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Quo Vadis Industry 4.0? Position, Trends, and Challenges

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ABSTRACT Industry 4.0 vision and its mandated digital transformation are radically reshaping the way business is carried out and the way overall industrial processes and collaborations are operating. In this work, the objective is to analyze the current level of adoption of Industry 4.0, via the footprint available in industrial and academic research works. The analysis performed reveals insights on how Industry 4.0 has impacted and is still influencing research and innovation in industrial systems, services, and business approaches. It also reveals pertinent trends on key enabling features, technologies and challenges associated with this 4^{th} industrial revolution, mainly focusing on the pathways for wider industrial adoption of Industry 4.0-compliant technologies and solutions.

INDEX TERMS Industry 4.0, cyber-physical systems, digital transformation, industrial digitalization.

I. INTRODUCTION

Three industrial revolutions have radically reshaped the industrial world, and most notably, the manufacturing sector. The 1^{th} industrial revolution was related to the introduction of mechanical production equipment driven by water and steam power, the 2^{th} one was based on industrial mass production organization and the use of electrical energy, and the 3^{th} one was based on the introduction of electronics and Information and Communication Technologies (ICT) in order to automate the production and machinery. Currently, we are witnessing the 4^{th} industrial revolution that is related to the smart automation based on the use of Cyber-Physical Systems (CPS) in industry [1]–[4], which are complemented with the Internet of Things (IoT) and Artificial Intelligence (AI) technologies, that are customized for industrial application.

This digital transformation vision towards the factory of the future (FoF) is being promoted worldwide with governmental initiatives regarding strategies, research, and innovation programs. Such efforts are included under the umbrella of country-specific initiatives such as “Industrie 4.0” in Germany, “Industria Conectada 4.0” in Spain, “Piano Industria 4.0” in Italy, “Smart Industry” in the Netherlands, “Catapult” in the UK, “Alliance Industrie du Futur” in France, and “I40” in Portugal. Other initiatives outside Europe are also promoting similar visions, such as “Industrial Internet of Things” in the USA, “Made in China 2025” in China, and “Robot Revolution Initiative” in Japan. The maturity level among the countries shows significant differences even if one concentrates on a single region, e.g., Europe [5]. There are several definitions of what Industry 4.0 entails [6]–[8], however, for this work, we do not focus on the subtle differences among the definitions or the country-specific innovation initiatives, but commonly consider all of them under the umbrella term “Industry 4.0”, as they share common ground towards a new sophisticated infrastructure that will be based on Industrial Cyber-Physical Systems (ICPS) that empowers industrial processes, services, systems, and applications.

The domain of the Industry 4.0 is complex and needs to be approached via a multi-angled view, as its implications pertain to business, technical, and socio-economic aspects [9]. Significant economic benefits are expected from Industry 4.0, e.g., it is estimated that the digitization and Internet-based networking of products and services generate approximately 110€ billion of additional revenues per year for the European industry [10]. On the business side, an increase of 45–55% is expected in the productivity of technical professions through the automation of knowledge work, a reduction of 30–50% of total machine downtime, a reduction of 20–50% in time to market and a reduction of 10–40% of maintenance costs [11]. Furthermore, a recent survey of more than 2000 companies from several industrial production sectors, claims an increase in the level of digitization and networking in the industrial companies by 2020 from 33% to 72% was predicted [10], while others [12] point to an adoption rate of around 50% of Industry 4.0 principles, concepts, and technologies until 2035 for the Western European countries. Such expectations are also of interest when they intersect with the adoption in small and medium-sized enterprises [13], which for instance, in Europe reflect the majority of companies. Because Industry 4.0 is about value creation and not only optimizing existing methods and processes, these examples point towards the significant influence that is expected to benefit from Industry 4.0, and which have implications, e.g., towards economic growth, innovation, and job creation.

In the Industry 4.0 context, several aspects come into play, including virtualization of products and services, new business models that are data-driven, and creation of collaborative ecosystems that bring business value [14], [15]. To realize this, autonomous and modular ICPS in production is needed, that can exhibit self-X features such as self-organization, self-optimization, self-adaptation, etc., all of which are vital to providing capabilities for decentralized and autonomous decision-making, connectivity and interoperability, modularity, service-orientation, optimized and real-time decision-making, virtualization, and human-machine integration. The realization of these capabilities implies the complete digitization and networking of the industrial manufacturing sector, which will require the use of several enabling technologies, namely Big Data, IoT, Edge, and cloud computing to support the data computational power and connectivity, Machine Learning (ML) and advanced data analysis algorithms for the analytics and intelligence, Virtual Reality (VR) and Augmented Reality (AR) for the human-machine interface, and additive manufacturing and collaborative robotics for the digital-to-physical conversion [16].

Addressing the challenges of Industry 4.0 is a continuous process, which is well reflected in industrial research efforts published in leading scientific journals, magazines, conferences, workshops, technical reports, standards, etc. It is of interest to see how Industry 4.0 aspects are reflected in literature, and attempt to identify the current level of adoption of Industry 4.0 principles and Industry 4.0 key enabling technologies, as well as its impact in the industry. This work attempts to provide some insights towards these directions, i.e., see the current adoption of Industry 4.0, its implications in industrial and academy communities, and acquire insights on how it is reshaping the industrial research and operational efforts in the industry. A systematic keyword-based literature review

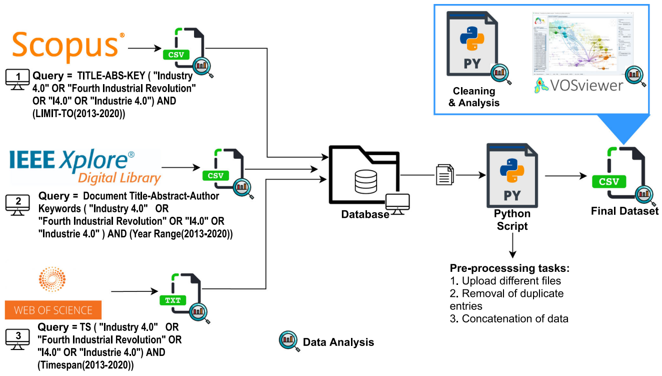

FIGURE 1. Data extraction and data analysis scheme.

analysis is performed, and insights are presented, including trends in industrial research. In addition to the performed analysis, challenges are discussed that emerge from the analysis, and that is expected to be in focus for the next years.

