This phenomenon is heavily fueled by IoT, Cloud Computing, and Big Data technologies. Differently than *Precision Agriculture*, it relies on more than just location information [213]. Indeed, it is based on data (enhanced by context) and situation awareness, triggered by real-time events [214].

As decision-making is expected to be a complex mix of human and computer factors in the future, **Big Data** allows to provide predictive insights to future outcomes of farming, to drive real-time operational decisions, and to reinvent business processes. Big Data applications are expected to change the way farms are operated and managed. Although there are doubts whether farmers' knowledge can be completely replaced by algorithms [215], key areas of change are real-time forecasting, tracking of physical items, and reinventing business processes. Some interesting examples are discussed in the following.

Remote sensing networks can be deployed for deploying fencing systems, e.g., for containing livestocks in defined areas or keeping animals apart from each other [216].

Autonomous, robotic, and unmanned aerial **vehicles** have been developed for farming purposes [217, 210], such as mechanical weeding, application of fertilizer, or harvesting of fruits; when equipped with hyperspectral cameras, these devices can be also used to calculate biomass development and fertilization status of crops [218], or reveal physiological and structural characteristics in plants and to allow for tracking physiological dynamics due to environmental effects [219].

For a more detailed vision about the benefits of Big Data to Smart Farming, we point to the survey by Wolfert et al. [213].

IV. ICT CHALLENGES AND FUTURE DIRECTIONS IN INDUSTRY 4.0

In this section, the main challenges introduced by the adoption of I4.0 paradigm and its main enablers are analyzed. In the following (Sections IV-A–IV-F), we go through the specific challenges derived by the technological enablers taken into consideration in the previous sections.

Moreover, we discuss the future directions as surfaced by our analysis, presenting other enablers (Section IV-G) that are not currently acknowledged as such in I4.0 paradigm, as well as new application scenarios (Section IV-H) that, despite not

Table XV: Main challenges of analyzed enablers in relation to I4.0.

Enabler	Main Challenges
Internet IV-A	reactiveness to malicious behavior ISPs conflicting interests network neutrality Internet censorship privacy issues ossification of protocols distributed nature regulation-related issues geographic distribution of nodes and links highly specialized and expensive physical devices strong growth for I4.0
IoT IV-B	energy communication standards scalability security
Cloud and Fog Computing IV-C	data privacy loosing control over data availability for critical services computing performance network performance monitoring strategies unequal coverage by mobile-edge unequal coverage by broadband
Robotics IV-D	human-robot interaction lack of shared industry standardization overcoming physical limitations (self-) repairing machines
Human-Computer Interaction IV-E	rethink Human-Computer interactions control of increasing complexity need for user-centered (re-)design mobile and context-sensitive user interfaces wearable computing
Open Source software IV-F	lack of open source reference implementations vendor lock-in management of licensing estimating the transitioning costs

belonging to the industrial economic sector, will be integrated with it within I4.0.

A. Challenges of the Internet in I4.0

To analyze the issues and the risks associated with this fundamental enabler in relation with the new I4.0 paradigm, the complexity of the Internet is best broken down along three aspects: the *logical topology*, the *communication protocols*, and the *physical infrastructure*.

Due to its highly decentralized nature, and its historical evolution as the interconnection of a multitude of independent entities (the *Autonomous Systems*, or *AS*es), the topology of Internet has not been explicitly designed, it is dynamically determined by the ASes through distributed algorithms, and cannot be exactly known, but must be inferred (i.e. *reverse-engineered*[7]).

Moreover, the complete control exerted by the AS on the traffic traversing it allows AS owners to manage such traffic in ways that maximize their profit. As an example, *bulletproof hosting* providers want to offer maximum availability to their clients e.g. by avoiding to address abuse complaints[221]. Other examples have ranged from reducing bandwidth for peer-to-peer file sharing applications [222] or competing communication services (VoIP) [223], up to actually modifying content, e.g. reducing size (and therefore quality) of images [224, 225], and introducing or substituting advertisements [226, 225]. These behaviors have led to the discussion on "**network neutrality**", that can be simplified as the principle that ISPs should treat packets independently from the information they bring, without discriminating them according to the applications, users, content, etc. (see Wu [70] for one of the first discussions of the term and its implications, and Antonopoulos et al. [71] for a recent one, after intervention by policy makers). In Industry 4.0 **the power of ISPs on the traffic they handle** can arguably have an even greater impact on the speed, efficiency and profitability of the distributed industrial manufacturing process.

In addition to this, as the ISPs are subject to the law of the state they are based at (in some cases they are even state-owned), they are often required to enforce surveillance or censoring on communications that traverse them. This specific variant of network neutrality violation is commonly referred to as "**Internet censorship**" [73], and carries its own set of political and ethical considerations, which in turn will reflect on economical and technical issues (e.g. arms race between censorship and circumvention tools, enforcement of national borders and weaponization of domestic Internet traffic) [227].

Summarizing, robustness to both faults and targeted attacks, as well as the limits on performance, highly depend on topology: its knowledge and control is of paramount importance that further increases with the envisioned evolution towards I4.0 requirements. Despite this, neither topology [228, 229], not network performance guarantees [230, 231] nor network neutrality [232, 233], nor censorship [234], nor malicious actors [221] are easy to detect and assess, thus requiring specialized monitoring tools, systems, and infrastructures to be designed and deployed [235, 236, 231, 237, 238]. The impact of such factors on the effectiveness of I4.0, and ultimately on its possibility of expansion to different geopolitical areas, is an uncertainty hardly addressable beforehand, and cannot be understated.

