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Industry 4.0: A survey on technologies, applications and open research issues

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ABSTRACT

Originally initiated in Germany, Industry 4.0, the fourth industrial revolution, has attracted much attention in recent literatures. It is closely related with the Internet of Things (IoT), Cyber Physical System (CPS), information and communications technology (ICT), Enterprise Architecture (EA), and Enterprise Integration (EI). Despite of the dynamic nature of the research on Industry 4.0, however, a systematic and extensive review of recent research on it is has been unavailable. Accordingly, this paper conducts a comprehensive review on Industry 4.0 and presents an overview of the content, scope, and findings of Industry 4.0 by examining the existing literatures in all of the databases within the Web of Science. Altogether, 88 papers related to Industry 4.0 are grouped into five research categories and reviewed. In addition, this paper outlines the critical issue of the interoperability of Industry 4.0, and proposes a conceptual framework of interoperability regarding Industry 4.0. Challenges and trends for future research on Industry 4.0 are discussed.

1. Introduction

Modern industry industrial development has lasted for several hundred years and has now the era of Industry 4.0 comes. The concept of Industry 4.0 was initially proposed for developing German economy in 2011 [60,87]. According to Lukač [45], the first industrial revolution begins began at the end of the 18th century and is was represented by mechanical production plants based on water and steam power; the second industrial revolution starts started at the beginning of the 20th century with the symbol of mass labor production based on electrical energy; the third industrial revolution begins began in the 1970s with the characteristic of automatic production based on electronics and internet technology; and right now, the fourth industrial revolution, namely Industry 4.0, is ongoing, with the characteristics of cyber physical systems (CPS) production, based on heterogeneous data and knowledge integration. The main roles of CPS are to fulfill the agile and dynamic requirements of production, and to improve the effectiveness and efficiency of the entire industry. Industry 4.0 encompasses numerous technologies and associated paradigms, including Radio Frequency Identification (RFID), Enterprise Resource Planning (ERP), Internet of Things (IoT), cloud-based manufacturing, and social product development [5,19,36,37,41,42,55,60,75,81,82,86,88].

The goals of Industry 4.0 is are to achieve a higher level of operational efficiency and productivity, as well as a higher level of automatization [81]. As Roblek et al. [60] and Posada et al. [58] point out, the five major features of Industry 4.0 are digitization, optimization, and customization of production; automation and adaptation; human machine interaction (HMI); value-added services and businesses, and automatic data exchange and communication. These features not only are highly correlated with internet technologies and advanced algorithms, but they also indicate that Industry 4.0 is an industrial process of value adding and knowledge management.

Despite of the dynamic nature of the research on Industry 4.0, however, a systematic and extensive review of recent research on Industry 4.0 is not available. Accordingly, this paper conducts a comprehensive review on of Industry 4.0 and presents an overview of the content, scope, and findings of Industry 4.0 by examining existing literatures in all databases within the Web of Science and Google Scholar. Altogether, 88 papers related to Industry 4.0 are grouped into five research categories and are reviewed. In addition, this paper outlines the critical issue of the interoperability of Industry 4.0, and proposes a conceptual framework of interoperability regarding Industry 4.0. Challenges and trends for future research on Industry 4.0 are discussed.

The rest of the paper is structured as follows: the methodology of this study is introduced in Section 2. Section 3 groups the selected paper into five categories and reviews them in details.

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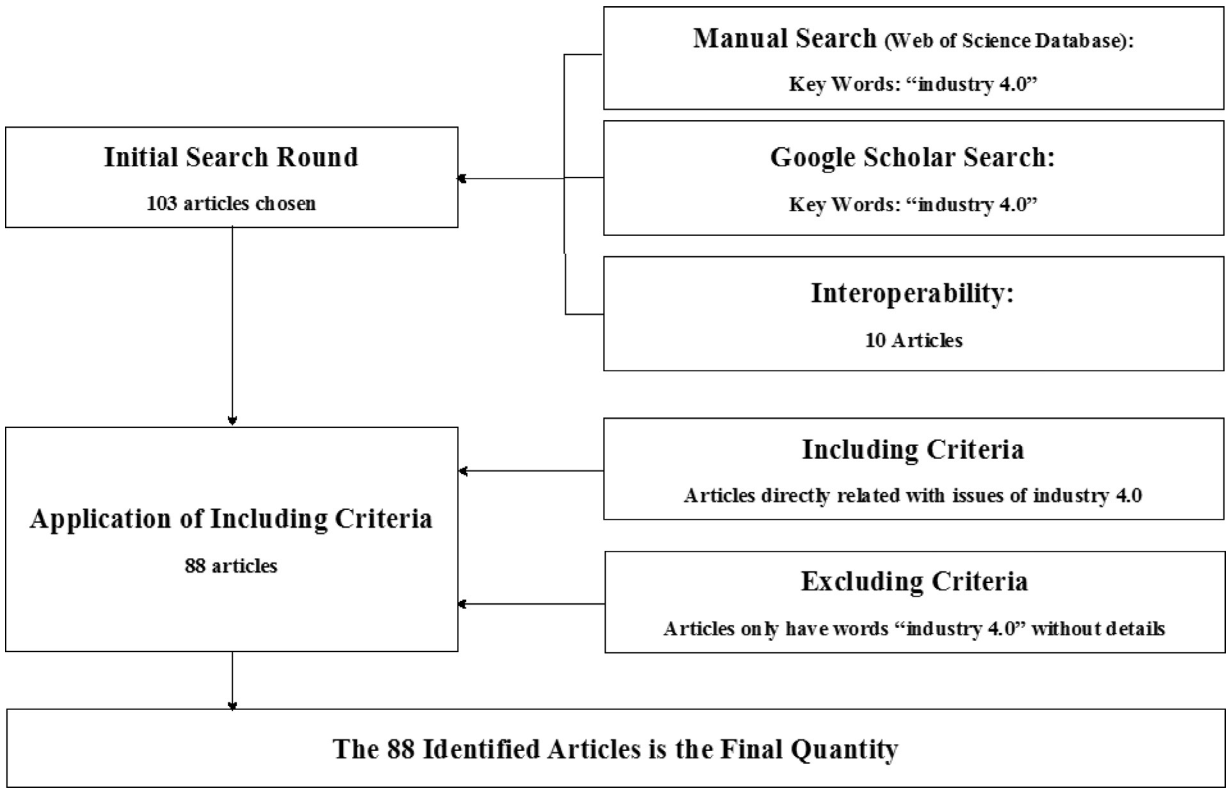