The paper is organized as follows: After the introduction in Section I, the methodology used to gather the material and perform the analysis is discussed in Section II. Based on the dataset retrieved from scientific repositories, the application of automated techniques and human analysis, Section III and Section IV summarize the findings. Section V points out the most critical challenges that emerge, while Section VI rounds up the paper with conclusions and an overview of potential further directions.

II. METHODOLOGY

The aim of this work is to extract insights about the current position, trends, and future challenges that pertain to Industry 4.0. To do so, an analysis of several articles that contained specific Industry 4.0 relevant keywords has been performed. Automated methods to search scientific repositories, and applying ML techniques combined with human analysis, were employed.

The dataset was acquired from well-known databases such as Scopus, WoS, and IEEE Xplore, which cover well all publications from major scientific publishers, and also include results from others, e.g. ACM and Springer, that are not directly accessed. Such analyses utilizing these document repositories is common in text-based analysis [17]–[21]. Specifically, documents were selected containing the case-insensitive as well as variations of keywords: *"industry 4.0" OR "industrie 4.0" OR "fourth industrial revolution" OR "I4.0"*, as illustrated in Figure 1. The query searches these terms in the title, abstract, and keywords of the papers. The time interval chosen for this search was between 2013 and 2020, resulting in a dataset containing 13.636 documents after the removal of duplicated entries. The size of the dataset is, therefore, larger than what is analyzed in similar studies, e.g., [17]–[21].

The dataset analysis was conducted with various tools, including custom Python scripts and utilization of the OpenRefine tool for dataset cleanup, as well as the VOSViewer for the creation of network maps and visualization. Processing the dataset included lemmatizing the words as well as determining the evolution of the type of publications, word frequency, frequency of publications by country, a correlation between technologies and domain applications, a correlation between design principles and enabling technologies, and the evolution of enabling technologies. This approach was used for all results presented in the paper, e.g. the analysis of technological trends in Figure 12, performed for the periods 2006–2012 and 2013–2019, uses a subset of the dataset containing the specific technology and timeframe analyzed.

There are several limitations pertaining to the methodology of this work, including the dataset construction. The operationalized query used for the data extraction from the scientific repositories considers only the major terms related to Industry 4.0 (as discussed in this section). However, these keywords are prevalent in Europe (and to a large degree in associated with the original Industrie 4.0 ideas and results in Germany), and as such, other worldwide similar programs like the "Industrial Internet of Things" in the US and the "Made in China 2025" in China, maybe underrepresented in the dataset. As such, it is seen as future work to expand the terms further and potentially link them ontologically with satellite terms, in order to create a more representative dataset that is more inclusive and has sufficient representation of other worldwide initiatives.

Another issue is related to the method. Firstly we have conducted a keyword-only text extraction from the repositories, and for the search, only specific fields were searched, i.e., title, abstract, and keywords. This decision was motivated in order to narrow the search scope, and also it was considered that if Industry 4.0 was a prevalent topic in the paper, this would most probably be reflected as a term in one of those fields. However, this is a limitation, as papers related to Industry 4.0 that do not have these terms in those areas or do not use the well-known keywords are not considered.

Overall, while we do not claim that the dataset is complete, nor that the utilized methods are without issues, they are sufficient and suitable for the scope of this research, as the derived dataset and its analysis enabled us to extract some insights concerning Industry 4.0 and utilize them for further critical discussions in this work.

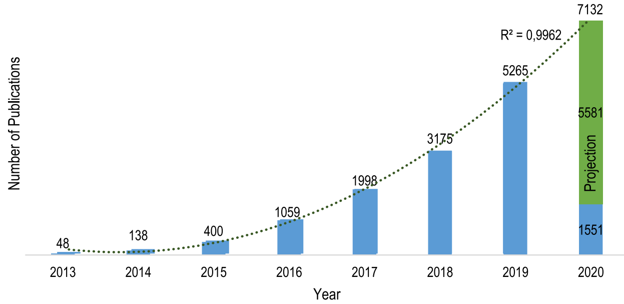

FIGURE 2. Overall evolution of Industry 4.0 publications.

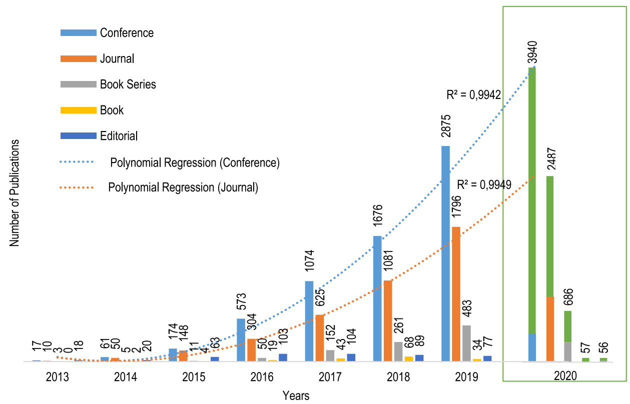

FIGURE 3. Detailed view of publication types related to Industry 4.0.

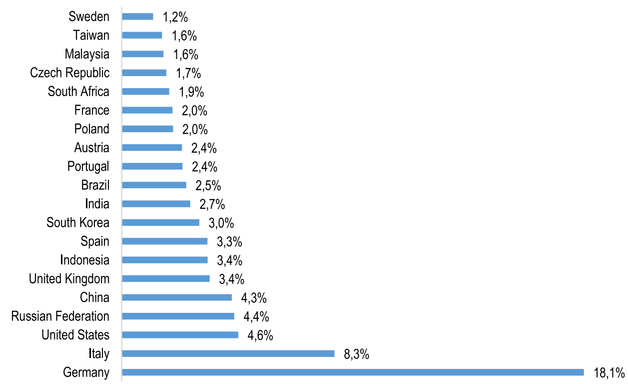

FIGURE 4. Geographical distribution of Industry 4.0 related publications.

III. CURRENT STATUS OF INDUSTRY 4.0

A. ARTICLE DEMOGRAPHICS

The initial analysis aims to understand the demographics of the publications associated with Industry 4.0. Figure 2 illustrates the evolution of the number of publications referring to Industry 4.0 over the years. The growing interest of the research community in the Industry 4.0 topics is evident, especially after 2016. Considering the available up to now data for 2020, and the exponential trend so far, an estimation is also made for 2020 (represented by the green box), which is expected to expand further the interest in the domain.

Taking a closer look, as shown in Figure 3, on the distribution of publications per type (the green box in 2020 represents a projection based on the extrapolation performed in Figure 2), one can observe the significant increase per publication type. The results show continuous growth in the conference papers, but mostly a consolidated increase in journal papers, which reflects and reinforces the relevance of Industry 4.0 topics of the scientific community in the last years. Such evolution is expected since early results in conferences take some time to materialize in mature journal papers and also for the community to generate interest in books dedicated to specialized issues relevant to Industry 4.0.