Regarding the *communication protocols*, the main issue faced by the Internet is the **ossification of most of the protocols that underpin its basic functionalities** i.e., their resistance (and resilience) to changes, despite the well documented issues, shortcomings, and challenges that protocol designers have raised about the popular and spread implementations in the last 20 years.

The IP protocol has undergone a major change of version in 1995, when version 6 was standardized (as a solution to several shortcomings foreseen for the then current version, IPv4). One of the main motivations behind the changes to the IP protocol, leading to the proposed transition from IPv4 to IPv6 is related to the total number of addresses, exhausted by the unexpected expansion of the Internet and of personal computing, and resulting in a serious bottleneck for the further realization of the Internet of Things (see Section II-B). However, when in 2011 the official exhaustion of available IPv4 addresses was publicly notified, after more than 15 years from the standardization of

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[7] This inference process defines the research field of *topology discovery*, carried on mostly from partial active and passive measurements on the Internet while it is operating [220].

the solution, this new version was still marginally adopted, and as of 2014 it reached 3% of the user base of a popular website (Google), and was supported by 4.5% of top $1M$ websites by popularity [74].

Similar issue is faced by BGP: since its standardization in the early nineties, it has been the instrument of attacks, of censorship enforcement, and also cause of global-scale faults and outages, and while several solutions have been proposed they still lack adoption [76].

Same again for DNS, the protocol translating human-readable and meaningful *domain names* to (numerical) IP addresses: it is currently the single most exploited protocol for enforcing surveillance and censorship [234], and the proposed solution for its several security issues, DNSSEC, while standardized in 1997, is still far from widespread at the time of writing, for a number of reasons that are analyzed in detail by Herzberg and Shulman [75], and are common to other Internet protocols.

In fact, all these protocols share the characteristics of being **distributed**, i.e. their functioning is the result of the interaction of several parties, with different roles, costs, decisional autonomy, motivations, and capabilities. Moreover, they are the foundation of Internet operations, and their modifications need to be gradually (and carefully) introduced into this global system that simply can not be switched off for an update. Recent trends leading to the decoupling between hardware devoted to the control and the data plane, as well as to the convergence of the control algorithms towards (logically) centralized implementations, become considerably more popular with Software Defined Networking (SDN)[239]. The consequence is that, while the elementary functions remain strictly tight to hardware (data plane), the logic governing them can be not just *configurable* (as done in traditional devices), but completely *programmable* (software control plane) in a vendor-independent language, opening to a revolution in the way network protocols are developed, tested, and deployed. Again, even in this case the importance of open standards and open source implementations as opposed to proprietary languages and tools cannot be overstated. These approaches are clearly leading to a change of course, although their applicability is likely confined mostly to intra-AS management operations, and have seen most real-world applications in datacenter networks.

The impact of this status on I4.0 is evident, as the requirements in terms of security, reliability, and timeliness linked with distributed manufacturing and closed-loop customer-production interactions are extremely demanding, while currently operating protocols were not designed for such requirements, and as just discussed they have proved very hard to replace.

Moreover the ever increasing business value related to information flow will exacerbate the conflicts of interest between the many Internet stakeholders and actors, and also likely increase malicious behavior. On the plus side, all the mentioned protocols that today regulate the Internet are open standards, in the strongest meaning of the expression: this has allowed the widest discussion, contribution, and testing to improve them (see Section II-H for more details).

While the logical topology of the Internet at the AS-level has been studied extensively, showing high resilience to random faults, its physical deployment has been found to be **differently affected by faults and attacks** [240]. Communication technologies used in long-distance links are specifically expensive to deploy and maintain, and more exposed to attacks and faults (submarine and landline cable cuts frequently cause long-lasting outages, and satellite links are subject to *space weather* [241]). In more general terms, wireless links are more convenient to deploy (not requiring digging nor cable maintenance) and are therefore favored in new deployments in developing countries. On the other side, wireless links are subjected to higher packet drop and higher delay variability, also offering less predictable performance due to interference [242, 243]. For an analysis of technical challenges of wireless networks in I4.0 we refer to [244]. While wireless networks have proven an effective enabler for nomadic and mobile computing, the radio spectrum is a shared resource, severely limiting the bandwidth and the number of concurrent devices that can use it: due to the increasing density of wireless devices and communications expected in I4.0 this scarcity will likely be an issue. Solutions in this aspect are being investigated by the field of *cognitive radio networks*, or CRN, (an opportunistic communication paradigm that adaptively searches and uses spare radio resources) [245], often leveraging Software-Defined Radio technology for its inherent flexibility.

The adoption of Software Defined Radio (SDR), which allows to radically change the management of the physical radio channel, has seen its own **challenges related to regulation**: as radio frequency usage is strictly regulated in most countries, SDR required new laws, the introduction of new device classes, and new certification procedures, limits, and requirements. The dynamic nature of SDR makes certifications specifically challenging, forcing requirements—that previously were essentially hardware-related—to extend to the software and management domains (e.g. requiring subsystem preventing the installation of unauthorized software) [246]. Similarly, CRNs required changes to regulations that oversee frequencies licensing, allowing and defining criteria for frequency sharing[247]. Other solutions leverage new portions of the spectrum still less exploited, as visible light, possibly “piggybacked” on room illumination [248].