Fig. 1. Literature selecting and identifying procedures.

Challenges and directions for future research are introduced in each category. A framework of interoperability for Industry 4.0 is proposed as well. Section 4 summarizes and concludes this paper.

2. Methodology

This study follows the two-state approach initiated by Webster and Watson [92] to conduct a literature review. This approach has the capability of locating rigorous and relevant research, and then guaranteeing the quality and veracity of the articles finally selected [84]. The process of this approach is shown in Fig. 1.

At the first stage, "Industry 4.0" was chosen as the keyword to search published papers from 2011 to 2016 collected by Web of Science and Google Scholar. The search returned 103 results, which indicates that Industry 4.0 is an emerging research topic. Next, citations of these 103 papers were extracted from Google Scholar. At the second stage, these 103 papers were carefully reviewed and unrelated papers were dropped. At the end, 88 papers were left. The distribution of publication years of these papers and their citation numbers are shown in Fig. 2.

From 2011 to 2016, the annual average number of published papers on Industry 4.0 was 13 and the average annual citation is 157. The annual number of published papers increased from one in 2011 to 33 in 2016. A quick increase occurred in 2014 from one in 2013 to 11. Annual citation of these papers reached a peak in 2014, with the number of 461. The changes in the number of published papers and citations indicate that Industry 4.0 began to attract attention in literature from 2014. The 88 papers are then grouped into five research categories, as shown in Table 1.

The distribution of the categories indicates that more attention has been paid to technologies / tools and applications regarding Industry 4.0 in recent literature. This indicates that Industry 4.0 is not only an integration of CPS, ICT, Enterprise Architecture (EA), and IoT, but that it is also an interoperability process.

Table 1
Research categories of the selected 88 publications.

Research categories	Number of publications
Concept and perspectives of Industry 4.0	18
CPS-based Industry 4.0	12
Interoperability of Industry 4.0	11
Key technologies of Industry 4.0	20
Applications of Industry 4.0	27
	Total: 88

3. Industry 4.0: the state of the art

This section summarizes the content of selected 88 papers, which are grouped into five research categories. Potential directions for future research are discussed in the research category, as well.

3.1. Concept and perspectives of Industry 4.0

Scholars have defined Industry 4.0 from diverse perspectives in this research category (Table 2). For instance, according to the Consortium II, Fact Sheet [14], Industry 4.0 is "the integration of complex physical machinery and devices with networked sensors and software, used to predict, control and plan for better business and societal outcomes." Henning and Johannes [25] define Industry 4.0 as "a new level of value chain organization and management across the lifecycle of products." Hermann et al. [26] define Industry 4.0 as "a collective term for technologies and concepts of value chain organization." They note that, within the modular structured Smart Factories of Industry 4.0, CPS monitor physical processes, create a virtual copy of the physical world and make decentralized decisions. They point out that over the IoT, CPS communicate and cooperate with each other and humans in real time, and that the Internet of Services (IoS), both internal and cross organizational services, is offered and utilized by participants of the value chain. So far, there is no unanimously adopted definition of Industry 4.0.