It is also of interest to investigate the countries involved in the Industry 4.0 publications, as these are reflected in the dataset. The geographic distribution illustrated in Figure 4,

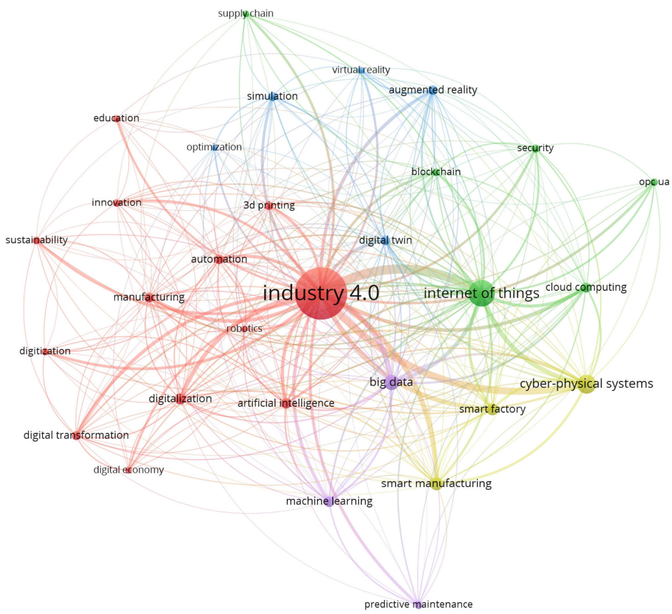

FIGURE 5. Co-occurrence keyword map for Industry 4.0 related publications.

considers the affiliation of the authors of each article, using a composite score coming out from all authors listed in the publication, with linearly decreasing weights (where the first author weighs more than the second, the second more than the third, and onwards). The results are normalized according to the maximum achieved value.

As expected, Germany is the country that most contributes to the publication of Industry 4.0 related articles. This does not come as a surprise, as Germany very early kick-started its Industrie 4.0 program, which laid detailed research and development (R&D) visions, actions, and targets for academia and industry almost a decade ago. However, Figure 4 also provides additional insights, as it clearly shows that other countries within Europe use the same terminology, and from the relevant positions in the graph, one may also relate to the degree of penetration of Industry 4.0 concepts and ideas for these countries. In addition, Figure 4 shows that other countries beyond Europe use the same terminology, that there is cooperation among countries on the domain, and that the phenomenon is not geographically constrained. It is also possible to observe that the Industry 4.0 topics are widely spread internationally, mainly to those countries where the government R&D programs are actively promoting the digital transformation, e.g., Italy, United States, China, United Kingdom, and Spain.

The frequency of terms used in the dataset is shown in Figure 5, which covers the 2013-2020 period. The clusters of the terms that have similarities (e.g., being used in the same papers) are shown, while the thickness of the links among them shows the level of their correlation. As it can be seen, the appearance of "cyber-physical systems", "smart factory", "industrial internet", "digital transformation", "digitalization" and "smart manufacturing" as the most common terms clearly

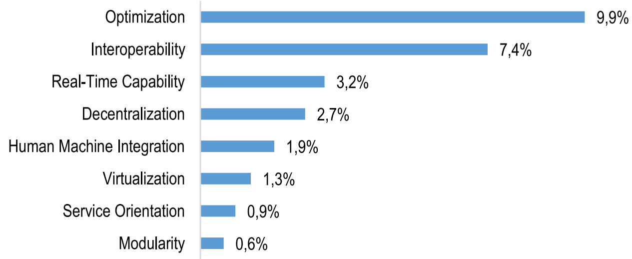

FIGURE 6. Design principles in Industry 4.0 related publications.

shows that Industry 4.0 is related to the application to industrial systems following the 4^{th} industrial revolution. "Optimization", "interoperability", "simulation", "IoT", "cloud computing", "Big Data", "additive manufacturing", "virtual reality" and "digital twin" terms also show the existence of some important characteristics and technologies associated to this new paradigm.

B. INDUSTRY 4.0 DESIGN PRINCIPLES

Industry 4.0 is built upon several key design principles, and among them, an integral role is attributed to the ICPS paradigm as well as the Asset Administration Shell (AAS) that accompanies the assets along their life cycle [22]. Several considerations about the design of Industry 4.0 systems are reflected in the keywords of the articles.

As shown in Figure 6, optimization, and interoperability, followed by decentralization and real-time capability, are the most relevant design principles. These results reflect the importance that the authors have put towards developing decentralized but interoperable digitized and networked solutions in the scope of Industry 4.0. These include additional considerations, e.g., the realization of systems that can embed AI techniques to analyze collected data regarding the process optimization, and on occasion, also addressing real-time constraints. The human-machine integration appears just after these four key design principles, which reflect the importance of the human role in the ICPS life cycle, given that humans can be the most flexible piece (asset) in the system. Other aspects are also evident such as service orientation and virtualization, which is now at a mature level in the industry.

C. KEY ENABLING TECHNOLOGIES

Industry 4.0 is based on the development and application of service-oriented business performed using ICPS as a backbone platform, complemented with several key enabling communication and information technologies, namely IoT, Big Data, Edge and Cloud Computing, Multi-agent Systems (MAS), Data Analytics, Additive Manufacturing, VR/AR and Collaborative Robotics, among others [10], [16]. These concepts and associated technologies are well-reflected within the dataset, as shown in Figure 7. It has to be noted that some areas, e.g., ICPS, encompass diverse concepts and technologies themselves.

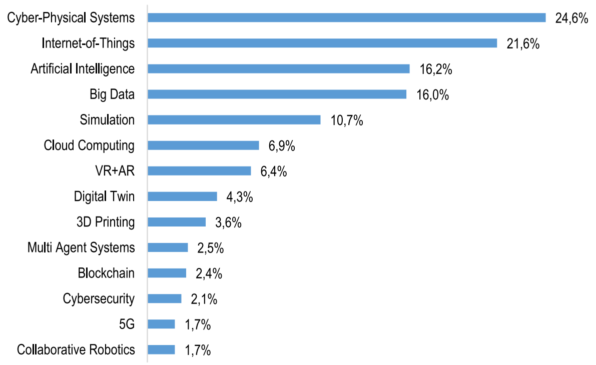

FIGURE 7. Enabling technologies in Industry 4.0.