Geographic distribution of nodes and links of the Internet infrastructure has been determined essentially by market opportunity (in turn, driven by population density, local economy, and physical and bureaucratic obstacles). These circumstances have caused an uneven coverage and service of world areas and populations (*digital divide*). Such uneven infrastructure will pose constraints to the development and deployment of Industry 4.0 especially for areas that could greatly benefit from it. On the other hand, new economic factors pushed by I4.0 are likely to foster deployment of new infrastructures in areas previously not profitable.

When transmitted through the Internet, the mix of wired and wireless links that a packet will traverse is not known beforehand, thus the *best effort* service that is experienced can be highly variable, moreover the latency that the transmissions experience can be more than two orders of magnitude greater than the physical minimum [249]. Some applications can not tolerate neither high latency nor high variability: this has led to the development of high-performance networks (dedicated to

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special activities such as High Frequency Trading) [250], that notably are *not* part of the Internet, but provide an example of technologies and deployments with the characteristics that will be required by several I4.0 applications [249, 251]. Indeed, **communication performance** plays a major role for machine-to-machine communications, especially for what concerns control and safety applications, and mission-critical services in general. *Latency* and *reliability* are the two main design criteria usually considered, and while they have benefited from a steady innovation across the past *generations* of telecommunication standards [101], the new application scenarios envisioned by I4.0 call for further research in line with 5G goals of *ultrareliable low-latency communication*: below-millisecond latency and *nine nines* (99.9999999%) reliability [252]. In this context, the *energy* amount required by communication protocols for establishing and keeping communications active is also critical, as directly impacts device battery lifetime and therefore communication longevity. The energy-efficiency of mobile communications has been explored in [253] regarding device-to-device (D2D) communications and its interplay with cellular communications. Varghese and Tandur [244] focused on these aspects for what concerns 5G communications. The authors also discussed the I4.0 performance requirements, resulting in the constraints reported in the following: latency should be less than 5 ms; battery life greater than 10 years; reliability higher than 99.99%; access points should support dense connections with hundreds of thousands field devices. These proposals highlight promising trends of energy-focused research for wireless access networks in the I4.0 vision. Regarding the application layers of the protocol stack, Yokotani and Sasaki [254] compared MQTT and HTTP in terms of required bandwidth and server resource consumption. Similarly, Silva et al. [255] evaluated the performance in terms of latency for two communication protocols (MQTT and websocket) emulating an inter-continental scenario, finding that the latencies of the protocols were comparable but depended on the direction of the communication.

For what concerns the **physical devices** composing the Internet, those composing the backbone (*core routers*) are usually highly specialized devices requiring high-performance hardware. They can be costly and therefore hard to replace, thus contributing to slowing down the protocol changes: the huge budget needed for the IPv4-to-IPv6 transition represents a compelling example. Moreover, the *de facto* (hardware and software) implementation of popular network devices, that is often different from the standard recommendations, has also negatively impacted some potentially useful applications of the standard [256]. The physical communication infrastructure is expected to experience a **strong growth under the exploding demands from I4.0**: almost a decade ago a shift towards a more uniformly spread infrastructure and increasing bandwidth demands were already detected [257], and are expected to further grow, with the consequent management issues. Along with the growth of the sheer capacity that the network is able to manage, other structural and protocol-level changes are ongoing.

Actually the so-called *Fifth Generation* (5G) communication infrastructure is heavily based in integration of heterogeneous networks, in an *All-IP* interconnection scenario, while being specifically targeted at a number of goals (including massive IoT, eHealth, ubiquitous broadband access, high-speed mobility) [258] that concur to the realization of Industry 4.0. 5G cellular networks are expected to significantly facilitate communications inside and among CPSs through different technologies, although a number of challenges (e.g., related to efficient spectrum utilization, spectrum sensing, and link utilization) have to be faced by providers to allow the massive number of CPSs to securely access the cellular spectrum [259], and efficiently share the resources even in *ultra-dense* scenarios [260].

Regarding the physical infrastructure, we add that a clear overall trend towards both softwarization and adoption of open standards can be seen, considering—besides the already mentioned Software Defined Networking—also the paradigms known as Network Function Virtualization (NFV) [261], and SDR [246]. The common characteristic of these paradigms lies in moving to software even basic functionalities previously implemented in hardware (previously necessary due to the economy of powerful enough computing systems), thus guaranteeing increased flexibility. This allows for a gradual network testing and deployment, thus making devices highly reconfigurable and "future compatible", as well as enables networks with sophisticated functions to be realized as either physical middleboxes or virtualized appliances (as Virtual Network Functions) [262]. In some cases these new solutions bring unforeseen issues of their own, as in the case of SDR related to energy efficiency, due e.g. to traffic steering in service-function-chaining enabled networks [262] and SDN-enabled power hungry appliances [263].

These technologies also allow the intelligent sharing of resources among different clients, benefiting from economies of scale (extending to the access network infrastructure the business model that drove cloud computing). This is the case for *network slicing*, that along with the new possibilities brings forth also new security concerns, that are aggravated for critical systems such as CPPSs. The new research trends addressing these issues explore the range from *private 5G networks* [264], to *micro-segmentation* [265], to securing end-to-end communication services [266].