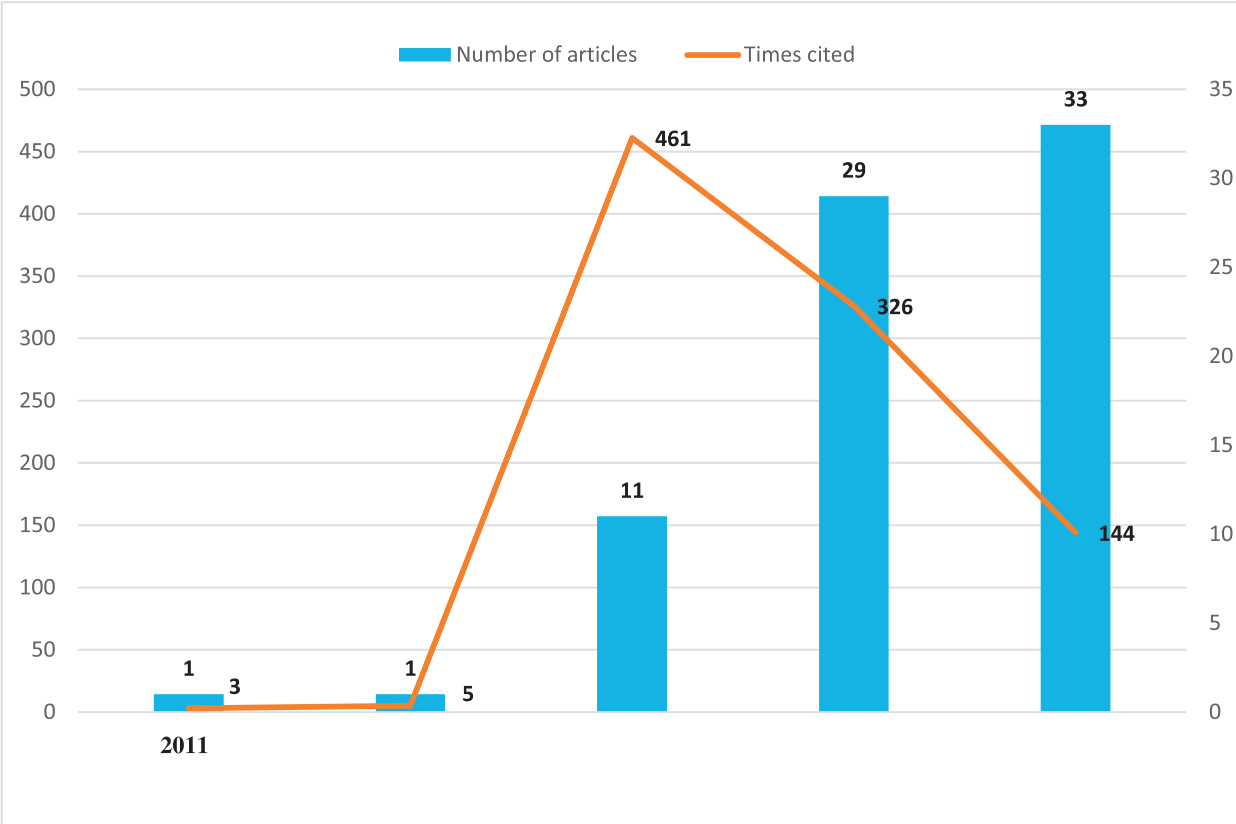

Fig. 2. The distribution of publication years and citations (2011–2016).

Table 2
Publication in the research category of concept and perspectives of Industry 4.0.

Research category	Publications
Concept and perspectives of Industry 4.0	Bagheri et al. [4] Baur and Wee [5] Consortium II. [14] Drath and Horch [16] Henning Kagermann and Johannes Helbig [25] Hermann et al. [26] Kube and Rinn [36] Li et al. [40] Lukač [45] Pfeiffer [55] Pfeiffer and Suphan [56] Posada et al. [58] Singer [75] Staley and Warfield [77] Varghese and Tandur [85] Vogel-Heuser and Hess [87] Warfield [91] Xu [95] Zhou et al. [101]

Industry 4.0 facilitates inter-connection and computerization into the traditional industry. The goals of Industry 4.0 are to provide IT-enabled mass customization of manufactured products; to make automatic and flexible adaptation of the production chain; to track parts and products; to facilitate communication among parts, products, and machines; to apply human-machine interaction (HMI) paradigms; to achieve IoT-enabled production optimization in smart factories; and to provide new types of services and business models of interaction in the value chain [72,73]. Industry 4.0 brings disruptive changes to supply chains, business models, and business processes [68]. The principles of Industry 4.0 are interoperability, virtualization, decentralization, real-time capability, service orientation, and modularity [72,73]. In terms of features, Industry 4.0 can provide more flexibility, reduce lead times, customize with small batch sizes, and reduce costs [72,73]. The key fundamental principles of Industry 4.0 include cloud/intranet, data integration, flexible adaptation, intelligent self-organizing, interoperability, manufacturing process, optimization, secure communication, and service orientation [33,87]. Based on the papers in this research category, Industry 4.0 can be summarized as an integrated, adapted, optimized, service-oriented, and interoperable manufacturing process which is correlate with algorithms, big data, and high technologies.

Table 3
Publication in the research category of cyber-physical systems (CPS) based Industry 4.0.

Research category	Publications
Cyber-Physical Systems (CPS) based Industry 4.0	Bagheri et al. [4] Brettel et al. [9] Harrison et al. [24] Ivanov et al. [29] Ivanov et al. [30] Jazdi [31] Kobara [34] Lee et al. [38] Mosterman and Zander [49] Pérez et al. [54] Schuster et al. [71] Shafiq et al. [72]

Table 4
Publication in the research category of interoperability of Industry 4.0.

Research category	Publications
Interoperability of Industry 4.0	Berre et al. [6] C4ISR [10] Chen et al. [12] Gorkhail and Xu [21] IDABC [27] IEEE [28] Lu [44] Romero and Vernadat [61] Ruggaber [63] Sowell [76] Synergy [79]

3.2. Cyber-Physical Systems (CPS) based Industry 4.0

As an emerging technology, Cyber-Physical Systems (CPS) are expected to offer promising solutions to transform the operation and role of many existing industrial systems [7,23,46,96,98,100]. This research category has thirteen papers, as shown in Table 3, which cover CPS. CPS are industrial automation systems that integrate innovative functionalities through networking to enable connection of the operations of the physical reality with computing and communication infrastructures [4,24,31,38,48,49,72].

