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Intelligent Manufacturing in the Context of Industry 4.0: A Review

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ABSTRACT

Our next generation of industry—Industry 4.0—holds the promise of increased flexibility in manufacturing, along with mass customization, better quality, and improved productivity. It thus enables companies to cope with the challenges of producing increasingly individualized products with a short lead-time to market and higher quality. Intelligent manufacturing plays an important role in Industry 4.0. Typical resources are converted into intelligent objects so that they are able to sense, act, and behave within a smart environment. In order to fully understand intelligent manufacturing in the context of Industry 4.0, this paper provides a comprehensive review of associated topics such as intelligent manufacturing, Internet of Things (IoT)-enabled manufacturing, and cloud manufacturing. Similarities and differences in these topics are highlighted based on our analysis. We also review key technologies such as the IoT, cyber-physical systems (CPSs), cloud computing, big data analytics (BDA), and information and communications technology (ICT) that are used to enable intelligent manufacturing. Next, we describe worldwide movements in intelligent manufacturing, including governmental strategic plans from different countries and strategic plans from major international companies in the European Union, United States, Japan, and China. Finally, we present current challenges and future research directions. The concepts discussed in this paper will spark new ideas in the effort to realize the much-anticipated Fourth Industrial Revolution.

1. Introduction

Industry 4.0, a German strategic initiative, is aimed at creating intelligent factories where manufacturing technologies are upgraded and transformed by cyber-physical systems (CPSs), the Internet of Things (IoT), and cloud computing [1,2]. In the Industry 4.0 era, manufacturing systems are able to monitor physical processes, create a so-called "digital twin" (or "cyber twin") of the physical world, and make smart decisions through real-time communication and cooperation with humans, machines, sensors, and so forth [3]. Industry 4.0 combines embedded production system technologies with intelligent production processes to pave the way for a new technological age that will fundamentally transform industry value chains, production value chains, and business models.

In the context of Industry 4.0, manufacturing systems are updated to an intelligent level. Intelligent manufacturing takes advantage of advanced information and manufacturing technologies to achieve flexible, smart, and reconfigurable manufacturing processes in order to address a dynamic and global market [4]. It enables all physical processes and information flows to be available when and where they are needed across holistic manufacturing supply chains, multiple industries, small and medium-sized enterprises (SMEs), and large companies [5,6]. Intelligent manufacturing requires certain underpinning technologies in order to enable devices or machines to vary their behaviors in response to different situations and requirements based on past experiences and learning capacities [7]. These technologies enable direct communication with manufacturing systems, thereby allowing problems to be solved and adaptive decisions to be made in a timely fashion. Some technologies also have artificial intelligence (AI), which allows manufacturing systems

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to learn from experiences in order to ultimately realize a connected, intelligent, and ubiquitous industrial practice.

Similar concepts to intelligent manufacturing include cloud manufacturing and IoT-enabled manufacturing. In order to fully understand intelligent manufacturing in the context of Industry 4.0, this paper reviews 165 papers from the Scopus and Google Scholar databases and clearly presents key concepts such as intelligent manufacturing, IoT-enabled manufacturing, and cloud manufacturing. Next, this paper discusses key technologies such as the IoT, CPSs, cloud computing, big data analytics (BDA), and information and communications technology (ICT) that are used to support intelligent manufacturing. Worldwide movements in intelligent manufacturing are then discussed, including cases from government bodies and giant companies in the European Union, United States, Japan, and China. Finally, future perspectives are highlighted for the inspiration of industrial practitioners and academia.