B. *Challenges of IoT in I4.0*

According to a survey of about 200 automation executives conducted in 2015 [267] the main *perceived* challenges and issues in IIoT are—in decreasing order of concern: cybersecurity, lack of standardization, legacy-installed base, significant upfront investments, lack of skilled workers, internal system barriers, liability of current technologies, social/political concerns. Of these, we here discuss the ones rooted in technical issues or solvable technically, albeit it is not easy, due to the wide-range nature of the IoT field, to define the exact set of technologies pertaining to each issue.

With extreme synthesis, considering that IoT consists of interconnected smart objects, two main sources of issues can be identified: (i) the communication technologies and (ii) the design of smart-objects.

For what concerns the latter, **energy** management is a major technical challenge in design and developing IoT systems. Research is needed on energy harvesting, energy conservation, and the goal of not wasting any energy under operation (zero-entropy systems) [268]. In addition to this, the use of non-silicon substrates for developing smart components is also being heavily researched, to reduce the dependency to silicon with all related problems, like packaging and recycling [268].

Regarding **communication standards**, several mechanisms are used (similarly to what happened at the beginning of the Internet). Trappey et al. [84] present an up-to-date structured list of IoT standards specifically focused to the manufacturing IoT application scenario (IIoT), where they analyze international and biggest national patents portfolios regarding the different layers of IIoT, finding close to 6000 patents. Literature witnesses how existing popular standards for brokering messages through the cloud (such as MQTT) do not always satisfy the needs of IIoT. For instance, Happ and Wolisz [104] provide an overview of the challenges with discovery and guaranteed delivery to a certain number of subscribers over publisher/subscriber networks in IoT settings and present different possible solutions.

In more general terms, while I4.0 aims at implementing IoT within the production environments such to significantly improve flexibility and adaptability of production systems, currently proposed solutions driven by politics and research still consist in vendor-specific and isolated production systems [21]. A crucial requirement is the definition of mechanical, electrical, and communication standards between vendor-specific subsystems. To make the I4.0 vision a success, these proprietary approaches must be replaced by open and standardized solutions. Indeed, the added value of open-source software implementations (such as open OPC UA [269]) would be the ability to stabilize the ongoing theoretical work.

Scalability is another important challenge to be taken into account, as IoT is expected to be composed of up to trillions devices. In this context, where interconnected objects will outnumber by several orders of magnitude those composing classical Internet, performance and manageability would benefit from organization in hierarchical subdomains, as devices can be unlikely connected in a mesh [268]. Moreover, further research is required to develop and design appropriate IoT **security** solutions, e.g., primitives resilient to run-time attacks as well as scalable security protocols. While security and privacy concerns affect several enablers, IoT devices are specifically troublesome from this point of view, as their appearance of everyday-objects, or their small dimensions, or the fact that are wearable, all lead to easily overlooked security and privacy risks. In addition to this, due to their heavily distributed deployment and management, common management tasks like enumeration, discovery, and update become daunting (and thus, less likely to be performed regularly, or at all), further limiting the mitigation and containment procedures that should be applied in case of exposed vulnerabilities.

As for today, IoT systems are not sufficiently enhanced to fulfill the desired functional requirements and bear security and privacy risks, as the issue of having sufficient security both on devices with limited capabilities and in the network interconnecting them has yet to be addressed convincingly [270]. Indeed, IIoT systems generate, process, and exchange vast amounts of security-critical and privacy-sensitive data, which makes them attractive targets of attacks [270]. Technological architectures preserving the respect of privacy have to be developed and used as a basis for any future development [268]. Cyberattacks on IIoT systems are very critical since they may cause physical damage and even threaten human lives. The complexity of these systems and the potential impact of cyberattacks exacerbates the risk [270, 271]. Existing security solutions are inappropriate since they do not scale to large networks of heterogeneous devices and cyberphysical systems with constrained resources and real-time requirements. Protecting IoT requires a holistic cybersecurity framework covering all abstraction layers of heterogeneous IoT systems and across platform boundaries [270].

Additionally, trusted geolocation information of IoT devices composing a critical infrastructure is essential. Although methods have been proposed (also indirect ones, such as the one by Islam et al. [272] using covert channels), the definition of a controlled trade-off between geolocation for security concerns, and privacy of direct users or affected third parties, remains an open issue.

C. Challenges of Cloud Computing in I4.0

Cloud Computing is a fundamental enabler of I4.0, presenting solutions to a number of issues that arise related to data management and processing, possibly encountered in e.g, manufacturing, logistics, and marketing processes. However, it poses other challenges in its own right.

Since solutions based on cloud allow applications to process valuable data in third-party's infrastructures, their adoption introduces severe issues about **data privacy** concerning both hardware and software aspects [273]. These issues are often generated by the limited **trust in the infrastructure provider** and from the related concern of losing **control over data** [274]. Indeed, in this framework, data sharing must be often handled with innovative technologies and tools when moved to the cloud.

Although high availability characterizing cloud-based services helps organizations reduce application downtimes and provide uninterrupted services [275], often (e.g., in the case of critical applications), multi-cloud solutions (i.e., transparently relying on multiple providers) have to be adopted to further improve **availability for critical services** [276].

