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PIS: IoT & Industry 4.0 challenges

Frédéric Le Mouël and Oscar Carrillo

Abstract In the era of Industry 4.0, digital manufacturing is evolving into smart manufacturing. This evolution impacts companies in three main areas: organization, people, and technologies. This chapter analyzes the Internet of Things (IoT) and Cyber-Physical Systems (CPS) - key technologies transforming the physical world into a digitalized physical world. IoT and CPS provide factories with sensing capabilities, perform data and context capture and allow them to act/react to optimize the value chain. We survey the recent state-of-the-art development of the Industrial Internet of Things (IIoT) - also known as IoT and CPS in the context of Industry 4.0, from a protocol, architecture, and standard point-of-view. We also explore key challenges and future research directions for extensive industrial adoption of these technologies.

1 Introduction

Industry 4.0 - a term coined by H. Kagermann et al. - was introduced as the Fourth Industrial Revolution in the context of the development of the German economy (Kagermann et al., 2011). Following the First Industrial Revolution with water and steam engine as a source of power, the Second Industrial Revolution with mass production and globalization, the Third Industrial Revolution with automation and digitization, the Fourth Industrial Revolution concept was popularized by K. Schwab from The World Economic Forum (Schwab, 2016, 2017). Industry 4.0 stands out as the evolution from digital manufacturing to smart factories (cf Figure 1).

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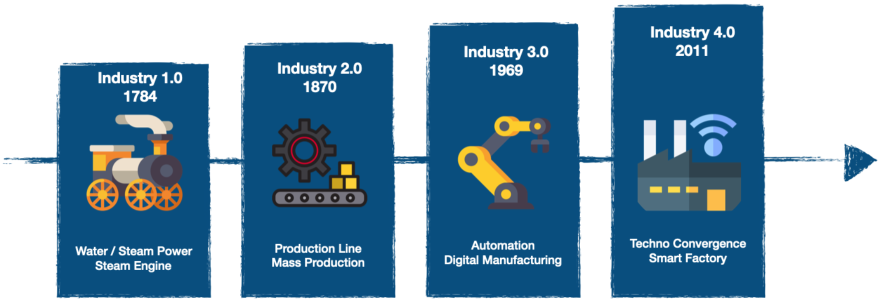

Fig. 1 Industry 4.0 - The Fourth Revolution

Despite significant efforts from the research community, no unanimous definition of Industry 4.0 is currently adopted (Lasi et al., 2014; Qin et al., 2016; Piccarozzi et al., 2018; Boyes et al., 2018; Kiangala and Wang, 2019). Its characterization (Buer et al., 2018) or roadmap (Paravizo et al., 2018; Beier et al., 2020) are not clearly defined. Its complexity makes it difficult to focus on scope, objectives, and holistic development (Meissner et al., 2017; Buer et al., 2018; Derigent et al., 2021).

Rupp et al. have compiled keywords, concepts, and citations in an exhaustive bibliometric analysis within the scope of research literature and have formed a concise definition of the Industry 4.0 paradigm:

> "Industry 4.0 is the implementation of Cyber-Physical Systems for creating Smart Factories by using the Internet of Things, Big Data, Cloud Computing, Artificial Intelligence and Communication Technologies for Information and Communication in Real-Time over the Value Chain." Rupp et al. (2021)

From this clearly technology-oriented definition, Industry 4.0 emerges as the convergence of four major technological trends (cf Figure 2) :

Physical World Digitalization The first requirement to optimize any kind of value chain is to have information about ongoing processes. The *Internet of Things (IoT)* refers to physical objects or groups of objects with sensing and communication abilities that connect and exchange data over public or private networks. Machines or humans are embedded with electronic sensors or actuators to generate data. *Cyber Physical Systems (CPS)* are systems including mechanisms where physical objects, humans, and software are closely intertwined to create new levels of sociotechnical interactions. CPS involves transdisciplinary approaches - merging the theory of cybernetics, mechatronics, design and process science. The principal aim is to produce constant interactions between the real physical world and a virtual world representation to indicate the best decisions (Boyes et al., 2018).

On-demand Computing On-demand computing is an enterprise-level delivery model in which computing resources are made available to the user when needed.

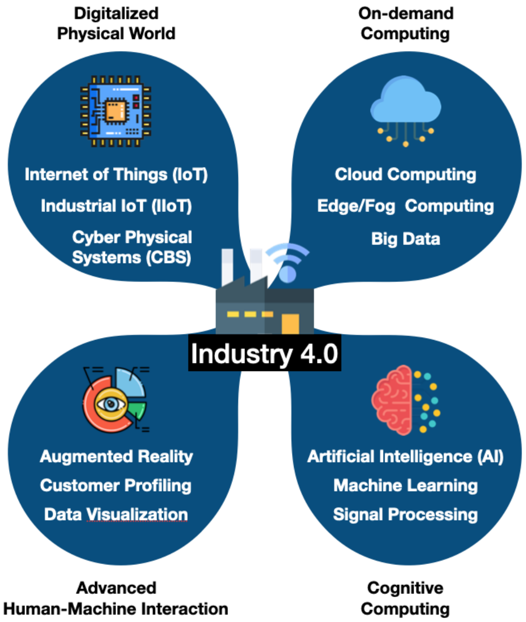

Fig. 2 Industry 4.0 - The Four Major Enabling Technologies

Cloud Computing is a key technology of on-demand computing. Cloud Computing is the on-demand availability of different remote services over the Internet, especially data storage, networking, and computing power. *Edge and Fog Computing* are also key technologies complementary to Cloud Computing. Edge and Fog Computing are distributed computing paradigms bringing computation and data storage closer to the data sources. Edge Computing architectures perform computation and storage on the embedded devices or the gateway at the network's edge, in close proximity to the physical location of sensors creating the data. Fog Computing architectures act as mediators between the edge, the core network, and the cloud for various purposes, such as data processing or data geo-distribution (Hong and Varghese, 2019). Finally, *Big Data* refers to structured, semi-structured, and unstructured datasets that are too large or complex to be dealt with by traditional data-processing application software. Big Data requires the previous computing architectures to be stored and analyzed to reveal patterns, trends, and associations, especially those relating to human behavior and interactions (Chen et al., 2014; Khan et al., 2017).