As seen in Figure 7, IoT, AI, and Big Data are the key enabling technologies most cited in the Industry 4.0 related articles, meaning that at this stage, the data collection, storage, and analysis assumes crucial importance in the digital transformation process. These technologies can be seen as the pillars and the most representative of Industry 4.0, aligned with the key design principles reflected in Figure 6. The growth of the importance of technologies regarding simulation and digital twin evidences their importance in the implementation of the next stage of the digital transformation, namely the design, implementation, operation, and maintenance of ICPS and the AAS [23], as defined by the Reference Architectural Model for Industrie 4.0 (RAMI 4.0) [22]. This relationship is captured in Figure 8, and provides a coherent way for the integration and interaction of Industry 4.0- and Industrial Internet-compliant components via AAS within RAMI 4.0. [24].

A main concrete objective for research and particularly for innovation activities, related to the implementation of Industry 4.0-compliant solutions, is the formal technical implementation of the AAS containing the layers 2–6 of the vertical dimension (digitalization and networking of assets) within the RAMI 4.0 specification. For achieving such objective, the following challenges can be highlighted: (i) The AAS specifying the entire life cycle (following the IEC 62890) of Assets positioned within the IEC62264 (ISA'95) and/or IEC 61512 (ISA'88), i.e., products, equipment, machinery, and production systems; (ii) The AAS enabling the interoperable exchange of information between value creation partners within an I4.0-network; (iii) The AAS specifying and implementing (preparing and structuring) information in a package for being exchanged between I4.0-components and systems (digitalized assets); (iv) Moreover, designed available for non-intelligent and intelligent Assets and containing digitalized data and information, correctly modeled, the AAS becomes a real implementation of the "digital twins" of the digitalized assets, facilitating cross-vendor interoperability of assets through their networking by an I4.0-conform communication [23], [25].

Cybersecurity, blockchain, and 5G are also noticed in Figure 7, reflecting the fundamental importance of these issues in distributed systems exchanging data and is aligned with the international research and innovation programs, e.g., the upcoming 100€ billion research and innovation program framework "Horizon Europe", as well as multi-annual roadmaps and strategic research and innovation agendas of industry platforms [26]. 5G is expected to be the prevalent key enabling communication technology that will boost even more the use of IoT, Edge, and link to Cloud technologies, and will also impact other areas including, for example, the collaborative robots (as shown in Figure 7).

Figure 9 shows clearly the evolution of these enabling technologies, and as it can be seen, some have a very steep slope (e.g., AI and IoT), which indicates the recent rapid increase in interest within the research community. It is no surprise that in continuation of the digital transformation envisioned within Industry 4.0, the application of IoT as well as AI in industry, are seen as key enabling technologies. Both technologies can be utilized to enhance existing processes or enable the realization of new ones. Also, others such as Big Data related to Analytics, Digital Twins, and Simulation are well reflected, and they maintain a continuous and consolidated growing, again indicating a strong interest in them.

By correlating the design principles and enabling technologies, as shown in Figure 10, some interesting observations can be made. Industrial IoT, simulation, AI, MAS, and Big Data have a strong presence in the optimization design principle, but also industrial IoT, AI, and Big Data are closely related to the engineering of the Industry 4.0-systems with real-time capability. It is also noticed that blockchain, 3D printing, cybersecurity, and 5G have not yet significant presence in the key design principles, which may be explained by their relatively early stage of development, which has not led to their wider adoption yet.

D. INDUSTRY 4.0 APPLICATION DOMAINS

Industry 4.0 comprises several domains such as industrial manufacturing, logistics, maintenance, energy, health, agriculture, and retail. In order to acquire new insights, we have carried out a bigram analysis in order to create the correlation of the design principles and enabling technologies with the different domains, and the results are shown in Figure 11.

It is observed that production and manufacturing are the two domains that dominate, as most of the technologies and design principles relate to them. This is also understandable, since these foster the birthplace of Industry 4.0 efforts in Germany. Logistics, maintenance, health, and supply chain appear as growing applications with some sizable footprint; however, retail and agriculture are less represented.

IV. TRENDS IN INDUSTRY 4.0

Another type of analysis conducted aimed to analyze the technological trends associated with Industry 4.0 in more recent years. For this purpose, two consecutive periods were taken into consideration: the first period from 2006–2012, which represents the early era where several Industry 4.0 related technologies were developed (although not explicitly linked

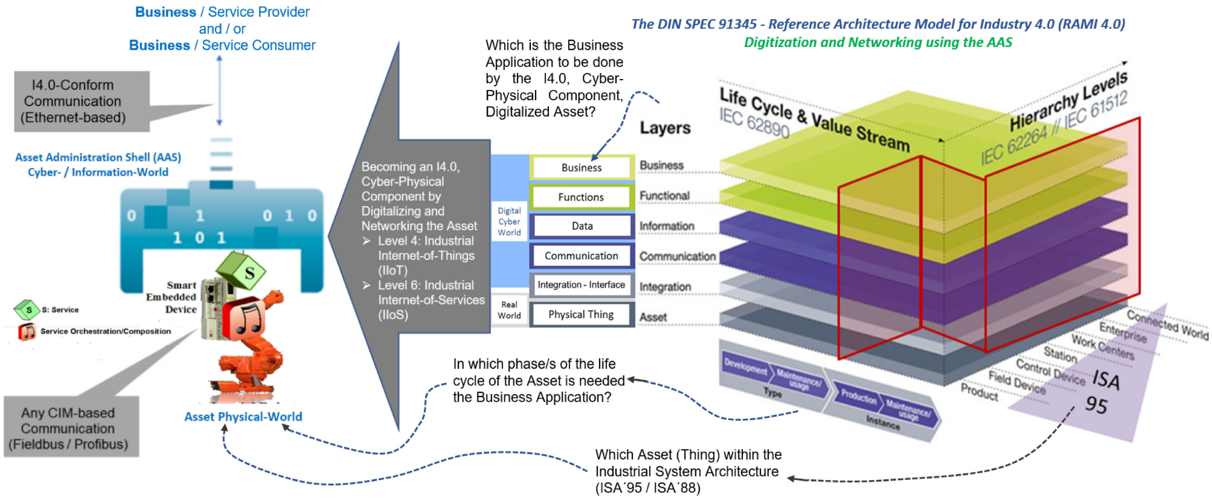

FIGURE 8. Asset Administration Shell in the RAMI 4.0

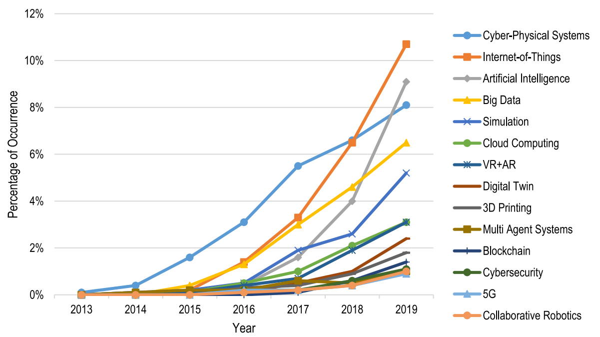

FIGURE 9. Evolution of the key enabling technologies.