Published data from 2005–2016 regarding intelligent manufacturing have been gathered from the Scopus database (Fig. 1), which shows a steady increase in papers on this topic. Fig. 1(a) shows the published documents on intelligent manufacturing from 2005 to 2016. From 2005 to 2006, the number of articles increased sharply, from around 100 to 150; from 2007 to 2014, the number then increased at a stable rate. From 2014 to 2015, another significant increase occurred, with 225 documents being published in 2015. Fig. 1(b) shows the top sources publishing works related to intelligent manufacturing. The top five serials are the *International Journal of Advanced Manufacturing Technology* (83), *Computer Integrated Manufacturing Systems* (69), *Journal of Intelligent Manufacturing* (49), *International Journal of Production Research* (46), and *Expert Systems with Applications* (33). Fig. 1(c) lists the top universities or research institutes publishing in this research area. The top five universities are Shanghai Jiao Tong University (42), Beihang University (31), Zhejiang University (29), Chongqing University (20), and Tsinghua University (20). Fig. 1(d) shows the top scholars publishing in this area, and Fig. 1(e) lists countries or regions that are active in this field, of which China, the United States, and the United Kingdom are the top three.

These articles are sourced from the Scopus and Google Scholar databases with a focus on key concepts such as intelligent manufacturing, IoT-enabled manufacturing, and cloud manufacturing. By analyzing these key technologies and related worldwide movements, future perspectives are highlighted.

2. Major concepts

The manufacturing industry is the basis of a nation's economy and powerfully influences people's livelihood. Emerging technologies