Cognitive Computing Cognitive Computing refers to technology platforms that mimic the way the human brain works by incorporating advanced aspects of artificial intelligence and signal processing. *Signal Processing* focuses on analyzing, modifying, and synthesizing signals such as scientific measurements, sound, natural language, and images or videos. After any data capture, filtering noise from data and structuring the signal impacts any future knowledge representation. *Artificial* *intelligence (AI)* refers to intelligence demonstrated by machines, as opposed to the natural intelligence displayed by animals and humans. Traditional goals of AI include knowledge representation, reasoning, perception, planning, learning, processing, and decision-making. *Machine Learning* is a subset of AI that has recently regained popularity with advances in artificial neural networks, deep learning, and reinforcement learning (Lee et al., 2018; Verbraeken et al., 2020).

Advanced Human-Machine Interaction is the field studying the design and the use of computer technology interfacing between people and computers. Following the effort to provide multi-modal interfaces (audio, visual, feedback-based), *Augmented Reality (AR)* and *Virtual Reality (VR)* are key technologies where the reality of the physical world is supported and mixed with the use of digital 3D models. AR/VR are mainly used to build and assemble complex components and architectures, and to read and document technical systems in real-time (Xiong et al., 2021). *3D-printing* is, at the same time, a physical world augmentation and an advanced human-machine interacting system. 3D-printing plays an essential role in Industry 4.0 by enabling the direct production of high-complexity digital 3D models, making it suitable for individual production of experimental small-sized batches to large production with high added-value (Rong et al., 2018).

This chapter focuses on Industry 4.0-enabling technologies to digitalize the physical world and how to apply them to industrial and manufacturing contexts - hereby referred to as *The Industrial Internet of Things (IIoT)*. Interactions of the IIoT sensing part are also detailed in regards of adaptation capabilities of the on-demand and cognitive computing, and advanced human-machine interaction parts.

The chapter is structured as follows: Section 2 details the current state-of-the-art. Section 3 presents existing protocols, architectures and standards. Section 4 identifies gaps and challenges that need to be addressed in future research directions, before to conclude in Section 5.

2 State of the Art

In IIoT environments, a machine/device can communicate and share information seamlessly inside or outside the industrial ecosystem. The interoperability is a key point to guaranteeing these exchanges in the industrial ecosystem. IIoT interoperability is most of the time referred to as Machine-to-Machine/Device-to-Device communication interoperability (M2M/D2D), where multiple devices can exchange knowledge and their understanding of the context (e.g., mockups, constraints, processes, states, operations, etc.) within a single hop or multiple hop distance. The main goal is to establish a robust and ubiquitous communication among the heterogeneous embedded devices in the network. Machine connectivity, proximity, identification, and messaging are the cornerstones for conceptual M2M/D2D communications in IIoT environments.

Table 1 Summary of existing IIoT approaches according to PIS criteria

Authors	Context	Heterogeneity			Transparency	Adaptation			Opportunistic	Determinism	Automatic	Interactive
		Network	Machine	Data		Energy	Latency	Throughput				
Pradhan et al. (2018)	Smart City	LTE, IEEE 802.11b/g/n, LoRaWAN, NATO IST 147, MQTT	RFID, spo2, heart, muscle sensors	XML, JSON	Technical (Network)				✗	✗		
Guan et al. (2017)	Smart City	ZigBee, MQTT, WLAN	Smartphone, gateway	VICINITY API	Technical (Network)				✗	✗	✓	
Pramukantoro et al. (2018)	Smart City	6LoWPAN, Bluetooth, CoAP, MQTT, Websocket	ESP 32, ESP 8266, RPI		Technical (Network)	✗	✓	✓	✗	✗		
Žarko et al. (2019)	Smart City	HTTPs, AMQP		JSON, RDF	Technical (Data)					✗		✓
Pramukantoro et al. (2017)	Smart City	IEEE 802.11b/g/n, CoAP, MQTT, Websocket	MCU, DHT 22, gateway	JSON	Technical (Data)	✗	✗	✓	✓	✗		
Doumbouya et al. (2014)	Healthcare, Mobility		Smartphone	XML, XTML	Technical (Data)					✗		
Alaya et al. (2015)	Smart City	HTTP, CoAP		IoT-O semantic	Technical (Semantic)					✗		
Yang and Wei (2019)	Smart City			Rules, SIA, Tabdoc	Technical (Semantic)	✗	✓	✓	✗	✗	✓	✓
Epple et al. (2017)	Smart Factory			IEC61360	Technical (Semantic)					✗		
Ray et al. (2019)	Smart City, Healthcare	Bluetooth, IEEE 802.11b/g/n, MQTT	Motor, GRS sensor, Gateway		Platform (Device)	✗	✓	✓	✗	✗		
Xiao et al. (2014)	Smart *	HTTP		XMPCDC, XMP	Platform (Device)	✗	✓	✓	✗	✗		✓
Negash et al. (2019)	Smart Factory	HTTP, Zigbee, BLE			Platform (Device)	✗	✓	✓	✗	✗	✓	
Golchay et al. (2011)	Smart City, Mobility	IEEE 802.11b/g/n, LTE	Gateway, Smartphone	JSON	Platform (Device)	✓	✓	✓	✗	✗		
Fraile et al. (2018)	Smart Factory	IP			Platform (Cross-domain)					✗	✓	
Valtolina et al. (2019)	Smart City			JSON, ontology	Platform (Cross-domain)	✗	✓	✗	✗	✗		✓
Bröring et al. (2017)	Smart City	BIG IoT API: HTTP, MQTT, CoAP		JSON-LD, XML	Platform (Cross-domain)					✗		
Pereira et al. (2016a)	Healthcare	HTTP, CoAP	Gateway, smartphone	JSON	Platform (Architecture)	✓	✓	✗	✗	✗		
Gyrard et al. (2014)	Smart City, Healthcare	SenML	RFID	OWL	Platform (Architecture)					✗		
Pereira et al. (2016b)	Smart City, Healthcare, Mobility	HSUPA, HSDPA, IPv4, HTTP	Gateway, Smartphone, GPS	JSON	Platform (Architecture)	✓	✓	✗	✗	✗		

There are several challenges to designing an interoperable IIoT environment, and here are the two main ones:

1. a massive amount of heterogeneous IIoT devices are sharing resources, and the majority of the IIoT devices are constrained in terms of storage and processing,
2. the industrial IIoT applications mainly rely on a composition model with an advanced single and centralized orchestrator (Praveen Kumar et al., 2019).