Shafiq et al. [72] define CPS as "the convergence of the physical and digital worlds by establishing global networks for business that incorporate their machinery, warehousing systems and production facilities" (p. 1149). Monostori et al. [48], on the other hand, note that "CPS are systems of collaborating computational entities which are in intensive connection with the surrounding physical world and its on-going processes, providing and using, at the same time, data-accessing and data-processing services available on the Internet" (p. 621). CPS consist of microcontrollers that control the sensors and actuators. Data and information are exchanged among embedded computer terminals, wireless applications, houses, or even clouds. The complex, dynamic, and integrated CPS will collaborate planning, analysis, modeling, design, implement, and maintenance in the manufacturing process [37].

Because CPS combine information and materials, decentralization and autonomy play important roles in improving the overall industrial performance [30]. CPS are capable of increasing productivity, fostering growth, modifying the workforce performance, and producing higher-quality goods with lower costs via the collection and analysis of malicious data [62]. Jazdi [31] presents an application of CPS and demonstrates its redefined aspects, work processes, and development methods. Ivanov et al. [29] argue that dynamic models are needed in CPS to coordinate activities in manufacturing procedures and to achieve an optimization of production. Based on a structure dynamic control (SDC) mechanism, they develop a service-oriented dynamic model for dynamic scheduling and collaborating CPS networks in Industry 4.0.

Shafiq et al. [72] assert that the combined structure of Virtual Engineering Objects (VEO), Virtual Engineering Process (VEP), and Virtual Engineering Factory (VEF) is a specialized form of CPS. VEO is a procedure of knowledge transition and data mining in which one can capture and reuse the experience of engineering artifacts and can further benefit decision-making in industrial design and manufacturing [9,34,71,72]. VEO integrates IT systems at different hierarchical levels throughout a manufacturing process. Furthermore, it can assist CPS to be more flexible and reconfigurable in a manufacturing process. It is an effective and critical system that performs knowledge management well and plays an important role in factory planning [58]. VEP is a knowledge representation of manufacturing process with all operation-required information available, whereas VEF is an experience-based knowledge representation of an engineering factory [72]. Shafiq et al. [72] argue that the integrated mechanism of the three components is needed to build the structure of Industry 4.0 and to achieve a higher level of intelligent machines and advanced analytics.

Regarding the future of CPS, the challenges for scholars and practitioners are how to implement CPS and how to improve CPS to become more reliable, stable, and capable are. Xu et al. [97] point out that with the advances in wireless communication, smartphones, and sensor network technologies, CPS will make a large impact on new ICT and enterprise systems technologies. Jazdi [31] points out that distributed remote applications based on software agents are the direction for future research on CPS. Monostori et al. [48] note that both CPS and the cyber physical production systems (CPPS) of Industry 4.0 will be activated and enforced by the development of computational entities, data-related procedures, manufacturing automation and technology, and information and communication technologies (ICT). They further point out that CPPS will dominate manufacturing systems by integrating with CPS as a new generation of industry. CPPS involves humans, machines, and product, and combines computation, networking, and physical processes together in the production process in order to make the production more cost- and time-efficient with highly qualified products [3,37]. The embedded computers and networks in CPPS serve as headquarters to monitor and to control the physical processes, feedback loops, and performance evaluations in the production process. Pérez et al. [54] propose a framework for CPPS which consists of the Production Process Model (PPM), the Information Exchange Model (IEM), and the Plant Information Model (PIM). Roblek et al. [60] present an application of CPPS in which healthcare providers track patients via mobile applications, sensors in clothing, and surveillance cameras in apartments for providing timely services.

In addition, another research direction is to develop a network of VEO, which has a wide applicability of engineering artifacts integrating dual-computerized and real-world representation ranging from simple stand-alone artifacts to complex multitasking machines [9,58,72]. Information exchanging with autonomy and with intelligence is triggered by the real and the virtual productions. A VEO is able to add, store, improve, and share knowledge through manufacturing system [72].

3.3. Interoperability of Industry 4.0

Industry 4.0 has two key factors: integration and interoperability [12,44,61]. Integrated with malicious applications and software systems, Industry 4.0 will achieve seamless operations across organizational boundaries and will realize networked organizations [63]. Interoperability (Table 4) is one of the major advan-