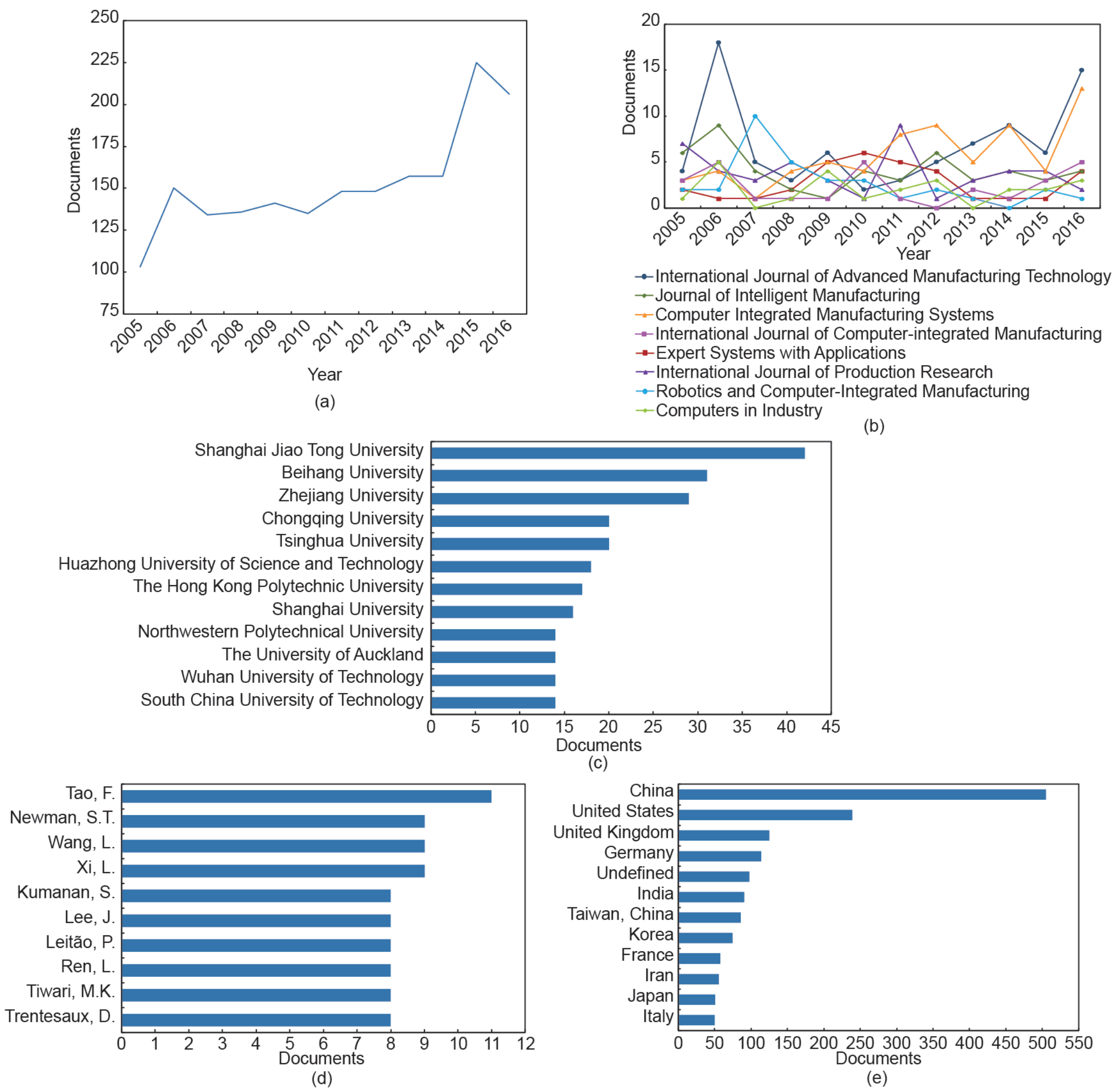

Fig. 1. Statistics from Scopus database (search keywords: "intelligent manufacturing"; Date: 31 March 2017). (a) Published documents per year; (b) published documents by source; (c) published documents by affiliation; (d) published documents by author; (e) published documents by country/region.

can have game-changing impacts on manufacturing models, approaches, concepts, and even businesses. This section reviews three major advanced manufacturing technologies: intelligent manufacturing, IoT-enabled manufacturing, and cloud manufacturing.

2.1. Intelligent manufacturing

Intelligent manufacturing (also known as smart manufacturing) is a broad concept of manufacturing with the purpose of optimizing production and product transactions by making full use of advanced information and manufacturing technologies [8]. It is regarded as a new manufacturing model based on intelligent science and technology that greatly upgrades the design, production, management, and integration of the whole life cycle of a typical product. The entire product life cycle can be facilitated using various smart sensors, adaptive decision-making models, advanced materials, intelligent devices, and data analytics [9]. Production efficiency, product quality, and service level will be improved [10]. The competitiveness of a manufacturing firm can be enhanced with its ability to face the dynamics and fluctuations of the global market.

One form of realization of this concept is the intelligent manufacturing system (IMS), which is considered to be the next-generation manufacturing system that is obtained by adopting new models, new forms, and new methodologies to transform the traditional manufacturing system into a smart system. In the Industry 4.0 era, an IMS uses service-oriented architecture (SOA) via the Internet to provide collaborative, customizable, flexible, and reconfigurable services to end-users, thus enabling a highly integrated human-machine manufacturing system [11]. This high integration of human-machine cooperation aims to establish an ecosystem of the various manufacturing elements involved in IMS so that organizational, managerial, and technical levels can be seamlessly combined. An example of IMS is the Festo Didactic cyber-physical factory, which offers technical training and qualification to large vendors, universities, and schools as part of the German government's Platform Industrie 4.0 strategic initiative [12].

AI plays an essential role in an IMS by providing typical features such as learning, reasoning, and acting. With the use of AI technology, human involvement in an IMS can be minimized. For example, materials and production compositions can be arranged automatically, and production processes and manufacturing operations can be monitored and controlled in real-time [13,14]. As Industry 4.0 continues to gain recognition, autonomous sensing, intelligent interconnecting, intelligent learning analysis, and intelligent decision-making will ultimately be realized. For example, an intelligent scheduling system can enable jobs to be scheduled based on AI techniques and problem solvers, and can be offered to other users as services in an Internet-enabled platform [15].

2.2. IoT-enabled manufacturing

IoT-enabled manufacturing refers to an advanced principle in which typical production resources are converted into smart manufacturing objects (SMOs) that are able to sense, interconnect, and interact with each other to automatically and adaptively carry out manufacturing logics [16]. Within IoT-enabled manufacturing environments, human-to-human, human-to-machine, and machine-to-machine connections are realized for intelligent perception [17]. Therefore, on-demand use and efficient sharing of resources can be enabled by the application of IoT technologies in manufacturing. The IoT is considered to be a modern manufacturing concept under Industry 4.0 and has adopted recent advances, such as cutting-edge information technology (IT) infrastructure for data acquisition and sharing, which greatly influence the performance of a manufacturing system.