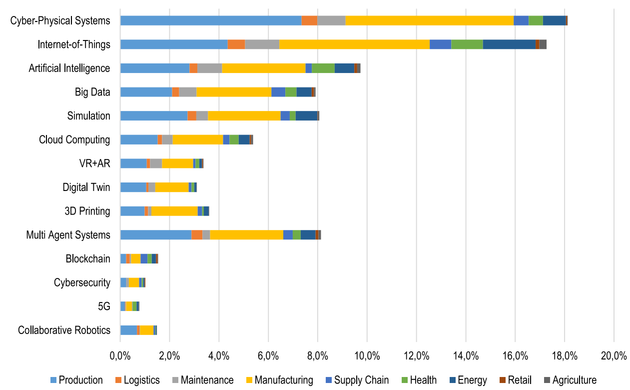

FIGURE 11. Correlation between technologies and domain applications.

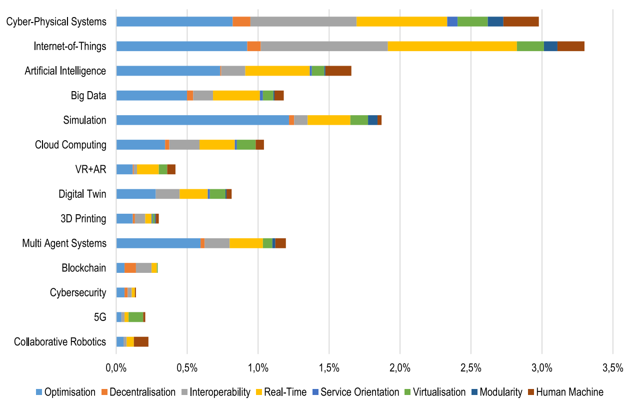

FIGURE 10. Correlation between design principles and enabling technologies.

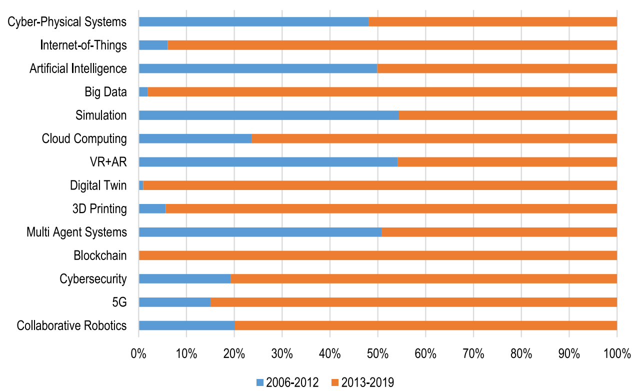

FIGURE 12. Comparison of the adoption of enabling technologies for the 2006–2012 (early) and 2013–2019 (contemporary) periods.

to Industry 4.0), and the period 2013–2019, which represents the more contemporary one.

Figure 12 provides a comparative view of the two periods, before and after the official introduction of the Industry 4.0. 2013 was selected as a pivotal point for this segmentation, as it is marked by the presentation of the final report of the working group on Industrie 4.0 in the Hanover Fair.

The analysis of the achieved results shows that the technologies nowadays associated with Industry 4.0 were already developed to a degree before the official introduction of Industry 4.0 paradigm. This comes as no surprise since there has been observed a continuous development of ground-breaking concepts and technologies, which have set the baseline for the Industry 4.0 vision. In the contemporary period (2013–now), all these enabling technologies have registered a significant increase of attention by the research community, with particular emphasis on IoT, Big Data, Blockchain, and 3D printing.

It may, therefore, be possible to consider that the presentation of the Industry 4.0 vision, as well as the inclusion of selected promising and suitable technologies in Industry 4.0 context, also acted as a booster to the further use and development of these enabling technologies for ICPS. In a sense, from 2013 onwards, we have a significant focus on this new era of enabling technologies and concepts that ride the vision set by Industry 4.0 and which have significantly contributed to the digital transformation in the industry, as this is reflected in innovation and industrial research.

Considering the analysis of the key enabling technologies discussed in Section III, as well as key roadmaps set out by industry associations, we can acquire additional insights on the convergence of visions as well as potential influencing technologies and design principles that that may impact the next decade. Several roadmaps exist at the national and international levels, and an analysis of them is seen as future work. In Europe, the best representative is the Multi-Annual Plan (MASP) [27] and the Strategic Research and Innovation Agenda (SRIA) [26] stemming from three European industry associations, i.e., AENEAS, ARTEMIS-IA, and EPoSS, that represent Electronic Components & Systems (ECS) stakeholders. The specific SRIA clearly delineates the challenges and strategic priorities related to Industry 4.0-compliant solutions and Industrial Cyber-Physical Systems for the European industry in order to become globally competitive and have a beneficial societal and economic impact. As such, the SRIA [26] captures well the game-changing directions towards a number of key domains such as transport & smart mobility, health & well-being, energy, digital industry, digital life, systems & components, connectivity & interoperability, safety–security–reliability, computing & storage, process technology, equipment, materials and manufacturing for ECS, etc.

Another way to acquire additional insights beyond the industry roadmaps is to see specific efforts that are in the core of Industry 4.0, such as the RAMI 4.0 [22] and AAS [23]. The analyzed dataset showed a significant increase in references to RAMI4.0 aspects in the literature after 2016, the year also the RAMI 4.0 was standardized in DIN [22], which denotes the growing interest in it.

Industry 4.0 is about digital transformation, which, in conjunction with digitization and digitalization, aims to migrate industry to a new era of ecosystem-wide interactions and increased optimization of its business processes via the usage of ICT. These processes imply changes and adjustments for all actors along the industry value stream and value chain, and associated business process [15]. For such change to happen, the stakeholders must be buy-in to the new capabilities offered by the Industry 4.0-compliant solutions. This convincing process starts not only with publications about research and innovation results but particularly with clear real demonstrations of implemented Industry 4.0-compliant solutions in lighthouse use cases that show tangible benefits for the adoption of the new technologies, models, and ways to conduct business. Currently, in Europe, there are several research and innovation actions that are targeted towards established industrial research agendas such as the ECS SRA [26] and aim at demonstrating results that are on the high end of the European Commission’s Technology Readiness Level (TRL) [28]. However, even with European-wide initiatives, there are significant disparities among European countries [5].