On one hand, several organizations and collaborative institutes such as IEEE[1], IETF[2], and 3GPP[3] explicitly develop and standardize industrial M2M communications. OM2M is one of the universal M2M platforms for industrial applications, where computing devices, gateways, and networks are the building blocks of the ETSI-M2M standard (Ali et al., 2017). Table 1 categorizes IIoT research activities according to the main criteria involved to reach an adaptive and extensible system:

- **Heterogeneity:** IIoT devices are heterogeneous in terms of hardware capabilities, network interfaces and data format supported to interact.
- **Transparency:** We classify transparency capabilities of IIoT systems in two levels: technical integration or platform integration. Technical integration is the possibility to deal with the interoperability issue - either at the network level with compatible protocols, or at the data level with supported data format, or at the semantic level with substitution rules. Platform integration allows to deal with higher levels of interoperability issues - either to integrate new devices, to communicate cross-domain, or to rule all the actors of a domain or sector-specific architecture.
- **Adaptation:** Adaptation criteria in our classification refer to protocol and platform capabilities to adapt and optimize their energy, latency and throughput.
- **Opportunistic:** Opportunistic criteria show the ability of the IIoT system to discover and benefit from its context. In IIoT systems, we particularly classify the system scaling ability in this criteria.
- **Determinism:** Determinism criteria describes the ability of the IIoT system to reproduce the same result from a given context.
- **Automatic:** Automatic criteria validate the IIoT system's ability to automatically make a decision and adapt to an unknown context.
- **Interaction capabilities:** In Industry 4.0, IIoT systems grab context information, to be processed by the cognitive computing part, and to be displayed by the Human-Machine Interaction part. The interaction criteria do not expose the HMI's ability to visualize data, but the HMI's ability to maintain and administrate the IIoT system itself.

The first nine rows of the table show that standardizing communications leads to technical transparency - either at the protocol level, for data format, or semantic integration. These approaches optimize device point-to-point communications, such

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[1] https://standards.ieee.org

[2] https://www.ietf.org/standards

[3] https://www.3gpp.org/specifications

as latency or throughput criteria. They even sometimes take opportunistic advantages of network characteristics, but can not globally optimize the energy of the whole network and system (Mao et al., 2021).

On the other hand, a possible solution to these challenges is categorizing devices into tiers and orchestrating edge-fog-cloud technology into the IIoT environment. Mature cloud technology provides unlimited data collection and sharing resources across distributed IIoT environments, and fog networking supports the industrial processing chain by delivering a faster response to delay-critical industrial applications. In 2011, Cisco introduced the Fog Computing paradigm to process low-latency industrial applications near the sensing devices (Bonomi et al., 2012), or even on edge devices/gateways (Cao et al., 2020; Bajic et al., 2019). Later OpenFog Consortium[4] - now merged with the Industrial Internet Consortium[5] - was founded to develop and standardize Fog Computing (OpenFog Consortium, 2018). Fog Computing supports QoS-aware data processing, productivity, mobility, and agility, making interoperable IIoT ecosystems geographically distributed over the network. Cloud computing and its supporting technologies - such as container-based cloud, serverless computing, and cloudlet - support interoperable data processing enabling big data analysis, data migration, and data virtualization by providing a pay-as-you service model. Some standards associated with cloud interoperability are ISO/IEC 19941 (ISO/IEC, 2017), IEEE P2301 (IEEE, 2020), and OCCI (Ahmed-Nacer et al., 2017). Furthermore, some modeling languages like TOSCA (Binz et al., 2014), CAML (Bergmayr et al., 2014a), HOT (Markelov, 2016) support cross-cloud data transfer, where data can be moved from one service provider to another service provider without modifying the structure and format of the data (Bergmayr et al., 2014b).

By incorporating edge-fog-cloud infrastructures into healthcare (Javaid and Haleem, 2019), agriculture (Liu et al., 2021), smart city/building/home (Karaköse and Yetiş, 2017; Aheleroff et al., 2020), logistics (Barreto et al., 2017; Lin and Yang, 2018), automotive sector (Cronin et al., 2019), and manufacturing (Wu et al., 2017; Pilloni, 2018; Frank et al., 2019; Ghobakhloo, 2020), many - domestic or international (Bettiol et al., 2020) - companies have developed their IIoT environments with the creation of added value (Akdil et al., 2018; Josefsson, 2020; Elango, 2022) and contribution to circular economies (Dantas et al., 2021). Despite these efforts, as shown in Table 1, very few approaches are automatic, take advantage of the context in an interactive way, and - because of the unpredictable nature of IIoT communications - none are deterministic.

3 Existing Solutions

Existing solutions are presented in the following sections, first, with a bottom-up approach in Section 3.1, describing IIoT protocols allowing to built IIoT environment

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[4] https://web.archive.org/web/20181222131011/http://www.openfogconsortium.org

[5] https://www.iiconsortium.org

connections. Then, Section 3.2 details the top-down approaches with Industry 4.0 architectures, allowing to build the global IIoT view. Finally, Section 3.3 presents existing adopted standards.

3.1 IIoT Protocols

Connectivity in today's world includes a set of heterogeneous devices (e.g., sensors, smartphones), network architectures (e.g., Ad hoc, Bluetooth), and large distributed environments (e.g., Ethernet, HomePlug). This complexity is a big challenging issue for industries (Spachos and Plataniotis, 2020). On top of that, devices have their own distinct issues and goals such as energy, latency, scalability, safety that further extend these challenges to the next level. The IIoT main goal is how to build a device-friendly protocol stack so that the devices can communicate with each other, inter-operate, exchange their knowledge and meet their desired objectives (Palattella et al., 2013). However, the existing OSI and IP models are unsuitable to adopt the distributive nature of IIoT and the diverse interoperability issues (Sharma and Gondhi, 2018). It, therefore, requires a separate protocol stack, which is scalable, flexible, cost-efficient, and business-oriented.

Several academic efforts and standardized institutes (e.g., IETF (Moran, 2021) and ITU-T[6] (ITU-T Study Group 20, 2020)) defined 4-levels of IoT protocol stack for ultra-reliable and low-latency communication with the objective of incorporating large numbers of low-powered IoT devices.