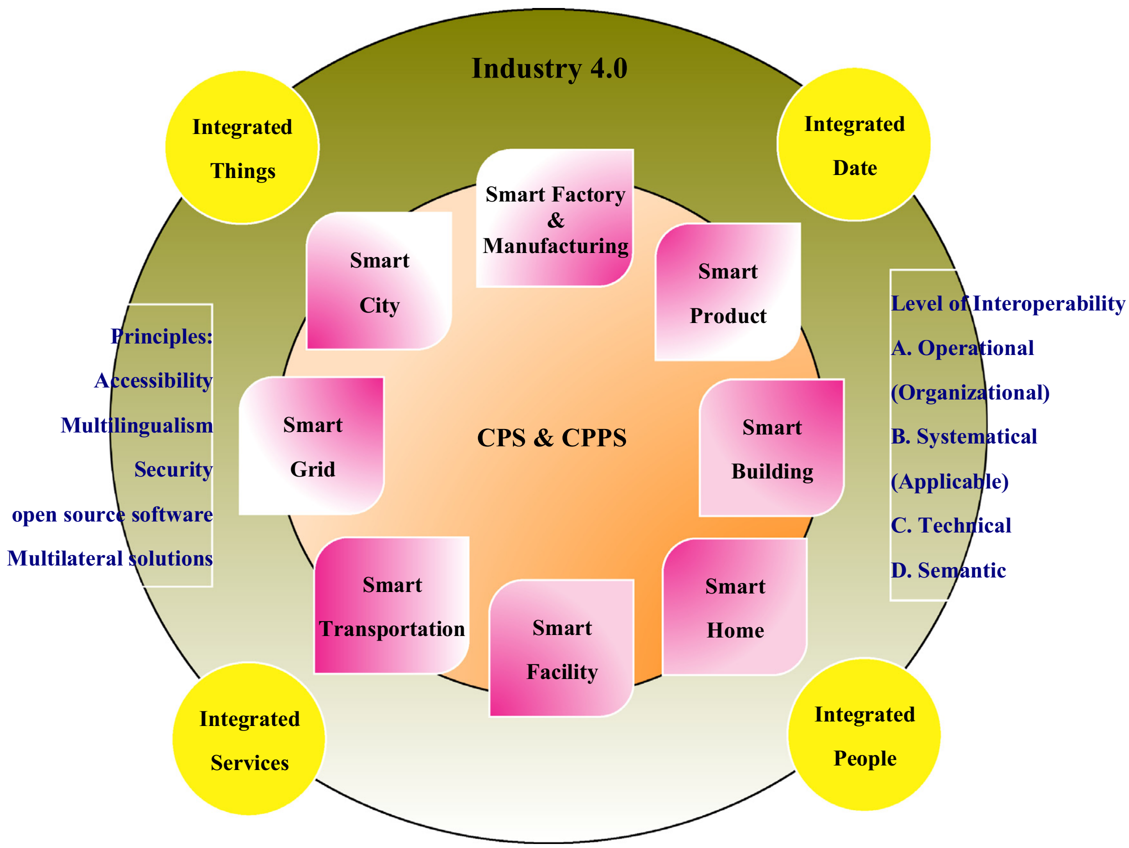

Fig. 3. The framework of interoperability of Industry 4.0.

tages of Industry 4.0. According to Chen et al. [12], interoperability is "the ability of two systems to understand each other and to use functionality of one another." It represents the capability of two systems exchanging data and sharing information and knowledge [79]. The interoperability of Industry 4.0 will synthesize software components, application solutions, business processes, and the business context throughout the diversified, heterogeneous, and autonomous procedure [6].

The architecture of the Interoperability of Industry 4.0 includes four levels: operational (organizational), systematical (applicable), technical, and semantic interoperability [6,21,28,63,76,79]. Specifically, the operational interoperability illustrates general structures of concepts, standards, languages, and relationships within CPS and Industry 4.0. The systematical interoperability identifies the guidelines and principles of methodologies, standards, domains, and models. The technical interoperability articulates tools and platforms for technical development, IT systems, ICT environment, and related software. The semantic interoperability ensures information exchange among different groups of people, malicious packages of applications, and various levels of institutions. These four levels of operation make Industry 4.0 and CPS more productive and cost-saving. Fig. 3 shows the framework of interoperability of Industry 4.0.

Literature has shown that Industry 4.0 has three frameworks, namely Command, Control, Communications, Computers, Intelligence, Surveillance and Reconnaissance (C4ISR); Interoperable Delivery of European eGovernment Services to public Administrations, Business and Citizens (IDABC); and Advanced Technologies for Interoperability of Heterogeneous Enterprise Networks and their Applications (ATHENA) [6,63,76,79].

3.3.1. C4ISR

C4ISR was developed by the U.S. Department of Defense (Dod) in 1996 to integrate the relationships, principles, and guidelines of U.S. military. C4ISR has operational, systematic, and technical level of views. The operational view describes the nature of each need line's information exchange in detail for the purpose of determining what degree of information-exchange interoperability is required [76]. The systematic view first identifies what system supports are required, and then translates the required degree of interoperability into a set of system capabilities, and finally compares current/postulated implementations with the needed capabilities [76]. The technical view articulates the criteria that should govern the compliant implementation of each required system capability [76]. The goal of C4ISR is to ensure the integration and interoperability among these three levels of views. Ultimately, the interoperability can reach across joint and multi-national organizational boundaries.

3.3.2. IDABC

European Interoperability Framework (EIF) Version 1.0 provides a reference on interoperability for the IDABC program and delivers pan-European e-government services to citizens and enterprises [79]. The EIF framework implements interoperability through organizational, technical, and semantic dimensions. Organizational interoperability identifies the actors and organizational processes. Technical interoperability defines the interfaces, standards, and protocols for the integration of IT-systems and software. Semantic interoperability ensures information exchange among involved people, applications, and institutions.

3.3.3. ATHENA

Derived from three multidisciplinary approaches: enterprise modeling, architectures and platforms, and ontology, the ATHENA

Table 5
Publication in the research category of key technologies of Industry 4.0.