V. FUTURE CHALLENGES

Several challenges/barriers related to Industry 4.0 [7], [8], [20], [21] and more specifically ICPS [2]–[4] have emerged. Combining such challenges, with the results of this analysis but also the essential information issued in the Multi-Annual Plans (MASPs) and Strategic Research and Innovation Agendas (SRIAs) of Industrial Associations and Platforms like [26], [27], [29], enables the calibration of such insights. Table 1 summarizes some of the most critical issues to implement Industry 4.0 and points out the main actions required to address each one of these challenges. The findings below are in line with similar systematic literature reviews [17], [19]–[21].

A. EDUCATION, NEW SKILLS, AND JOB PROFILES

The success of Industry 4.0 strongly depends on the skills and competences that the workforce can have along the different dimensions of the new vision, and mainly related to the development and implementation of key enabling technologies, as well as the development and use of the new business process that the new digitization and networking paradigm proposes.

Expertise and new skills are now crucial to implement this vision and enable the acceptance of Industry 4.0, including finding qualified personnel [30]. It should be noted that several job profiles such as information and digitization/digitalization engineer, big data analyst, data scientist, machine learning engineer, and cloud services experts, did not exist ten years ago [31]. This is also attested in a recent analysis of Industry 4.0 related job profiles [32]. Enabling the workforce to acquire the required knowledge [33] and skills to respond to challenges and expectations of the industry when implementing the Industry 4.0, as well as migrating legacy industrial systems into Industry 4.0-compliant systems are seen as vital. Such know-how requires multidisciplinary knowledge [33] and skills, which need to be acquired via the educational systems [34], as well as complementary training and lifelong learning for employees. Especially considering the effects of COVID-19 in business, the trend for online learning and training via Massive open online courses (MOOCs) [35] is reinforced, which fits well with other complementary activities such as VR for employee training [36].

TABLE 1. Challenges and Actions for Implementing Industry 4.0

Challenge	Major Actions	Difficulty	Priority
Education, Training and future of work	Multidisciplinary education provided by vocational and academic institutions	high	high
	Lifelong learning, upskilling and competence development	medium	high
	Expertise in developing/using both hardware and software systems	high	medium
	Working with latest productivity tools, in online environments, with distributed teams	low	medium
Interoperability and standardization	Development and adoption of standardized data models, and services	high	high
	Adoption of industrial communication standards	medium	high
	Servification of distributed functionalities	medium	low
	Open standards and rapid integration of new technologies	high	medium
	Strategies to easily migrate legacy systems to new ICPS infrastructures	medium	low
Digital twins, simulation, and Artificial Intelligence	IoT, cloud/edge technologies and 5G for real-time interactions	low	high
	AI/ML for predictive and prescriptive analytics (incl. diagnosis and optimization)	medium	high
	Simulation of ICPS in virtual models	medium	high
	Simulation of complex scenarios at ICPS system of system level	high	low
HPC platforms and communication infrastructures	Distributed HPC infrastructures with data federation	low	high
	Distributed computational infrastructures capitalizing on cloud/fog/edge	medium	high
	Guaranteed real-time dependable communication and interaction among critical systems	high	high
	Service/data federation and data lifecycle management for distributed HPC infrastructures	medium	medium
Human in the loop and human-machine cooperation	Adoption of user-friendly HMI incl. AR/VR, NLP, gestures, etc.	medium	medium
	Collaboration and Symbiotic interaction among humans and ICPS	high	high
	Human–centered design and ML-driven assistance for tasks	medium	high
Cybersecurity, trust, and privacy	Security and privacy management at system and system-of-systems level	medium	high
	Dependable systems and ML-driven trusted decision making for critical systems/services	high	high
	Real-time ML-driven monitoring, identification and response to attacks	medium	high
	Utilization of new approaches e.g. blockchain, quantum computing	high	medium
Business, societal and ethical aspects	Beyond technology: business impact, corporate social responsibility, socio-economic impacts	high	high
	Convince stakeholders for the benefits of the digital transformation	medium	high
	Ethics in artificial intelligence fueled autonomous systems	high	medium

The new generation of industrial engineers that will work on aspects related to Industry 4.0 areas need beyond integrating multidisciplinary and cross-domain knowledge to also focus more on understanding the complex dynamic systems and system of systems (SoS) perspective [37]. They will have to be able to navigate and utilize new paradigms and concepts such as SoS Engineering, data and information modelling, digitization/digitalization methods and tools, engineering digital twins, simulation of systems and infrastructures, semantics, interoperability, as well as emergent technologies such as Industrial IoT, Big Data and advanced data analytics, digitized lifecycle engineering. Additionally, in the ICPS context, engineers are not anymore dealing only with the physical counterpart, i.e., hardware, but increasingly with the cyber counterpart of complex industrial systems, which requires an integrative learning process to understand their interplay, how to link systems in their [15] and what the impacts might be. Lifelong learning is seen as crucial here, since due to the rapid advances in hardware but mostly in software, the acquired knowledge quickly becomes obsolete and needs to be kept pertinent.

The job profiles requested for Industry 4.0 related tasks show a mixture of soft skills and diverse technical expertise in new technologies [32]. Education aims to prepare the professionals for today's jobs rather than for ones of the future [38] since it is difficult to determine what will be tomorrow's jobs. However, the early identification of new job profiles targeting future needs is vital to train professionals for emerging demands. This is challenging, but universities that are at the forefront of research, and have an early glimpse of things to come, should adjust in a timely manner their offered programs and specializations to cover these needs. The matching of predicted industry needs, technology trends, and a plan on how to address them in order to be able to sufficiently cover new job profiles within Industry 4.0-compliant ecosystems [39] is seen as a key to thriving Industry 4.0 utilization [38].

B. INTEROPERABILITY, STANDARDIZATION AND MIGRATION

Interoperability is one central issue for a successful implementation of Industry 4.0 [40], being related to the capability of different systems and services to be able to connect and interact transparently. In the ICPS context, this need for interoperability emerges from the difficulties of integrating data from various sources and services that can understand each other's semantics, across the different layers of RAMI 4.0. Additionally, the migration process conducting to the integration of legacy systems, both at Operational Technology (OT) as well as Information technology (IT) and between them, assumes crucial importance for the operation of such systems, e.g., PLC, RC, CNC, databases, SCADA (Supervisory Control and Data Acquisition), and MES (Manufacturing Execution System) systems [41].