IIoT applications can become more efficient, intelligent, flexible, and diverse by considering the benefits of new networking technologies. Therefore, in order to meet the specific IIoT requirements, several design objectives need to be considered. Table 2 summarises popular IoT/IIoT interoperable protocols, giving their characteristics and detailing their abilities according to PIS criteria:

- **Adaptation to power consumption:** Power supply is one of the prerequisites for establishing an industrial technology center for any country. Moreover, this metric is directly related to the economy. Industries such as smart grids, smart cities, mining and manufacturing are the most affected areas of the power supply. Therefore, an interoperable IIoT ecosystem also demands energy-efficient communication protocols between lightweight IIoT devices.
- **Security adaptation:** Industrial digital technology encourages the connection of new devices, thereby increasing new thread factors and unknown risks to the industrial installations. These threads can be internal or external. Network segmentation, user access, and policy management are the three critical factors of industrial security (Benias and Markopoulos, 2017).
- **Adaptive QoS:** QoS network resource management and system capabilities for IoT communications are supported with a secure backbone. QoS can include delays, latency and bandwidth variations, and packet loss to provide stable and

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[6] https://www.itu.int/en/itutelecom

Table 2 Summary of existing IIoT protocols according to PIS criteria

				Characteristics					Adaptation			Transp.	Opportunistic
OSI Layer	Protocol	Standard	Context	Transport	Frequency	Range	Data rate	Messaging	Power	Security	QoS	Interop.	Reliability
Physical	Zigbee	IEEE802.15.4	Industry	-	2.4 GHz	10-100 m	250 kbps	-	Low	✓	✓	✓	✓
Physical	RFID	ISO/IEC	Industry	-	960 MHz	200 mm	640 kbps	-	Low	✓	-	✓	✓
Physical	NFC	ISO/IEC	Smartphones	-	13.56 MHz	4m	424 kbps	-	Low	✓	-	✓	✓
Full Stack	SigFox	SigFox	Industry	Both	862-928 MHz	50 km	1 kbps	-	Low	✓	✓	✓	✓
Full Stack	NB-IoT	3GPP	Smart City	Both	200 KHz	10 km	1 Mbps	-	Low	✓	✓	✓	✓
Datalink	Z-Wave	IEEE 802.15.4	Smart Home	UDP	915 MHz	30-100 m	100 kbps	-	Low	✓	-	✓	✓
Datalink	HomePlug GP	IEEE 1901-2010	Industry	-	28 MHz	2 km	1 Mbps	-	Low	✓	✓	✓	✓
Datalink	Dash7	ISO/IEC 18000-7	Industry	-	433 MHz	5 km	200 kbps	-	Low	✓	✓	✓	✓
Datalink	LoRaWAN	LoRaWANR 1.0	Smart City	-	868,915 MHz	15 km	50 kbps	-	Low	✓	✓	✓	✓
Datalink	Bluetooth	IEEE 802.15.1	Smart Home	TCP	2.4 GHz	10-150 m	1 Mbps	-	Low	✓	✗	✗	✓
Datalink	BLE	IEEE 802.15.1	Industry	-	2.5 GHz	100 m	2 Mbps	-	Low	✓	✗	✓	✓
Network	6LoWPAN	IEEE 802.15.4	Infrastructure	-	-	-	-	-	Low	✗	-	✓	✗
Network	WiFi	IEEE802.11	Transport	UDP	2.4-5 GHz	50 m	200 Mbps	-	Medium	✓	✗	✓	✗
Network	RPL	IETF	Routing	-	-	-	-	-	Low	✓	✓	✓	✓
Network	IPv4	RFC 3927	Identification	TCP	-	-	-	-	Low	✓	✓	✗	✗
Network	IPv6	IETF	Identification	Both	-	-	-	-	Low	✓	✓	✗	✓
Application	HTTP	HTTP 1.1	Healthcare	Both	-	-	-	Req\Res	High	✓	✓	✗	✓
Application	CoAP	RFC 7252	Industry	UDP	-	-	-	Req\Res	Low	✓	✓	✗	✓
Application	XMPP	IETF	Industry	TCP	-	-	-	Req\Res	High	✗	✗	✗	✓
Application	WebSocket	IETF	Industry	TCP	-	-	-	Pub \Sub	Low	✗	✗	✗	✓
Application	MQTT	ISO/IEC 20922	Industry	TCP	-	-	-	Pub\Sub	Low	✗	✓	✗	✓
Application	Mosquitto	MQTT v3.1	Messaging	TCP	-	-	-	Pub\Sub	Medium	✗	✓	✓	✓
Application	HiveMQ	HiveMQ 4	Messaging	TCP	-	-	-	Pub\Sub	Low	✗	✓	✓	✓
Application	VerneMQ	VerneMQ	Messaging	TCP	-	-	-	Pub\Sub	Low	✓	✓	✓	✓
Application	ZeroMQ	ZeroMQ	Industry	TCP	-	-	-	Both	Low	✓	✓	✓	✓
Application	paho MQTT	paho MQTT	Messaging	TCP	-	-	-	Pub\Sub	Low	✗	✓	✓	✓
Application	AMQP	OASIS	Messaging	TCP	-	-	-	Pub\Sub	Low	✓	✓	✓	✓
Application	Rabbit MQ	Rabbit MQ	Messaging	TCP	-	-	-	Both	High	✓	✓	✓	✓
Application	WS-N	WS-N	Industry	-	-	-	-	Pub\Sub	High	✓	✗	✗	✓
Application	STOMP	STOMP 1.2	Industry	TCP	-	-	-	Pub\Sub	Medium	✗	✗	✓	✓
Application	DDS	DDS 1.4	Industry	Both	-	-	-	Pub\Sub	High	✗	✗	✓	✓

reliable services through traffic monitoring, resource usage, and channel subscription/allocation constraints. From the user's point of view, QoS parameters can be user satisfaction, cost, processing time, and other network- or system-level parameters.

- **Transparency through interoperability:** Protocol transparency is the ability of a device or application to work independent of the type of protocol used, and a device or application that can work as such is deemed protocol transparent. For protocols, we considered the transparency through the interoperability if the user/application is - or not - concerned with the intermediate operations needed to convert when disconnecting, discovering, or recovering.
- **Opportunistic reliability:** This criterion is the ability of an object to reach a target under specified conditions for a given time, and to adapt to new context conditions. Reliability is a key performance metric for calculating the correlation between actual and optimal production volumes in industrial environments where the main goal is to increase revenue generation.