Moreover, cloud **performance** is another critical aspect making the cloud a multi-faceted element in I4.0: in spite of being a tool to provide on-demand metered services on the one hand, on the other hand computing performance and—above all—**network performance** and efficiency of communication protocols also constitute barriers for I4.0 goals. In fact, poor bandwidth and unpredictable latency are catastrophic when transferring high volumes of traffic or messages in strict temporal deadlines, respectively. This aspect further increases the criticality of the digital communication infrastructures connecting end users to the cloud. The search for a **sustainable solution** to this issue, guaranteeing the necessary QoS while keeping the energy consumption of the datacenter as low as possible, adds more complexity to this task, that remains an open research issue [277]. While the adoption of adequate **monitoring strategies** is mandatory [111, 278, 279], in several contexts the cloud cannot meet all the requirements of I4.0 applications (e.g., new delay-sensitive applications, such as virtual reality and smart building control) thus requiring new architectures to be designed [280] in order to address the proliferation of pervasive mobile devices generating big amounts of data to be stored and processed. *Fog Computing* [62] and related paradigms—i.e. FMEC or *Mobile Cloud* [281]) aim at mitigating these issues, increasing dependability providing user-centric services and dealing with the transfer of cloud services to the edge network (or even within the radio access network in close proximity to mobile subscribers). However, it is worth noting that as of today, delivering these services in a distributed way between end devices and traditional cloud datacenters cannot be intended as the ultimate solution as it introduces further challenges. In fact, these approaches clearly downsize some of the mainly claimed benefits of Cloud, negatively impacting economies of scale and introducing non-trivial deployment and management issues to either the cloud user or the infrastructure providers. As an example, scheduling close-to-devices edge resources and managing their interaction with the devices and the much powerful Cloud is still an active field of research [282]. Although these solutions are expected to increase their popularity over time, the existing requirements in terms of infrastructure proximity potentially introduce **new forms of digital divide** between the areas that are covered by edge-cloud infrastructures and those that are not. To mitigate this and related issues, research is ongoing on the different possibilities in decoupling the local Fog/Edge from the core Cloud, e.g. by using the Cloud as a centralized repository for predictive models, that are run and updated by the close-to-devices Fog [283].

D. Challenges of Robotics in I4.0

Recent tentative solutions of Robotics applications to new scenarios are also highlighting major problems, as also seen in recent DARPA robot challenges [139]. Indeed, emerging scenarios in the framework of I4.0 are going to raise new challenges related to cooperation with humans or teleoperation, remote—even global—development, monitoring, and maintenance of robot facilities, as well as integration of robots from multiple vendors (leveraging better APIs and standards which satisfy real-time performance requirements) [139].

Arguably the most innovative and challenging issue is the **human-robot interaction** [284, 285]. Indeed, even though in some contexts I4.0 only needs limited human intervention [27], the role of human is still considered as irreplaceable some other times [153] (e.g., running of sophisticated machines). Therefore, user interfaces of cyber-physical systems involved in the production automation need to be well designed and focused on the specific industrial application requirements. In fact, due to the extensive automation expected in I4.0, the cooperation of humans and robots in *hybrid teams* is likely unavoidable and calls for research [138]. As a result, the meaning of the concept of teamwork is going to be redefined, as hybrid teams are going to be designed [138]. In addition, research results report how close human-robot cooperation in the industrial context needs adaptive mechanisms in order to avoid a change of working routines for the operators [286].

In more general terms, according to the theoretical framework of I4.0, human labor is considered a service thus human-robot cooperation is just another new option to connect services in an IoT manufacturing application [132]. In this regard, implementations of augmented reality applications have been realized (see Section II-F) to compare and evaluate the usage of such interfaces in a production cell comprising an industrial robot (such as smart glasses with mid-air gestures or smart phone with touch interaction) [153]. These solutions have suffered from **lack of shared industry standardization**: as of the time of writing, even the *guidelines* for Augmented Reality hardware and software functional requirements are still ongoing research and discussion from industrial consortia [287].

Other challenges regard the technologies of sensors, actuators, and the structural properties of the robots: these limit the **physical possibilities**, and cost (and therefore, applications) of robots, therefore are constantly undergoing research and development. Notable goals regard **(self-) repairing machines**, as required by the increased complexity and fast obsolescence of robots, and also by the *cradle-to-cradle* design approach (one of the facets of cyber). The subfield of *continuum robotics* [288] researches tools and technologies (currently focused on surgery) that can be likely adopted also for machine inspection and repair. Similarly, *biomimetic* approaches [289] (currently aimed at human-like prosthetics) will likely also be used to improve the androids in their interaction with humans and with tools and environments designed for human use.

Currently these new approaches have yet to be extended outside the field that has driven their adoption, therefore it remains to be seen if and how effective they will result in mitigating or solving the challenges. Less radical approaches that still remain to be explored to reach the goals of I4.0 regard the *intelligent requirements* of the manufacturing devices: the configurable controller and self-reconfigurable robots are examples of solutions for function expansion of manufacturing units [290].

Moreover the field of Robotics, due to its centrality in manufacturing infrastructures, is likely the most impacted by the I4.0 industrial revolution. Thus regarding this field the research, technical, and management challenges closely match the ones intrinsic to the I4.0 paradigm at large, namely knowledge-driven workflow restructuring, transition from local proprietary systems to distributed and open systems, deep integration with heterogeneous communication technologies: we refer to Chen et al. [290] for an overview of such challenges emerging from an industrial case study.