The achievement of this demand, as well as in general for implementing RAMI 4.0-compliant solutions, requires the use of existing industry standards [42], as well as their potential

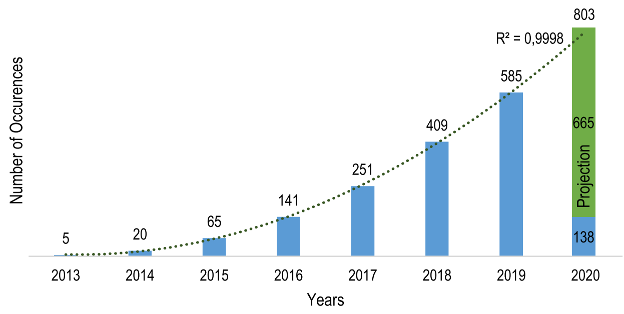

FIGURE 13. **Evolution of the cumulative references to standards.**

adaptation to encompass the Industry 4.0 envisioned capabilities. Particularly concerning connectivity [43] and interoperability related issues, standards addressing data models, e.g., AutomationML, B2MML, and FIWARE, and ICT, e.g., OPC-UA, REST and MQTT, need to be properly realized in the enterprise architectures. It is also required the adoption of some technological choices in the design process: the use of service-orientation to encapsulate functionalities as services and loosely-coupled approaches actively contribute to the interoperability and scalability of the system. Industry 4.0-compliant solutions mean working with a set of well-defined standards and norms, starting with those that constitute the background dimensions of the RAMI 4.0. Analyzing the dataset of Industry 4.0 papers, it is possible to verify a consistent increase in the adoption of these industry standards over the years, as shown in Figure 13. Among these standards, the most frequently mentioned are the IEC 62541 – OPC-UA, IEC 61131 – PLC OPEN XML, VDMA 24582 – Condition monitoring, IEC 61804 – Function Blocks for process control, and ISO/IEC 20140 – Energy Efficiency. Note that the numbers provided for the year 2020 (in green) are a projection based on the analyzed data.

An essential action is the identification of gaps and the initiation of actions to define new standards or complement existing ones with the missing functionality. When the new enabling technologies, as well as the new requirements imposed by such systems, are taken into account, the creation of a unified approach that builds on existing efforts has the potential to boost Industry 4.0 while also making the migration process towards it easier. The establishment of best practices, especially those linked with credible migration strategies, are needed to support the industry transition from their traditional rigid and centralized production systems towards the new decentralized, autonomous, and intelligent ICPS infrastructure. This migration should be an evolutionary process based on the continuous, phased, and smooth transition of existing systems and not a disruptive process, to preserve investments that are already done in brownfield infrastructure [41], [44]. However, greenfield investments to new infrastructures offer a unique opportunity to avoid the complexities of migration and focus on cutting-edge technology, which, however, bears the potentially higher risk and cost. Overall cost, performance, and sustainability can serve as useful indicators [45] towards addressing interoperability, standardization, and migration dilemmas.

C. VIRTUALIZATION AND DIGITAL TWINS

The application of the Digital Twin [46], which is a crucial technology in the Industry 4.0 context, will increase the efficiency of current automation systems and companies in 10% [47]. The Digital Twin is one of the top ten strategic technology trends and is expected that by 2023 the global market on this technology will grow by 38% annually, representing $16 billion [48]. Currently, the majority of Digital Twin research works focuses on manufacturing [46], but also other areas linked to Industry 4.0 are addressed.

In order to achieve the mentioned numbers, several actions should be taken. The integration of industrial IoT technologies is essential for performing the data collection to feed the Digital Twin. Moreover, the specification [23], development [49], and utilization of the AAS, as a concrete implementation of the Digital Twins within an Industry 4.0-compliant solution, is one essential challenge to be approached in the next couple of years [50]. The main challenges behind the digital twin technology include the interplay with Big Data [51], simulation [52], standardization [53], and also the security and privacy of the networks created for networking digitized data, virtual data, and information models [54].

The intelligence behind the decision support is another important challenge to be tackled. In this case, the simple use of ML techniques for data analysis may not always be sufficient to achieve the best results, being necessary to be combined with simulation capabilities. However, there are recent studies that show several limitations in the use of pure AI or simulations approaches for producing knowledge for decision-support [55]. The main problem with a mixed approach is the difficulty in the integration of the simulation models with AI techniques. Improving the modeling and simulation in digital twins is critical [54], and a possible way to do this is to integrate MAS applications to enhance the capabilities of generating different scenarios based on the interaction of multiple intelligent entities [56].

Last but not least, beyond security [54], the trust of the user is one of the most critical factors since this can dictate the acceptance or rejection of the Digital Twin system [57]. For this purpose, the development of trust mechanisms, supported with AI techniques, assumes an important role in developing fully functional and trustworthy systems [58].

D. HPC AND PROCESSING INFRASTRUCTURES

A crucial challenge to boost the implementation of Industry 4.0 is the need to have available not only a sophisticated communication infrastructure [43] but also computational infrastructures that store the collected data and run the AI and advanced data analytics algorithms, ranging from the edge and fog levels to High Processing Computing (HPC) infrastructures for the cloud computing level [7].

In the last years, we have seen the rise of powerful edge devices that provide the computational power to run AI algorithms at the edge, near to the data sources and in real-time [59]. Since algorithms running on the edge can provide a fast response to condition change and also reduce the size of data to be sent to the cloud by implementing pre-processing methods, and AI algorithms running in the cloud can provide optimization, prediction, and planning functions. Using distributed computational layers, it is imperative to balance the intelligence and data analytics correctly among edge, fog, and cloud layers, while respecting security, privacy and other federated data concerns.

Combined with these computational infra-structures, other key enabling technologies can boost the implementation of the Industry 4.0 principles. As an example, photonics is seen as one fundamental technology in digitalization, as assumed by the European Commission in its digitalization strategy, that could facilitate a change in data-center architectures [60]. Of equally high importance are 5G and its M2M capabilities that will provide the means to boost the communication between the distributed entities in ICPS systems [61].

E. HUMAN INTEGRATION

The human integration in ICPS [62] plays a crucial role in the era of the digital transformation, notably because humans are seen as the most flexible driver in an automated system, due to their flexibility and capability to solve unexpected situations. However, the full exploitation of the potential of humans in ICPS requires the use of human-centric design approaches, combined with technologies for the symbiotic integration of the human activities in ICPS [63], [64], e.g., using new user-friendly interfaces and VR/AR technologies.