IoT-enabled manufacturing features real-time data collection and sharing among various manufacturing resources such as machines, workers, materials, and jobs [18]. The real-time data collection and sharing are based on key technologies such as radio frequency identification (RFID) and wireless communication standards. By using RFID technology, physical manufacturing flows such as the movements of materials and associated information flows such as the visibility and traceability of various manufacturing operations can be seamlessly integrated [19,20]. RFID tags and readers are deployed to typical manufacturing sites such as shop floors, assembly lines, and warehouses, where smart objects are created by equipping manufacturing objects with RFID devices. This allows shop-floor disturbances to be detected and fed back to the manufacturing system on a real-time basis [21], thereby improving the effectiveness and efficiency of manufacturing and production decision-making.

Several real-life cases of IoT-enabled manufacturing have been reported. To improve manufacturing flexibility, an RFID-enabled real-time production management system for a motorcycle assembly line was introduced [22]. This manufacturing system is used in Loncin Motor Co., Ltd. to collect real-time production data from raw materials, work-in-progress (WIP) items, and staff so that items of interest are enhanced in terms of visibility, traceability, and trackability. A case study from an automotive part manufacturer, Huaiji Dengyun Auto-Parts (Holding) Co., Ltd., provides another example [23]. This SME engine valve manufacturer uses an RFID-enabled shop-floor manufacturing solution across whole operations. Based on RFID-enabled real-time data, an extension was made to integrate the manufacturing execution system and the enterprise resource-planning system. A case of implementing RFID-based real-time shop-floor material management for Guangdong Chigo Air Conditioning Co., Ltd. was reported in Ref. [24]. In this case, RFID technology provided automatic and accurate object data to enable real-time object visibility and traceability. More cases are available from the mold and die industry, automotive part and accessory manufacturing alliances, product life-cycle management, and aerospace maintenance operations [25–28].

2.3. Cloud manufacturing

Cloud manufacturing refers to an advanced manufacturing model under the support of cloud computing, the IoT, virtualization, and service-oriented technologies, which transforms manufacturing resources into services that can be comprehensively shared and circulated [29,30]. It covers the extended whole life cycle of a product, from its design, simulation, manufacturing, testing, and maintenance, and is therefore usually regarded as a parallel, networked, and intelligent manufacturing system (the "manufacturing cloud") where production resources and capacities can be intelligently managed. Thus, on-demand use of manufacturing services can be provided from the manufacturing cloud for all types of end-users [31].

In cloud manufacturing, various production resources and capacities can be intelligently sensed and connected into the cloud. IoT technologies such as RFID and barcodes can be used to automatically manage and control these resources so that they can be digitalized for sharing. Service-oriented technologies and cloud computing are the underpinning supports for this concept. As a result, manufacturing resources and capacities can be virtualized, encapsulated, and circulated into various services that can be accessed, invoked, and implemented [32]. Such services can be categorized and aggregated, given predefined specific rules. There are many different kinds of manufacturing clouds that handle various manufacturing services [33]. Different users are able to search, access, and invoke the qualified services through a virtual manufacturing environment or platform.

Cloud deployment modes, manufacturing resources modeling, and requirements and services matching are key concerns in cloud manufacturing. Since a virtual manufacturing environment or solution should be established for services sharing, cloud deployment approaches such as public, private, community, and hybrid clouds are needed so that a uniform and ubiquitous access can be provided to end-users. For example, the hybrid cloud is a mixture of several clouds that offers multiple deployment modes along with advantages such as flexible deployment and easy access to cross-business applications [34]. Various manufacturing resources such as machines and assembly lines should also be modeled into services that can be distributed and shared. German associations such as the German Electrical and Electronic Manufacturers' Association (ZVEI) have already developed an advanced approach; they have not only created a reference architecture on Industry 4.0 products and services (the Reference Architectural Model Industry (RAMI) model) [35], but also described a management or administration shell for several devices to allow consistent usage of data and resources [36]. However, such a development is challenging, since a vast number of physical manufacturing objects of various types and heterogeneous formats may introduce unexpected modeling complexity [37]. Manufacturing requirements and services matching within cloud manufacturing are important. This matching not only includes an optimal solution for service providers and customers, but also consists of service planning, scheduling, and execution [38].