Such protocol stack includes the sensing layer protocols (e.g., WSN, BLE, and RFID), network-layer protocols (e.g., cellular networks, IPv6, Internet), discovery protocols (e.g., DNS-SD, mDNS, Physical Web), semantic protocols (e.g., Web Thing Model, JSON-LD), device management protocols (e.g., OMA-DM, TR-069), service layer protocol (e.g., COAP, HTTP), and application layer protocols (e.g., DNS, DNP, SNMP, LwM2M, mobile application, and device management) (Lerche et al., 2012). Several updates have been made to incorporate this model into more communication technologies. Ray et al. (2019) have designed a new protocol stack by incorporating gateway level into the existing model. Other works (Agiwal et al., 2016; Vasudev et al., 2020; Wang et al., 2021) also added a separate security layer to secure the industrial network.. Over time, several new protocols have been designed (e.g., NFC, IEEE802.11, Bluetooth Mesh, and 5G) (Zezulka et al., 2018), and existing protocols modified (e.g., MQTT, CoAP, CoAP+, and CoAP++) to achieve interoperability (Iglesias-Urkia et al., 2017). In addition, several industrial proprietary and open-source application protocols such as 6LowPAN (Bonavolontà et al., 2017) and WirelessHART were proposed for industrial application (Devan et al., 2021). ISA100.11a has been designed for automation (Adriano et al., 2018). SigFox has been introduced for M2M communication (Goursaud and Gorce, 2015). BLE has been redesigned for low-powered communication, NB-IoT for smart metering. And LTE-MTC has been introduced for machine-level communication to make interoperable connectivity among heterogeneous devices (Mogensen et al., 2019; Dangana et al., 2021).

3.2 Industry 4.0 Architectures

An architecture represents a robust and ground-level understanding related to the scenarios that help to recognize problems and difficulties. A Reference Architecture (RA) provides a template solution for an architecture for a particular domain - in our precise case for Industry 4.0 (Clements et al., 2010). The key idea of designing a reference architecture (such as, for example, service-oriented architecture (SOA)) is to highlight modularity, scalability, adaptiveness, and interoperability among the connected heterogeneous devices in a real-time environment. Over the past decades, several reference architectures have been designed to establish IoT/IIoT ecosystems. Sarkar et al. (2022) have introduced a four-layer fog framework to handle latency-sensitive IoT applications. Mukherjee et al. (2019) have demonstrated three-level IIoT architecture for interoperable data processing. Viriyasitavat et al. (2019) have introduced a secure IoT architecture. Several other efforts (Al-Masri, 2018; Bedhief et al., 2019; Hou et al., 2019; Pallewatta et al., 2022) also proposed more profitable multi-tier IIoT architectures to meet industrial application requirements. Some standardized RAs (e.g., IEC30166 (ISO/IEC, 2020), RAMI (Hankel and Rexroth, 2015), BIG IoT (Bröring et al., 2017), IBM Industry 4.0 (Kiradjiev, 2017), FIWARE (Cirillo et al., 2019; Barriga et al., 2022), Arrowhead[7] (Delsing, 2017), Open Connectivity Foundation[8] (Park, 2017), ThingWorx[9]) have been proposed to address issues in the manufacturing industry (Wang, 2020). Some popular commercial reference architectures are AWS IoT[10], Azure IoT[11], Google Cloud IoT[12], and Predix IIoT[13]. Two standardizing organizations, namely Industrial Internet Consortium (IIC) and Platform Industrie 4.0[14], proposed RAMI 4.0 and IIRA architectures. These organizations are mainly focus on Industry 4.0 and interoperable IIoT-related research issues (Hankel and Rexroth, 2015). In the same vein, the architecture of IBM Industry 4.0[15] and the NIST[16] services-based architecture[17] are other popular design architectures. We focus on these four popular industrial reference architectures, which are discussed below:

1. **RAMI 4.0:** In a smart industry, the production objects must communicate automatically and autonomously with other devices (Hankel and Rexroth, 2015). To create a unified platform, industries and research institutions collaborated to design RAMI 4.0 in 2015, supporting a service-oriented architecture. RAMI 4.0 provides an interoperable framework by introducing a set of conceptual interoperability layers that combine all hierarchical IT components in a layer and life cycle model for the manufacturing industry (cf Figure 3). These are the integration layer, the business layer, the information layer, the functional layer, the asset layer,

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[7] https://arrowhead.eu/why-how/what-is-it/architecture

[8] https://openconnectivity.org

[9] https://www.ptc.com/en/products/thingworx

[10] https://aws.amazon.com/iot

[11] https://azure.microsoft.com/overview/iot

[12] https://cloud.google.com/solutions/iot

[13] https://www.ge.com/digital/iiot-platform

[14] https://www.plattform-i40.de

[15] https://www.ibm.com/topics/industry-4-0

[16] https://www.nist.gov

[17] https://www.nist.gov/programs-projects/service-oriented-architectures-smart-manufacturing-project

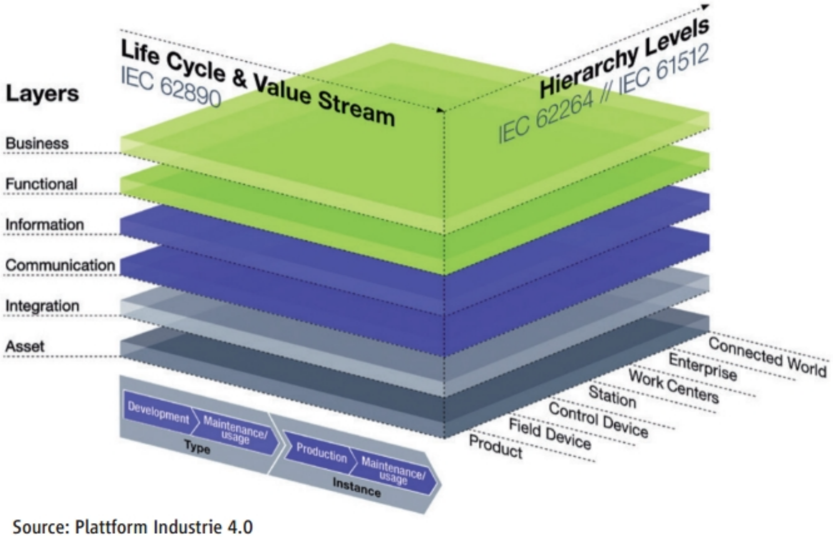

Fig. 3 Reference Architectural Model Industrie 4.0 (RAMI 4.0)

and the communication layer. With RAMI 4.0, complex processes are separated into easily accessible packages to provide data protection and IT security. The key objectives of RAMI 4.0 are to extend business and organization models, connect physical things to the real world, and transform the underlying world into a digital world.