Two main models for human activities are usually referred [63]: Human-in-the-Loop (HitL), related to tasks in which the worker (usually an operator) is directly participating in the production process and its control loop, and Human-in-the-Mesh (HitM), related to tasks in which the worker (usually a manager) is participating in the production planning process and its control loop. HitL tasks are more focused on the execution of the production processes and have an immediate impact on the quality produced products, while HitM tasks have a long-term impact on production efficiency and require sophisticated methods for planning and simulation based on data analytics and AI. In the scope of Industry 4.0, equal importance should be given to both.

The integration of humans and the collaboration among Industry 4.0 components (that include humans) has several dimensions that include safety [65], security [66], but also ethical considerations [67]. To better understand the role of humans in Industry 4.0, it is necessary to perform an implication and impact research study, from a socio-technical angle [68]. In the scope of Industry 4.0 related challenges and opportunities, new engineering approaches will need to be developed that are human-centric and focus on the interactions of humans with the other Industry 4.0 components [69].

F. CYBERSECURITY

Cybersecurity is an integral path of Industry 4.0 efforts [70], [71], especially considering that several systems are utilized in critical infrastructures that can be targeted even for political reasons, as the operationalization of Stuxnet [72] has shown. As envisioned in Industry 4.0, the majority of the developed systems, applications, and services go beyond their utilization in controlled environments, e.g., factories, and may expand towards consumer systems and interaction with them. Traditional research focusing on the pillars of information security, i.e., addressing confidentiality, availability, and integrity, is expected to continue. This implies, for instance, the development of new algorithms for encryption, authentication/authorization, attack detection, etc., that increasingly takes into consideration the unique characteristics, needs, and emerging trends on infrastructures for ICPS [70]. In parallel, additional evolutionary steps are expected that takes the state of the art research and development and advances it around ICPS and their ecosystem. As an example, intrusion detection systems (IDS) for ICPS that are part of critical infrastructures may evolve an adapt themselves in real-time, considering the behavior and roles of an ICPS within its operational context.

New cybersecurity challenges posed in Industry 4.0 are also expected to be a significant focus area. These challenges pertain to security, trust, and privacy management in non-controlled and highly dynamic environments, at ICPS as well as a system level. Systems of ICPS are expected to interact and even cooperate autonomously, e.g., autonomous vehicles self-regulating traffic at smart cities, etc. Also, due to the envisioned high utilization of ML in such systems, aspects about dependability, trust, and explainability for ML-driven decision making, especially for critical systems, are emerging. Finally, as other technologies evolve, synergies can be created, and their interaction with cybersecurity is eminent. Typical such examples include blockchain and quantum computing, both of which have the potential to reshape cybersecurity for ICPS. Managing cybersecurity in such diverse and highly sophisticated infrastructures is expected to be challenging [71], and therefore it should be addressed from a holistic point of view that includes technical and non-technical aspects [66].

G. BUSINESS ORIENTATION AND ETHICS

A crucial issue to be taken into account in the development of such smart ICPS systems is to look and think beyond the technology, taking special attention to business, social-organizational, economic, and ethical aspects. Beyond technology, financial and knowledge constraints are found to be key challenges for small and medium-sized enterprises that constitute the majority of Europe's businesses [13] and similar results are also evident in other studies [73]. In addition, other aspects such as resistance by employees or middle-management need to be considered as they hinder the adoption of Industry 4.0 [74].

As any other technology or product, a very initial step is to convince and empower the stakeholders about the benefits of

Industry 4.0 vision and technologies, identifying where they can help to improve the performance, competitiveness, and resilience of their systems. As such, Industry 4.0 is inherently linked with the circular economy [75]. The application of digital technologies and the digital transformation of existing ICPS and business systems only makes sense if the expected return has a positive business impact, e.g., new market opportunities, or may contribute to the improvement of the company's competitiveness. This issue is highlighted in the layers of RAMI 4.0 [22], where the top layer, called "Business", is related to business and organizational processes of the asset or system to be digitalized [76]. Besides defining how to digitally transform assets to Industry 4.0 components (via the AAS), it is crucial also to establish why this asset should be digitalized, i.e., which desired business functions should be offered as a service, and what assets should be digitalized to provide the desired functions [34].

Another dimension relevant for modern ICPS, uniquely since these are integrated increasingly into modern society and interact with users, is that of ethical design and decision making [67]. As ICPS expects to be fueled by AI, they require special attention to the boundaries of the autonomous decisions regarding the ethical frameworks under which they make decisions, as well as the ethical implication of the decisions and their effects on humans and society at large [77]. As we increasingly rely on AI and autonomous ICPS, we do place trust that they will make the best possible decisions; however, the criteria, ethical frameworks, cultural considerations, different legal and regulatory aspects, transparency and explainability of AI decision, etc., come on top of other challenges that need to be resolved [78] when creating ethical machines though is not without risk [79].

VI. CONCLUSIONS

The 4^{th} industrial revolution is reshaping the existing industrial production systems through a digital transformation process, based on the ICPS complemented with IoT and AI to collect and extract value and knowledge from the massive amount of available data. The Industry 4.0 initiative is the most well-known face of this revolution, attracting a growing interest by industry and scientific communities.

This paper has analyzed and discussed the current state of implementation of Industry 4.0, as this is reflected in a rich dataset collected from several literature repositories. Particularly this work has presented insights about the trends in the adoption of the design principles and enabling technologies, as well as towards the identification of future challenges related to Industry 4.0. The results show that the Industry 4.0 initiative was highly correlated to the increased interest in specific technologies and concepts related to ICPS, including industrial IoT, Big Data, data analytics, additive manufacturing, digitization and networking, service-oriented business processes. In particular, ICPS, industrial IoT, and industrial AI are those that mostly impact these new systems in the future. Additionally, decentralization, interoperability, real-time capability, and optimization are the most critical design principles for the near future implementation of Industry 4.0 compliant systems.

The results presented are in line with other similar studies [17]–[21], while the critical discourse on the challenges revealed additional insights and directions. These challenges are mainly based on the fact that digitized and adequately modelled data/information is at the disposal for being analyzed and used to support all functions associated with the different phases of the life cycle of the physical and cyber-part of a RAMI 4.0-compliant solutions. Apart from the technological challenges, the business, social-organizational and ethical aspects are also pivotal and require to be treated at par with the technological ones, if Industry 4.0 concepts and technologies are to be accepted.

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