2.4. Comparisons

The three abovementioned concepts are significant in the context of Industry 4.0, since modern advanced manufacturing systems will have tremendous effects on our future lives. In order to fully understand these concepts and identify their differences and similarities, Table 1 [11,33,39–50] highlights a comparison from four perspectives: major characteristics, supporting technologies, major research, and applications.

From Table 1, it can be observed that these concepts have been widely studied and implemented. They share some similarities, such as the aims of intelligent/smart decision-making in manufacturing systems and the optimization of various manufacturing resources [51]. Several technologies, such as the IoT, cloud computing, and BDA, are used within these three main concepts. Such technologies will be detailed in the next section. The research focuses of these concepts are different and are based on different ideas. For example, intelligent manufacturing concentrates on human-machine and machine-to-machine interactions, while IoT-enabled manufacturing highlights real-time data for production-decision models and SMO modeling. Cloud manufacturing focuses on the configuration and modeling of manufacturing services. From an application perspective, IoT-enabled manufacturing has been successfully implemented, with a large number of industrial cases being reported in the literature, supported by professional training and educational concepts. However, intelligent manufacturing and cloud manufacturing are still in the research or proof-of-concept stage, and have a limited number of real-life cases. The standardization concept is strongly presented by powerful associations such as ZVEI. The reported cases for intelligent manufacturing and cloud manufacturing are divided into two categories: illustrations of system architecture, and demonstrations of rigged scenarios in a virtual manufacturing company; however, they may yet be far from real-life implementation.

3. Key techniques

This section reviews some key technologies used in intelligent manufacturing, including the IoT, CPSs, cloud computing, BDA, and other ICTs.

3.1. The Internet of Things

The IoT refers to an inter-networking world in which various objects are embedded with electronic sensors, actuators, or other digital devices so that they can be networked and connected for the purpose of collecting and exchanging data [52]. In general, IoT is able to offer advanced connectivity of physical objects, systems, and services, enabling object-to-object communication and data sharing. In various industries, control and automation for lighting, heating, machining, robotic vacuums, and remote monitoring can be achieved by IoT. One key technology in IoT is automatic identification (auto-ID) technology, which can be used to make smart objects. For example, as early as 1982, researchers at Carnegie Mellon

Table 1
Comparisons of key concepts.

Concepts	Major characteristics	Supporting technologies	Major research	Applications	Refs.
Intelligent manufacturing	• AI-based smart decision-making • Advanced automotive production • Adaptive and flexible manufacturing systems	• Big data processing • Advanced robotics • Industrial connectivity services • Last-generation sensors	• Advanced manufacturing decision-making models • Human-machine integration • AI-enabled machine learning • Machine-to-machine connectivity	• A smart manufacturing system with a portrait of an ISO STEP tolerancing standard • A product life-cycle test bed enabling intelligent manufacturing • Agent-based IMSs • Intelligent manufacturing planning and control systems	[11,39–42]
IoT-enabled manufacturing	• Auto-ID technology-based smart manufacturing system • Real-time data collection • Real-time visibility and traceability of production processes • Real-time manufacturing decision-making	• IoT • Wireless production • BDA • Cloud computing	• Real-time data-driven decision-making models • Real-time data visualization • SMO modeling • Models of SMO behaviors	• An RFID-based resources management system • An IoT-enabled smart construction production system • An RFID-based job shop WIP inventories management system • An RFID-enabled real-time production planning and scheduling system	[43–47]
Cloud manufacturing	• Manufacturing service distribution and sharing • Intelligent capability management • Manufacturing cloud service management	• Cloud computing • IoT • Virtualization method • Service-oriented technology	• Modeling of manufacturing resources and capabilities • Manufacturing services configuration • Manufacturing cloud architecture	• Data visualization in a cloud manufacturing shop floor • QoS-based service composition selection in a cloud manufacturing system • Smart cloud manufacturing using the IoT • A semantic web-based framework in cloud manufacturing	[33,48–50]

Auto-ID: automatic identification; STEP: standard for the exchange of product model data; QoS: quality of service.