2. **IIRA:** The term IIRA stands for Investment, Innovation & Research Alliance. This standardized architecture was first released in 2015 to encourage system architects from the industrial domain to build their own structures based on shared knowledge and principles (IIConsortium Architecture Task Group, 2019). The IIRA Reference Architecture provides a set of core principles and a common foundation for creating, reporting, communicating, and executing among IoT participants. It also permits building the system on top of IIoT - with no restrictions on the use of particular specifications or requirements of protocols. Similar to RAMI 4.0, the key features of this model are safety, security, resiliency, privacy, scalability, and reliability.
3. **IBM Industry 4.0 Architecture:** In 2017, IBM designed Industry 4.0 Reference Architecture to manage devices and provide cognitive services to users (Kiradjiev, 2017). This standardized architecture consists of two layers, namely the device layer and the platform layer. In the device layer (also called the edge layer), smart devices share the generated data with gateway devices and hybrid cloud servers. Furthermore, the platform layer is divided into the plant and enterprise layers, which are commonly used for data visualization and cloud data management. The platform layer also provides infrastructure services, application development, se-

curity, and data analytics through the API platform. IBM Industry 4.0 architecture also allows OPC-UA communication standards.

4. **NIST Service-Oriented Reference Architecture:** NIST has also proposed one of the most popular service-oriented reference architectures for the manufacturing industry (Lu et al., 2016; Ivezic et al., 2018). This architecture combines information technology and operational technology via a manufacturing service bus. It offers a business intelligence service that ensures communication between all the stakeholders. The design objectives of NIST RA are to provide real-time industrial services, operational services, virtual services, IT services, data analysis, and application management.

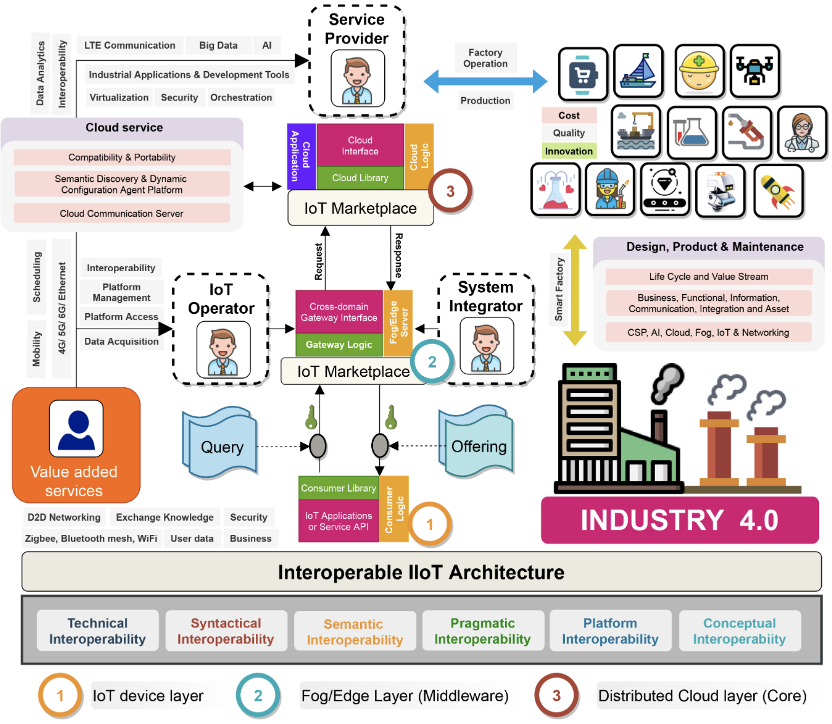

Fig. 4 Reference Architecture proposed by Hazra et al. (2021)

Even though the architectures vary by application domains, sensing devices, gateway, fog/edge server, and cloud infrastructures are the most common components in all architectures. Figure 4, for instance, presents an architecture, where heterogeneous devices and technologies are combined to achieve interoperability in a real-time environment. Here, the gateway devices are mainly designed for handling cross-domain interoperability (Patel et al., 2018), edge/fog servers are in charge of handling delay-critical industrial applications, and the cloud servers are deployed for storage and data analysis (Valtolina et al., 2019).

3.3 Standards

To achieve a good business assistance and a high productivity in the industrial environment, IIoT-related technologies must be engineered and standardized to analyze the specification of data exchange, manufacturing, and communication technologies requirements among the heterogeneous objects. The future of IIoT mainly relies on technology standardizations (e.g., IEEE 802.15.4a (Molisch et al., 2004), IETF) that include interoperability, usability, trustworthiness, and zero downtime business operations. Currently, several industrial consortiums, organizations (IEEE, W3C[18], OASIS[19]) and IoT management frameworks such as ITU-T, OCF, and oneM2M[20] are controlling the standardization of numerous IIoT technology (Kim et al., 2016). Further, standardization helps to shorten the chance of business monopoly and encourages new startups and services to grow.

Over time, many domain-specific standardizing organizations and institutes have worked (both collaboratively or individually) on a number of industry issues related to IIoT connectivity and communication, architecture, infrastructure and interoperability to provide services in various fields (e.g., mobility, smart city, manufacturing, agriculture, etc.) (Robert et al., 2017). Among them, some prominent workgroups emerged, such as standardized organizations for connectivity (3GPP[21], IETF6Lo[22], IEC[23], OSGi[24] (Manzaroli et al., 2010), ETSI DASH7[25]), standardized organizations for interoperability (IEEE PLC[26], IPv6 Forum[27], OMA[28],[29] (Delgado et al., 2005), oneM2M, DMTF[30], SNIA[31] (Zhang et al., 2013)), standardized organizations for application (OSGi), standardized organizations for infrastructure (ETSI TETRA[32], ITU-T, IEEE, IEC, OSGi), standardized organizations for IoT architecture (IEEE,

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[18] https://www.w3.org

[19] https://www.oasis-open.org

[20] https://www.onem2m.org

[21] https://www.3gpp.org

[22] https://tools.ietf.org/wg/6lo

[23] https://iec.ch

[24] https://www.osgi.org

[25] https://www.dash7-alliance.org

[26] https://standards.ieee.org/industry-connections/interoperability-and-compliance-testing