E. Challenges of Human-Computer Interaction in I4.0

In more general terms, HMI is a very active research field, whose issues and challenges are strictly specific to the characteristics of the adopted technologies. Indeed, technology progress brings new possibility, providing changes to the way men and machines interact with each other, and thus demanding for new research. Regarding I4.0, the revolution of the production systems will necessarily change the overall production workflow also imposing to **rethink Human-Computer interactions**. This is deemed to be one of the major challenges within I4.0 and is already subjected to exploration, funding, and research. The objective that is faced is to **control the increasing complexity** of networked and distributed production systems that is beginning to emerge, so that to avoid simply transferring it onto operators. Therefore, there is a need for ergonomically designed user interfaces, allowing for maximum user productivity, user acceptance, and user satisfaction [157].

Methodologies like **user-centered design** (UCD) [291] that include the usage of prototyping tools, representation of target user groups in form of persons or task modeling, help to take the user into account in every step of the product development. In more general terms, the application of human factors in the development of products is intensively used in the human-computer interaction field. As usability is a key evaluation criterion, it is important to adhere to clearly-structured, quality-assuring development processes to ensure high usability and a number of diverse heuristics, guidelines, and standards exist that can be used to support the development of usable user interfaces [292]. Without enforcing proper design approaches, visual, cognitive and task complexity can lead to solutions that are valuable only to the developers themselves, but are not usable without extensive training [293].

In order to accommodate for new requirements (such as integrated one-to-many access, broader functional range of automation components, rising complexity of monitoring systems, component position tracking, and worker mobility), **mobile and context-sensitive user interfaces** are needed as they allow active information filtering and only provide the users with information and interaction possibilities relevant to their current problem [294, 157]. A solution that is being investigated to this aim is the adoption of **wearable computing** in manufacturing, as it can increase the effectiveness of the interaction making it more natural and spontaneous. Wearables can increase the potentiality of IoT in the industrial environment, improving flexibility in the areas of production, warehousing, logistic, safety, and security. For instance, *smart glasses* provide the functionalities of smartphones in a hand-free format and therefore can be adopted in a number of contexts such as managing assembly and field services, navigation and mapping, remote technical support, as well as security solutions [27]. In addition, since increasing dynamics require adequate systems to support workers in a rapidly changing environment, wearable computing addresses scenarios where smart networked production systems are commonly implemented, giving rise to huge data volumes to be gathered and analyzed[146]. This makes HMI suffer the kind of issues that Big Data addresses (see Section II-D) [27]. The expected *wearable revolution* is therefore ultimately dependent on cloud computing for the huge datasets generated by wearable to be captured, processed in real time, and made ubiquitously available.

F. Challenges of Open Source software in I4.0

In the industrial sector the FLOSS has seen relatively slower adoption historically, but evident signs of changes are present—e.g. the transition from proprietary formats such OPC to open standards with multiple open source implementations available (UPC UA). The importance of Open Source for the adoption and evolution of IoT and IIoT has been investigated in Palm et al. [269]. The main challenges that is discussed in this work is the lack of completely specified open standards, and the related **lack of open source reference implementations**. The authors describe the case of OPC UA standard, that specifies the information model, but whose communication stack is distributed under non-open source license. While the authors present a solution to this problem (a public open-source project, *open62541*, dedicated to providing a platform-independent reference implementation), analogous issues affect other standards involved in IIoT.

Companies in sectors outside the industrial sector have seen varying speed of adoption of FLOSS tools, and face different challenges (and different benefits) from the adoption of FLOSS. We refer to Hauge et al. [295] for an in-depth survey and analysis of the motivations, issues, and benefits associated to FLOSS adoption in different categories of companies; in the following we mention the most relevant results. Indeed, analyzing the relations between the life span of a FLOSS project with internal and external project characteristics is helpful to developers, investors, and contributors to control the development cycle of the software project. Accordingly, Liao et al. [296] proposed a prediction model to estimate project life span in FLOSS ecosystems.

Persisting effects of **vendor lock-in** conditions associated to legacy systems, managed with proprietary software, are common to virtually all companies regardless of the sector. Examples are proprietary protocols and document formats, that force the retainment or adoption of proprietary software to manage machines or interact with third parties, thus preventing the creation or adoption of FLOSS to perform the same tasks. Other challenges regard the **management of *licensing***, i.e. if, what, and how distribute code interfacing with—or based on—FLOSS (e.g. an user interface is likely to provide competitive advantage, on the other hand having a community of users and developers testing, fixing, and implicitly advertising a product would constitute a highly valuable benefit). In general, the **difficulties in estimating the transitioning costs** (and some of the expected benefits) also can deter from a timely transition from proprietary to open-source software. From these analyses we derive that, much similarly to other enablers for Industry 4.0, significant challenges regarding FLOSS reside not in technological issues per-se, but also in the interaction with legacy conditions, corporate culture, market, and regulations.

G. Future technological enabler: Blockchain

Although the vision provided by I4.0 is becoming clearer and clearer over the time—thanks to both the increasing number of governmental initiatives stemming out as well as the research effort of the scientific community in this highly multidisciplinary research field—it is evident how the procedures and the ways this vision is actually implemented strictly depend upon the ICT evolution trends and their degree of maturity.