Research category	Publications
Key technologies of Industry 4.0	Adeyeri et al. [1] Albers et al. [3] Albrecht et al. [2] Cuihua et al. [15] Gruber [22] Jeng et al. [32] Lee et al. [39] Lin et al. [41] Mi and Zolotov [47] Niesen et al. [50] Obitko and Jirkovský [51] Qin et al. [59] Schabus and Scholz [65] Schumacher et al. [70] Siddiqui et al. [74] Vijaykumar et al. [86] Wan et al. [88] Weiss et al. [94] Yuan [99] Zug et al. [102]

project is built upon the FP5 thematic network Interoperability Development for Enterprise Applications and Software (IDEAS). ATHENA offers a holistic approach to deal with interoperability, heterogeneity, and complexity [6,63]. ATHENA is able to fulfill users' requirements in an entire industry. The ATHENA Interoperability Framework (AIF) collaborates the elements and solutions associated with methodologies and is involved with enterprise applications and software systems. AIF consists of conceptual integration, applicative integration, and technical integration [6]. Conceptual integration deals with concepts, meta-models, languages and model relationships. Applicative integration is about methodologies, standards, and domain models. Technical integration concerns technical development and ICT environments.

3.3.4. Challenges

The Interoperability of Industry 4.0 needs specific principles to guarantee the complete process of accuracy and efficiency. Eight principles are appropriate for Industry 4.0 to be interoperable: accessibility, multilingualism, security, privacy, subsidiarity, the use of open standards, open source software, and multilateral solutions [27]. Accessibility means that Industry 4.0 should offer equal opportunities for the related participants' public access without discrimination. Multilingualism means that Industry 4.0 should support multiple languages for effective delivery of information and knowledge in CPS. Security means that policies are necessary to be conducted and conformed to, in order to keep the information and the process safe and reliable. Appropriate risk assessment activities and security measures are needed. Universal standards are required to be processed by CPS among the participants and activities across diverse levels. Multilateral solutions allow the interoperability of Industry 4.0 to be achieved with the fulfillment of different requirements from different partners.

4. Key technologies of Industry 4.0

Industry 4.0 is marked by highly developed automation and digitization processes and by the use of electronics and information technologies (IT) in manufacturing and services [51,60,99]. Real-time integrating and analyzing massive malicious data will optimize resources in the manufacturing process and will achieve better performance. Mobile computing, cloud computing, big data, and the IoT are the key technologies (Table 5) of Industry 4.0 [22,60,86,88]. In particular, mobile computing and cloud computing provide powerful and accurate data and service for Industry 4.0 by integrating industrial IoT networks.

Pervasive integration of information and communication technology into production components generates massive amounts of various data. The development of algorithms for dealing with data will be one of major challenges in Industry 4.0. Mi and Zolotov [47] use deep learning (one type of Classification) from an H_2O machine learning framework and compare it with four multi-class classification algorithms available as services on Microsoft Azure. Schabus and Scholz [65] model the indoor space of a production environment and apply Geographic Information Science (GIS) visualized methods to improve the performance of smart manufacturing processes. Zug et al. [102] propose a potential approach for analyzing CPS configurations for manipulation throughout the automated generation of (sensor) error models based on the robot. This approach offers flexibility toward varying environmental conditions and stabilizes the quality as requested. Niesen et al. [50] present a holistic framework for data-driven risk assessment along with the results of expert interviews. This provides an approach to deal with heterogeneous data and to mitigate related risks. Schumacher, Erol and Sihn [70] propose nine dimensions to evaluate the maturity level of a factory.

In order to achieve transparency and productivity of big data, Lee et al. [39] address the trends of manufacturing service transformation and the readiness of smart predictive informatics tools. The prognostics-monitoring system is a trend of the smart manufacturing and industrial big data environment [39,86]. Cuihua et al. [15] present a novel approach to simplifying the scheduling problem of job shop scheduling actively by using RFID to collect real-time manufacturing data. Albers et al. [3] analyze quality-related production with an intelligent condition monitoring-based quality control system and develop a comprehensive descriptive model. Albrecht et al. [2] investigate the thermal-mechanical behavior of an implemented RFID-tag embedded in a transmission belt. The embedded tag is subjected to pressure load, which supports the embedding of the tag in the belt. Jeng et al. [32] introduce a temperature measuring device that uses a slip ring to transfer temperature sensor signals from a rotating spindle to the measuring instruments.

As a complex CPS, the IoT integrates various devices equipped with sensing, identification, processing, communication, and networking capabilities [97]. An IoT system consists of Industrial Wireless Networks (IWN) and Internet of Things (IoT) [41,86]. It includes machines and equipment, networks, the cloud, and terminals. An IoT system is capable of offering specific and personalized products. Users can customize products via web pages. Then, web servers transmit data to the industrial cloud and plants via wired or wireless networks. Based on the data received, the manufacturer will integrate design, and will optimize, manage, and monitor the production process in order to produce products efficiently. With the help of self-optimization and autonomous decision-making mechanism, machines and equipment will adopt more to improve the performance [60]. Since manufacturing and supply are dynamic, the life cycle of a product is changeable as well. In accordance with the changes, decentralization, self-optimization, and automation can assist the dynamic process more efficiently and effectively.

Multi-agents-based products, orders, machine processes, controls, artificial intelligence, and genetic algorithms present a comprehensive process of interoperability. The information flow is cooperated, coordinated, and communicated among the manufacturing participants and agents in CPS. Thus, the agent technology is an appropriate tool to deal with complexity and planning of manufacturing of Industry 4.0.

The development of IoT is associated with the development of Industry 4.0 [75]. IoT is the trend and direction for the new in-

Table 6
Publication in the research category of smart factory and manufacturing.