[27] https://www.ipv6forum.com

[28] https://omaspecworks.org

[29] https://technical.openmobilealliance.org

[30] https://www.dmtf.org

[31] https://www.snia.org

[32] https://www.etsi.org/technologies/tetra

Table 3 Summary of existing IIoT standards

Challenge	Organization	Standards	Context	Goals/Responsibilities
Device	3GPP	GPRS, LTE-Advanced Pro, HSPA	Smart device, industry, agriculture, smart city	Radio transmission, M2M communication, low latency network, high data rate
Device	ETSI	ETSI EN 301 406, ETSI TS 102 939 1	Smart device, industry, agriculture, smart city	Home automation, low energy radio transmission, security and authentication, cellular network
Device	IEEE - ISO/IEC	ISO/IEC/IEEE 21451-1:2010, ISO/IEC/IEEE 21450:2010	Agriculture, industry, smart city	Device interoperability, TIM and TEDS, smart interface, sensing and actuating
Device	IETF CoRE	CoAP	Smart city, agriculture, mobility, industry	Protocol design, request-response model, time-dependent access, transmission consistency
Device	oneM2M	BBF	Smart city, agriculture, mobility, industry	Message flow, protocol management, standard communication, M2M connectivity
Interoperability	AllSeen	AllJoyn	Smart device	Among D2D and software applications, secure communication, client/server model, interoperability testing
Interoperability	IEEE PLC	IEEE 1905.1a	Smart environment	Mac and physical layer design, smart home technology, wired and wireless
Interoperability	oneM2M	ETSI TS 118 112/118 123	Agriculture, smart device, mobility	Interoperability testing, ontology, smart home applications, data management
Connectivity	3GPP	ETSI TS 123 002, NB-IoT, LTE-ADVANCED	Smart city, agriculture, smart device, mobility	Core networking, delay-sensitive applications, network optimization, data transmission over a cellular network, radio telecommunication
Connectivity	ETSI DECT	ETSI TS 102 939-2, ETSI EN 300 175	Smart city, industry	M2M communication, industrial automation, low power communication, bi-directional data transmission
Connectivity	IEEE 802	IEEE 802.11 / 802.15.4	Smart device, mobility	Wireless transmission, MAC and physical layer design, unlicensed spectrum, WPAN and LR-WPANs
Connectivity	OASIS	MQTT	Smart device, mobility	M2M communication, publish/subscribe messaging, resource discovery, QoS guarantees
Infrastructure	ETSI TETRA	ETSI EN 300 392	Agriculture, smart environment	Digital radio system, bi-directional communication, large scale communication, transportation
Infrastructure	IEEE	802.11s	Agriculture, smart environment, smart device, mobility	Public WiFi, follow mesh topology, high data rate, mesh gateway
Infrastructure	ITU-T	ITU G.992.x, ITU G.651, ITU G.652	Smart device, mobility, agriculture, industry	Delay sensitive IoT data, audio, and video, QoS guaranteed, fiber technology
Infrastructure	oneM2M	ETSI TS 118 102, ETSI TS 118 101	Agriculture, smart device, smart environment, industry	IoT deployment, platform service, middleware interoperability
Infrastructure	IEC	IEC 61508	Agriculture, smart device, mobility, smart environment, industry	Safety system, control system, Industry application
Application	BBF	TR-069/CPE	Smart environment	Remote device management, application service management, auto configuration service, gateway and router
Application	OMA	OMA-DM/LWM2M	Smart device, smart environment	Data synchronization, mobility and fault detection, lightweight data model, device management
Architecture	IEEE	P2413	Agriculture, smart device	Industrial technology, agricultural framework, D2D communication, SOA architecture
Architecture	ICC	IIRA	Agriculture, smart device, smart environment	Framework for RA, device interoperability, high level abstraction, industrial viewpoint
Architecture	ITU-T	ITU-T Y.2060	Agriculture, smart device, smart environment	Four layer reference architecture, security management, cross-domain communication, business architecture
Architecture	oneM2M	ETSI TS 118 101	Smart city, smart device, mobility, agriculture, industry	M2M communication, service layer, end-to-end transmission, functional architecture

ITU-T, ISO/IEC JTC1[33]), standardized organizations for devices and sensor technology (3GPP, ETSI ERM[34], ISO/IEC, M2.COM[35]), standardized organizations for security and privacy (IEEE, ETSI DECT[36], ISO/IEC). We present a brief comparative analysis of standardized organizations and standards in Table 3. We divide our classification according to three main aspects:

1. **Challenge:** IIoT issues can be tackled at different levels to allow different manufacturers to have chip/hardware compatibility - inside the device, through the interactions - network connectivity or interoperability, inside the infrastructure, in the applications, or even though the global organization of the architecture.
2. **Context:** Standards can be used in different vertical application domains. Addressing specific domains completely guide the standard definitions.
3. **Goals/Responsibilities:** According to the level challenged, each standard can provide different abilities. Knowing the core responsibilities of each standard is essential to orient the standard choices to integrate into a Reference Architecture.

Moreover, some academic researchers have also been brought in to solve some standardization problems for industrial applications. For example, Weyrich and Ebert (2016) have talked about IIoT architectures and standards for an industrial environment. Deng et al. (2019) have highlighted the importance of IEEE 802.11ba for green IIoT in fast-paced industrial applications. Similarly, other works (Chi et al., 2014; Leonardi et al., 2019; Wang et al., 2019) also significantly impacted the IIoT domain, especially for long-range communications. However, there is still much room for improvement, especially concerning the interoperability challenge in the Industry 4.0 landscape.

4 Discussions

To face the great evolution of technologies, industries need to be flexible to adapt to new requirements and anticipate new needs. Future research still needs to address many challenges to guarantee a good fit between IIoT technologies and companies' businesses. We conclude this chapter by identifying some fundamental research challenges and future trends:

- **IIoT security issues:** Security is one of the essential criteria of Industry 4.0, which has always received the greatest attention from industry and the great public. For example, banking systems, telecommunication and retail sectors are always in need of securing their transactions from third parties (Khanboubi et al., 2019; Liu et al., 2019). This security challenge is even more significant as IIoT pushes the classically-closed IT security limits to be semipermeable to attacks (Tournier

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[33] https://jtc1info.org

[34] https://www.etsi.org/committee/1398-erm

[35] https://www.bosch-sensortec.com/news/sensor-platform-m2-com.html

[36] https://www.etsi.org/committee/dect

et al., 2021; Figueroa-Lorenzo et al., 2020). Digital society demands a more secure and reliable technology, where data can be distributed over the network and transactions validated and stored in chronological order. Blockchain is a decentralized and distributed technology that allows user data to be stored securely in a distributed way in the network, reducing the ability of data tampering. Even if costly (Sedlmeir et al., 2020), by incorporating blockchain into the industrial environment, both users and industry can securely connect without the help of a third party and create trust by having no central authority (Huo et al., 2022). Cybersecurity evolves toward the convergence of AI, IoT, blockchain and Edge Computing (Muhati et al., 2022) to detect cross-domain attacks (Tournier et al., 2020), to mitigate risks (Silva and Lepikson, 2022) by using advanced machine learning techniques, such as deep learning/reinforcement learning, to discover network patterns, identify and prevent intrusions (Vaiyapuri et al., 2021; Latif et al., 2021).