University applied an Internet-connected appliance to a modified Coke machine [53]. The IoT is now envisioned as a larger convergence of cutting-edge technologies such as ubiquitous wireless standards, data analytics, and machine learning [54]. This implies that a large number of traditional areas will be affected by IoT technology, as it is being embedded into every aspect of our daily lives.

RFID technology provides one such example. It has been reported that nearly 20.8 billion devices will be connected and making full use of RFID by 2020 [55]. Such a shift will influence most of industry, and especially manufacturing sectors. RFID technology has been used for identifying various objects in warehouses, production shop floors, logistics companies, distribution centers, retailers, and disposal/recycle stages [56]. After identification, such objects have smart sensing abilities so that they can connect and interact with each other through specific forms of interconnectivity, which may create a huge amount of data from their movements or sensing behaviors. The interconnectivity between smart objects is predefined; such objects are given specific applications or logics, such as manufacturing procedures, that they follow after being equipped with RFID readers and tags [57]. RFID facilities not only help end-users to fulfil their daily operations, but also capture data related to these operations so that production management is achieved on a real-time basis. IoT technologies have been widely used in industry. Table 2 [58–66] presents a list of typical applications of IoT.

Table 2 shows that IoT technology has been widely used in different fields such as smart cities, manufacturing, and healthcare. The aims differ for specific applications, so that improvements can be achieved. Developed countries such as France and developing countries such as China and India are working collaboratively to employ the IoT for specific projects. These collaborations not only enhance the development of IoT technologies, but also address global issues, since it is necessary for countries and districts to work collaboratively, especially when adopting a cutting-edge technology such as the IoT.

3.2. Cyber-physical system

A CPS is a mechanism through which physical objects and software are closely intertwined, enabling different components to interact with each other in a myriad of ways to exchange information [67,68]. A CPS involves a large number of trans-disciplinary methodologies such as cybernetics theory, mechanical engineering and mechatronics, design and process science, manufacturing systems, and computer science. One of the key technical methods is embedded systems, which enable a highly coordinated and combined relationship between physical objects and their computational elements or services [69]. A CPS-enabled system, unlike a traditional embedded system, contains networked interactions that are designed and developed with physical input and output, along with their cyber-twined services such as control algorithms and computational capacities. Thus, a large number of sensors play important roles in a CPS. For example, multiple sensory devices are widely used in CPS to achieve different purposes, such as touch screens, light sensors, and

Table 2
Typical applications of IoT.