Research category	Publications
Smart factory and manufacturing	Chen and Xing [13] Georgakopoulos et al. [19] Kolberg and Zühlke [35] Oses et al. [52] Paelke [53] Pisching et al. [57] Rüßmann et al. [62] Wang et al. [90] Sanders et al. [64] Scheuermann et al. [66] Shafiq et al. [73] Thames and Schaefer [81]

dustrial revolution [60]. By connecting humans and machines, IoT transfers and integrates knowledge among organizations and insider organizations. By facilitating information and knowledge, IoT improves the efficiency and effectiveness of knowledge development and management in industry 4.0. Specifically, IoT and industry 4.0 will change the relationship among customers, producers, and suppliers. Producing decisions will not be dominated by manufacturers and retailers. Instead, IoT and Industry 4.0 make customers more involved in decisions about quality and the customization of products. However, it is a challenge to construct a high level of secure IoT-based cybersecurity structure for Industry 4.0 due to the complexity and dynamic management process around the machine-to-human collaboration [81]. Therefore, software-defined cloud manufacturing engineering will be focused on adjusting and improving the operational aspects of the architecture and the effectiveness matched with agility, interoperability, configurability, programmability, and integration [81].

In addition, a fifth generation (5G) will be acquired in Industry 4.0 to accomplish latent, long, reliable, and secure communication and to meet the complex demands of emerging business paradigms [74,85]. Although 5G is still in its infancy, the technology of 5G is a necessary developmental step for the Machine-to-Machine (M2M) communication associated with Industry 4.0 and with the IoT.

Furthermore, as industries are becoming more complex and more knowledge intensive, massive data appears with Industry 4.0. The drawbacks of the heterogeneous data will hamper industrial development. Thus, big data management (data mining, data classification, and data storage) becomes a large challenge. Cloud architecture can be used for analyzing data depending on the security and safety structures. Machine learning algorithms for data mining associated with cloud services are a direction for future research [47,101].

5. Applications of Industry 4.0

The adaptability, the resource efficiency, and the integration of supply and demand processes are improved in Industry 4.0, therefore factories, production, cities, and potential intelligent equipment and objects become smart [85]. Demonstrating intelligence and knowledge, the term "smart" is used to refer to applications of Industry 4.0 in the literature. According to Stock and Seliger [78], the main applications of Industry 4.0 are Smart Factory and Manufacturing, Smart Product, and Smart City. Among the 27 papers in this research category, 13 are about Smart Factory and Manufacturing, 10 discuss Smart Production, and the other 4 introduce Smart City.

5.1. Smart factory and manufacturing

Industry 4.0 makes factories (Table 6) more intelligent, flexible, and dynamic by equipping manufacturing with sensors, actors, and autonomous systems [60]. Accordingly, machines and equipment will achieve high levels of self-optimization and automation. In addition, the manufacturing process has the capacity of fulfilling more complex and qualified standards and requirements of products, as expected [60]. Thus, intelligent factories and smart manufacturing are the major goals of Industry 4.0 [64]. Agent paradigm is recognized as one of the effective tools for smart manufacturing. Adeyeri et al. [1] identify the trends of the usage of agents and multi-agents in manufacturers' resource planning and offer a framework.

Industry 4.0 makes value-added integration occur horizontally and vertically in the manufacturing process [73,78]. Specifically, the horizontal procedure is integrated by value creation modules from the material flow to the logistics of product life cycle, whereas the vertical procedure integrates product, equipment, and human needs with different aggregation levels of the value creation and manufacturing systems. Intelligence and digitization are integrated from the raw material acquisition to manufacturing system, product use, and the end of product life. Lasi et al. [37] point out that Industry 4.0 drives manufacturing in two directions: the application-pull procedure and the technology-push procedure. The former induces dynamic changes caused by a new generation of industrial infrastructure. The latter requires higher level mechanization, digitalization and networking, and miniaturization.

In Industry 4.0, the manufacturing procedure will require more sensors, actors, microchips, and autonomous systems due to the quick development of technologies [37,52,60,62,64]. Advanced methodologies of analytics, CPS, and energy conservation measures (ECM) will be implemented in manufacturing, as well [52]. Based on high frequency energy metering, Oses et al. [52] propose a model for an injection machine to estimate the adjusted baseline with lower risks and uncertainties in measuring and verifying energy conversation. Shafiq et al. [73] propose an assimilation of virtual manufacturing at three levels: virtual engineering objects, virtual engineering processes, and virtual engineering factories. The integrated mechanism of the three levels will be helpful for building the structure of Industry 4.0 and for achieving a higher level of intelligent machines, industrial automation, and advanced semantic analytics.

The literature shows that smart manufacturing needs the coordination of services and physical flows [13,29,30,57,62,89]. Thames and Schaefer [81] introduce Software-Defined Cloud Manufacturing (SDCM), which is based on leveraging abstraction between manufacturing hardware and cloud-based applications, services, and platforms. Scheuermann et al. [66] describe an agile factory prototype which transfers agile software engineering techniques to the domain of manufacturing; they also propose a framework that depicts the impact and feasibility of customer changes during assembly-time. Paelke [53] presents an augmented reality system that supports human workers in a rapidly changing production environment. Wang et al. [90] examine the relationship between lean production and intelligent manufacturing, and propose a lean intelligent production system (LIPS) to improve production quality and efficiency and to reduce costs, in Industry 4.0.