All the enablers enlisted and analyzed in Section II constitute the technological pillars the I4.0 paradigm is built upon *today*. At the same time, they represent the *technological core* around which its future realizations can be developed. In fact, all these building blocks play—with different degrees of centrality, as also captured by the relations shown in Figure 3—critical roles: for instance, no I4.0 vision could be achievable without the Internet gluing layer, the additional knowledge provided by the capabilities of the big-data frameworks, or the technical and economical benefits granted by the cloud paradigm. This notwithstanding, this set of enablers is expected to grow and evolve, leaving room for either additional technology paradigms or the evolution of the existing ones to address the requirements of the specific application scenarios. As a result, while the core of the I4.0 ICT enablers cannot overlook those we have considered in Section II, the I4.0 vision itself can progress in line with the always-evolving technological scenario.

A clear example for this rapidly-changing scenario is represented by the role of the **blockchain technologies**, providing data structures that are replicated and shared among group members, that are distributed across a network: while these technologies in general were not taken into account in the initial vision of Industry 4.0 key aspects and roadmaps, the reverse (i.e. blockchain studies and services proposing applications for I4.0 or its main enabler IoT) is beginning to appear more and more consistently. The fundamental property of a Blockchain is that its members can transact (i.e. make updates to the distributed data structure) even if they do not trust each other, and also in absence of a trusted intermediary, still remaining confident that the transaction is agreed upon by the members [297]. Before Blockchains, the necessity of a trusted intermediary was unavoidable. These characteristics make them suitable for specific or new applications. After the well-known adoption for creating *cryptocurrencies* (i.e. an electronic payment system based on cryptographic proof instead of a trusted intermediary to guarantee payment certainty and solve the double-spending problem), a major step forward in the applications of Blockchain technology has been the creation of *smart contracts*, i.e. (distributed) systems that can store, verify, and execute the terms of an agreement. More in general, the authentication, authorization, logging and tracking functionalities could leverage Blockchains for several pillars of the I4.0 ecosystem such as the IoT [298], mobile/edge computing, Online Social Networks [299], Cyber-Physical Systems. On the other hand, for *smart contracts* implementations Blockchains will leverage Artificial Intelligence to describe [300] or translate from natural language [301] the terms of the legal contract.

The characterizing properties of Blockchains make them an almost ideal solution to many requirements implied by the collaborative vision of I4.0, specially with regards to security in horizontal integration and end-to-end integration, where automatic interactions happen between different enterprises or across multiple third-party administrative domains. Most examples pertain to IoT scenarios [297], including (i) secure and distributed management of firmware/software update for globally deployed devices; (ii) a billing layer for services and devices such as processing, energy, storage, etc.; (iii) a tracking system for supply chain deliveries.

On the other hand, Blockchains have a number of technical issues (mostly pertaining to performance) that are absent or efficiently solved in “ordinary” distributed database systems. One of the most considered challenges regarding applications of Blockchain to scenarios of interest for I4.0 is the **poor performance in terms of number of transactions per second** that Blockchains like Bitcoin can sustain. In fact, compared with global credit-card payments, Bitcoin results two to three *orders of magnitude slower* [302]. Other cryptocurrencies and other types of blockchain technologies are addressing this issue, that is still under active research [303]. While pseudonimity on the Blockchain is supported out-of-the-box, maintaining *anonymity* and **privacy** is much harder, as all the transactions appear on the shared data structure to be verifiable [304]. The lack of privacy is one of the motivations for *private blockchains*, that restrict participation to the blockchain networks to a selected, authorized set of participants (e.g., involved in the specific phases of the value network), but adding a significant management overhead.

Besides the aforementioned challenges, Blockchains present some less-technical ones related to secondary or external aspects of their applications. One most debated challenge is the **legal enforceability** of Smart Contracts, i.e. the relation between the promise/contract that is defined in a Smart Contract and its legal consequences in the affected juridical systems. While best practices are being defined, such as “dual integration” (a Smart Contract referring to a legal contract that in turns refers to the Smart Contract) it remains to establish what happens when the legal consequences differ from the result of the Smart Contract execution (e.g. due to programming bugs, or specification mistakes).

H. Other application scenarios

The potentialities envisioned through the I4.0 paradigm will evolve with the needs and the society, moving from the activities strictly related to the industrial context to a broader range of services and goals. Indeed, the integration-based nature of the I4.0 paradigm itself and its end-to-end principle make I4.0 hardly restrained to a specific economic sector. For instance, the scientific literature witnesses that healthcare as well as hospitality and tourism are two representative application scenarios showing how the I4.0 vision can be seamlessly migrated to services from the already discussed the primary (food production) and secondary (manufacturing) sectors. While the application of the I4.0 vision in healthcare and hospitality is not as mature as the other application fields we deal with in Section III, we believe that they are worth being discussed here as valuable (and very likely) future directions for the I4.0 paradigm.

Applications in the **healthcare sector** have the social and economic push to find new and more efficient solutions and can massively benefit from Industry 4.0 paradigm. More specifically, the deployment of novel pervasive monitoring applications and personalized healthcare solutions are fueled by the constant

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evolution of the I4.0 enablers, such as mobile technologies, big-data analytics, as well as the cloud and the IoT paradigms, which are driving to unprecedented opportunities. The resulting solutions in the health domain are expected to either replace or complement the existing ones [305].