- **IIoT ecosystem with energy harvesting:** IoT is an undeniable precursor to making useful measurements and controls for the Industry 4.0. Sensor deployment implies a massive demand for low-power battery-free/rechargeable wireless devices deployment. Additionally, recharging and replacing the batteries of hundreds or even thousands of IIoT devices can be laborious or even impractical (de Wolff, 2021). To address this challenge, several energy harvesting approaches such as low-powered communication protocols, light energy harvesting, kinetic energy harvesting, and thermal energy harvesting have been designed for IIoT applications (Sanislav et al., 2021). However, such strategies are not entirely suitable for dense IIoT deployment. As the IIoT devices are often deployed in unstable weather-dependent (Murphy et al., 2021) or faulty environments (Ahmed et al., 2020, 2021), relying on a single energy harvesting technique can lead to a number of other problems, such as power shortages, hardware failures, and intermittent uptime. To overcome this energy bottleneck, two or more energy harvesting techniques need to be integrated into IIoT devices for efficient power management (Sah and Amgoth, 2020), hybrid energy storage technologies for harvesting systems can be used (Altinel and Karabulut Kurt, 2019), and low-tech & green IIoT could be consider to reduce energy and temperature and CO2 emission rate in the environment (Patsavellas and Salonitis, 2019; Hu et al., 2021). These later points remain big challenges for the industry.
- **IIoT network and infrastructure virtualization:** 5G and its preceding 4G - known as LTE-Advanced - are known to build IoT-enabled intelligent services and application-oriented ecosystem. The increasing 5G demand for high-quality multimedia data and low-latency applications triggered several issues in industrial networks, especially the efficient, safe and secure allocation of resources (Brettel et al., 2014; Hazra et al., 2021). To implement this vision realistically in IIoT environments, the physical network must be divided into several separate logical networks of various sizes and configurations to allocate these resources to different types of services with different properties to guarantee. Virtualization through SDN and NFV bridges this gap between network configuration and network resources management (Barakabitze et al., 2020). Several efforts have

been made on combining SDN/NFV solutions with edge/fog/cloud architectures to develop new services and control over the network (Chalapathi et al., 2021). Container-based SDN controller with edge/fog federations has been proposed to make an interoperable industrial network (Rufino et al., 2017; Hou et al., 2019). Manufacturing companies can virtually control production with efficient delay-tolerant service provisioning and on-demand specific resource optimization, such as through WSN (Nkomo et al., 2018) or 3D-reconstruction (Badat et al., 2020). However, researchers still need to consider several other issues such as computing on IoT nodes (Blanco and Le Mouël, 2020), distributed scheduling, load balancing, easy network and cluster programmability (Fortier et al., 2021), multi-tenant services, hybrid SDN controllers, and 6G low-latency mobile service requirements (Du et al., 2020; Qadir et al., 2022) to take total control over the industrial networks.

- **IIoT standardization:** IoT protocols and their standardization are pillars of establishing IIoT ecosystems. Internet standards have shown a convergence adoption time of 10 to 20 years. IIoT domain is even more complex, having vertical-silo application domains. Several network protocols for IoT have been designed and standardized to address various challenges like naming, addressing, routing, flow control, congestion avoidance, and large-scale industrial deployment. These protocols, however, need to be adapted to the industrial requirements. Industrial applications are characterized by extreme conditions environments (high humidity, extreme temperatures, electromagnetic interference) that complicate the integration of low latency, real-time, determinism, frequent packet loss, and reliability properties in the definition of generic standards (Vitturi et al., 2019; Sari et al., 2020; Qiu et al., 2022). Standardization of the semantic representation and interoperability of the knowledge and the D2D interactions is also a great issue (Burns et al., 2019), and an agreed methodology among manufacturers would have to be established to meet the roadmap for standardization of Industry 4.0 proposed by Platform Industrie 4.0 (Platform Industrie 4.0, 2019).
- **From Industry 4.0 to Society 5.0:** Some studies analyze the complex, mutually generative range of economic, social and political transformations of the First, Second and Third Industrial Revolutions, and argument that the same criteria cannot be found about the alleged Fourth Industrial Revolution (Moll, 2021). Technologies undoubtedly continue to alter work, and lead to new varieties of work, but this evolution must also meet the broader social, cultural and geopolitical transformations to constitute a revolution. Society 5.0 concept has been introduced in Japan (Deguchi et al., 2020) and reframes two kinds of relationships: the relationship between technology and society and the technology-mediated relationship between individuals and society. Industry 4.0 advocates smart factories, while Society 5.0 calls for a supersmart society. The two visions differ in terms of measuring outcomes. Industry 4.0 aspires to create new added value and minimize manufacturing costs. Such down-to-earth outcomes allow for relatively simple and clear-cut performance metrics, such as productivity. By contrast, Society 5.0 aspires to create a supersmart society. The metrics, in this case, are much more complex. Metrics, such as sustainability, are of great importance (Beier

et al., 2020; Ghobakhloo, 2020). Having different social and industrial goals can greatly affect the interpretive structural modelling techniques structuring contextual relationships among the Industry 4.0 architectural functions. And can so, as a consequence, totally affect the way to deploy IIoT devices, infrastructures and services. Corporate social responsibilities, environmental dimensions (Potocan et al., 2021) or happiness (Ravina Ripoll et al., 2022) are metrics to be considered and technological deployment consequences are to be studied. Society 5.0 focuses heavily on the public impact of technologies and on the need to create a better society.

5 Conclusions

Industry 4.0 is a revolution transforming the industry with the emergence of IoT and related technologies. This revolution drives global industrial architectures into an advanced level of digitization and productivity - where customers can experiment with customized on-demand requirements. Customer satisfaction and company productivity can thus go hand in hand. This chapter mainly focused on Industry 4.0 connectivity capabilities - towards the Industrial Internet of Things - needed to capture the context. Specifically, we have stretched on this digitalization of the physical world from an industrial perspective. We have shortened the way protocols, architectures, and standards help companies adopt the emerging Industry 4.0 technologies. Finally, we have summarized our discussion by briefly reviewing several research challenges and future scopes.

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