5.2. Smart product

Ten papers, as shown in Table 7, address Smart Product. Supported by sensors and microchips, products in Industry 4.0 become smart [11]. The architecture of Industry 4.0, including ICT, IoT, CPS, cloud-formed data integration, standardized intelligent control, and visualized monitoring, allows human beings to communicate with products [67,68,83]. The existing production systems need to be integrated to cooperate with Industry 4.0 [43,67]. Schuh et al.

Table 7
Publication in the research category of smart product.

Research category	Publication
Smart product	Cao et al. (2015) Flatscher and Riel [18] Gorecky et al. [20] Long et al. [43] Monostori et al. [48] Schlechtendahl et al. [67] Schmidt et al. [68] Schuh et al. [69] Thoben et al. [83] Wang et al. [89]

Table 8
Publication in the research category of Smart City.

Research category	Publication
Smart City	Lasi et al. [37] Lom et al. [42] Roblek et al. [60] Tang [80]

[69] note that integrating working and learning is an efficient and effective way to improve the performance of Industry 4.0.

Industry 4.0 offers new technologies and challenges for production development [48,68,69]. It involves advanced automatic, knowledge, information, and real-time adopted production procedures [89]. Thus, smart products need to be created with high technologies in intertwined digital and physical processes [68]. Big Data, cloud computing, mass customization, IoT, and production time improvement are drivers that dominate the development of Industry 4.0 [60,68]. Schlechtendahl et al. [67] point out that the development of Industry 4.0 is a process of integration of smart production. Gorecky et al. [20] present a cyber-physical structure that provides intelligent user interfaces and context-sensitive user interfaces, as well as user-focused assistance systems. Flatscher and Riel [18] propose a strategic production planning process based on the core principles of integrated design to collaborate different trades of design, manufacturing, and procurement for long-term planning investment. Monostori et al. [48] present an approach that is based on information exchange for developing production systems for Industry 4.0.

5.3. Smart City

Smart City (Table 8) is "a city that comprises six factors in its development policy: smart economy, smart mobility, smart environment, smart people, smart living, and smart governance" ([60], p. 4). By combining the Internet, a telecommunications network, a broadcast network, a wireless broadband network, and sensor networks, IoT will accelerate the development of a new generation IT and knowledge-based economy [37,60,80].

Lom et al. [42] note that Smart City involves technical discipline, economic, humanitarian, and legal aspects. In a smart city, citizens change from users to key stakeholders. High technology becomes the dynamic enabler. Businesses become partners. Production is based on demand orientation. Products get smart during their life cycles. And transport is a smart service with advanced planning, efficiency, and effectiveness. Smart City aims to ensure the sustainability of cities, to improve quality of life and safety of the citizens, and to provide energy efficiency. However, the transformation from traditional city to smart city takes time. In addition, Branger and Peng [8] present a communication infrastructure for integrating services in automated homes.

6. Discussion and conclusion

This paper conducts a comprehensive review on Industry 4.0 and presents an overview of the content, scope, and findings of Industry 4.0 by examining existing literature in all databases within Web of Science and Google Scholar. The selected 88 papers are grouped into five research categories and reviewed. This paper presents a state-of-the-art survey of the ongoing research on Industry 4.0.

The development of industry is an integrated process of complexity and agility between human and machine [60]. Industry 4.0 increases the digitization of manufacturing with CPS, in which connected networks of humans and robots interact and work together with information shared and analyzed, supported by big data and cloud computing along entire industrial value chains [93]. Flexible and efficient production becomes possible in Industry 4.0 [16,26,40,43,56]. Industry 4.0 increases cost- and time-efficiency and improves product quality, associated with the enabling technologies, methods, and tools [3]. As a result, Industry 4.0 will accelerate industry to achieve unprecedented levels of operational efficiencies and growth in productivity [16,26,81].

Inspired by Industry 4.0, China has launched China Manufacturing 2025 (CM2025), which is on the track of Industry 4.0 and moved further. Industry 4.0 is about technological advancement, whereas CM2025 is about restructuring the entire industry and making it more competitive using advancement in production technology as just one of the instruments [17]. CM2025 shows that China is well positioned to adopt Industry 4.0 because Chia possesses strong and leading capabilities for digitization and big data, in some areas. The development of Industry 4.0 and China Manufacturing 2025 will rely upon more sophisticated technologies and applications than those that are available now.

Other than the IoT, CPS, ICT, big data, and cloud computing, Xu [95] notes that a variety of industrial information integration methods and techniques have been used in enterprise architecture and enterprise integration for Industry 4.0, such as business process management (BPM), workflow management (WM), Enterprise Application Integration (EAI), Service-Oriented Architecture (SOA), grid computing, enterprise resource planning (ERP), and supply chain management (SCM). These advanced mechanisms integrate industrial information and significantly improve the performance of enterprise information systems (EISs). As Romero and Vernadat [61] indicate, EISs are integrated systems that consolidate physical systems, decision systems, and information systems. EISs offers industrial organizations an IT platform to integrate and interoperate customized business processes and to share information across all functional aspects. These aforementioned technologies and methods will benefit Industry 4.0 and China Manufacturing 2025. New types of advanced manufacturing and industrial processes revolving around machine-to-human collaboration and symbiotic product realization will emerge. But there is still a long way to go to improve manufacturing up to the required level that will match all concepts with all dimensions [59].

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