The IoT paradigm provides a valuable framework to support health monitoring, in collecting health records and generating statistical information related to health condition [306–309]. Cloud- and IoT-based solutions are able to rapidly lower the risk of introducing errors if compared to methods requiring manual intervention [310]. Due to challenging requirements in terms of reliable network connection, in order to mitigate issues generated by the adoption of remote cloud services, Fog computing was proposed to enhance health monitoring systems, taking advantage of computing at smart gateways to provide advanced techniques and services such as embedded data mining, distributed storage, and notification service at the edge [280, 311]. In this context, wearable sensors are often combined with ambient sensors able to sense and control the parameters of the living environment (*ambient-assisted living, AAL*) when subjects are monitored in the home environment [312]. Furthermore, health monitoring applications have been clusterized in *in-body* e *on-body* according to the nature of the sensors adopted [313]. Novel architectures [314] are being proposed to interface such body sensors (by means of multiple wireless technologies) and cloud services. Indeed thanks to the Cloud paradigm, frameworks to collect patients' data in real time and perform appropriate non-intrusive monitoring can be easily implemented, e.g., for observation and emergency assistance [315] or for proposing medical and/or life style engagements [316].

The ongoing fourth industrial revolution is also affecting the whole **hospitality industry** where the challenges of mass customization, smart working, and digitalization also take place. The hospitality sector is therefore focusing on digitalization (both for customization or standardization) to generate long-term capabilities for more effective and efficient business intelligence. Information systems are given considerable importance in this context.

I4.0 in tourism and hospitality is increasing competitiveness through smart equipment, making use of information about customer characteristics, resources, energetic efficiency and urban production (e.g., smart destinations/smart cities) [317, 187] . Thanks to incremental innovations and technological advancements in ICTs (specifically IoT) supply chain results to be successfully enhanced and made more efficient. ICT progress is changing customer behavior and the traditionally structured tourism supply chain: in order to implement on-demand marketing and technological innovations supply chain is now forced to adopt a comprehensive infrastructure based on a more flexible organizational structure [187]. For instance, hospitality firms often have their own mobile apps for booking and other services. In addition, hotels are linked with different third party booking websites offering different options and packages for different hospitality firms, which provide collaborative supply chains [38] and create value added in terms of financial benefits and intangible assets such as improved networking, communication and customer services.

Shamim et al. [38] investigate the feasibility of I4.0 paradigm in the hospitality sector, discussing the management practices in the context of Industry 4.0 providing practical implications for managers and proposing a number of mechanisms to enhance the innovative capability by facilitating technology acceptance including digital enhancements and the implementation of CPS. Environmental changes due to IoT are launching new strategic choices, contributing to rebuilding of the knowledge value chain [52]. For what concerns demand, customer are expected to increase their awareness about the importance of the quality and reliability of information (both acquired and given) and technical condition of the products and services. This will also impact the real-time analysis and accumulation of information and consequently influence coming guidelines of value creation for the customers. However, questions about how to adapt IoT devices and control their impact over private-life aspects are also rising [318].

V. CONCLUSIONS

From our analysis of the scientific literature, a number of main technical enablers have emerged as a basis for Industry 4.0 or directly implied in it, all coming from the Information and Communication Technologies. The enablers that we surfaced are characterized by different maturity levels, ranging from Robotics (basis of the previous industrial revolution) to Blockchains. The nature of such enablers is heterogeneous, comprising vertical technological fields as digital communications, or broad research areas such as Artificial Intelligence. Moreover, they have developed historically in different contexts, even very far from industry and manufacturing, and the convergence of such distant fields envisioned for Industry 4.0 is a major source of innovation and benefits. On the other hand, either for their nature or for the tight integration required by I4.0, many enablers are strongly interrelated or even interdependent. In case of dependence, one offers solutions to requirements or issues of the other (see Figure 3). But in this case the dependent enabler also inherits the challenges and issues of the lower level one, often not immediately evident due to the difference of domain knowledge, and different historical path. In other cases the challenges are common, as they cross the traditional boundaries of research and application of the enablers. Such is the case of *security*, an umbrella term that acquires a number of specific meanings in the ICT domain already, but in the broader context of I4.0 further extends to infrastructure and economy, including physical security, safety, economic or financial security. In this case, the integration of different applicative fields can reveal new challenges and issues previously not known, as real-world deployment cases progress and are studied.

Similarly, *energy efficiency* is both a goal that is common to many of the enablers, and a new research endeavor deriving from contextualizing each enabler in the vision of I4.0. Indeed, by taking into account the whole data-driven design-production-delivery dynamic network envisioned by I4.0, multiple new possibilities for enhancing the overall energy efficiency can emerge. At the same time, it will become easier to evaluate possible externalities that from an energy-optimal solution of a technology considered in isolation could spill-over on other aspects of the value network of I4.0, actually lowering the overall efficiency.

The fundamental characteristic of I4.0, *integration*, remains the unavoidable source of its challenges. To successfully face these, the knowledge of the main enablers of I4.0 and their issues (often unknown outside each enabler-specific study field) is necessary. Indeed these challenges on the one hand can slow down or impede I4.0 development, on the other hand point to future research and experimentation trends, fostering a real-world successful implementation of I4.0. Our work—aimed at exposing part of the complexity hidden in the high-level depictions of I4.0—is a determined step in this direction.

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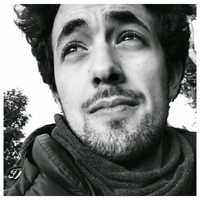

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