Industries/companies	Aims	Improvements	Future research	Refs.
Smart community, Canada and China	• Neighborhood watch • Pervasive healthcare	• Value-added services such as utility management and social networking • Suspicious event detection in neighborhood watch	• Cooperative authentication • Detecting unreliable nodes • Target tracking and intrusion detection	[58]
A cloud implementation using Aneka, Australia	• Sharing data between application developers • IoT application-specific framework	• A seamless independent IoT working architecture • Open and dynamic resource provisioning	• Integrated IoT and cloud computing • Big data for IoT applications	[59]
Healthcare and social applications, USA	• Improving the quality of human life • Examining potential societal impacts	• Enabling ambient intelligence • Ubiquitous communication • Increased processing capabilities	• IoT theory for management and operations • IoT data complexity analysis • IoT-enabled global business and commerce	[60]
Machine-to-machine measurement, Ireland and France	• Easing the interpretation of sensor data • Combining domains	• Cross-domain connection • Improved performance • Enhanced interpretation from users	• Domain knowledge extraction • Interoperable ontologies and datasets	[61]
Smart cities, Padova, Italy	• Providing open access to selected subsets • Building an urban IoT system	• Improved energy efficiency • Reduced traffic congestion • Smart lighting and parking	• Smart city data analysis • Smart connectivity • System extension	[62]
IoT Gateway system, China	• Helping telecom operators transmit data • Controlling functions for sensor network	• Improved functions such as data display, topology, etc. • Enhanced data transmission	• Advanced IoT Gateway functions • Security management	[63]
IoT application framework, India and France	• Developing an IoT application framework • Implementing the methodology to support stakeholders' actions	• Improved productivity of stakeholders • Improved collaborative work	• Mapping algorithm cognizant of heterogeneity • Developing concise notion for Srijan development language • Testing support for IoT application development	[64]
IoT-enabled energy management, Italy and Spain	• Illustrating energy management at production level • Proposing IoT-based energy management in production • Providing a framework to support the integration of energy data	• Integrated energy data management • Improved energy efficiency • Enhanced energy data analysis	• Conventional hypothesis testing • System extension	[65]
IoT-enabled real-time information capturing and integration framework, China	• Providing a new paradigm of IoT to manufacturing • Designing a real-time manufacturing information integration service	• Real-time information capturing • Improved logistics	• Optimal production using captured data • Prediction model of production exceptions	[66]

force sensors. Nevertheless, integrating several different subsystems is time-consuming and costly, and the whole system must be kept operational and functional. The heterogeneity and complexity of CPS applications result in several challenges in developing and designing high-confidence, secure, and certifiable systems and control methodologies [70].

Many industries have initiated projects in the CPS domain. For example, Festo Motion Terminal is a standardized platform that makes full use of an intelligent fusion of mechanics, electronics, embedded sensors and control, and software/applications [71]. Digital pneumatics allows self-adopting and self-adjusting subsystems [72]. Typical CPS applications have been reported in the form of using sensor-based communication-enabled autonomous systems. A vast number of wireless sensor networks can supervise environmental aspects so that the information from the environment can be centrally controlled and managed for decision-making [73]. Application of CPSs can be found in diverse fields. Table 3 [71,72,74–82] provides a list of typical applications of CPS.

Table 3 shows that CPSs are a research area of keen interest to both academia and industry. Different countries have invested in developing CPSs as a promising concept for maintaining competitiveness in the global economy. Multidisciplinary collaboration between engineers, industrial experts, and computer scientists has accelerated the advancement in designing and developing CPSs by identifying requirements, opportunities, and challenges in various sectors. As shown in Table 3, these advances have had significant effects on many fields, including medicine and healthcare, biology, civil structures, autonomous vehicles, intelligent manufacturing, and power distribution.

3.3. Cloud computing

Cloud computing is a general term that refers to delivering computational services through visualized and scalable resources over the Internet [30,83]. The scalability of resources makes cloud computing interesting for business owners, as it allows organizations to start small and invest in more resources only if there are rises in further service demand [84]. Based on recommendations from the National Institute of Standards and Technology (NIST), an ideal cloud should have five characteristics: on-demand self-service, broad network access, resource pooling, rapid elasticity, and measured service. This cloud model is composed of four deployment models—public, private, community, and hybrid—and three delivery models—“software as a service,” “platform as a service,” and “infrastructure as a service” [85]. Organizations of all types and sizes are adopting cloud computing to increase their capacity with a minimum budget and without investing in licensing new software, incorporating new infrastructure, or training new personnel [86].

Despite the significant benefits of cloud computing, critical challenges affect the reliability of this ongoing concept [87]. Researchers and service providers have conducted numerous studies to identify and classify issues related to cloud computing. Based on the literature, the most significant concern about cloud computing is related to privacy subjects and security [88–90]. Other challenges such as data management and resource allocation [91,92], load balancing [93,94], scalability and availability [95], migration to clouds and compatibility [96,97], and interoperability and communication between clouds [98,99] reduce the reliability and efficiency of cloud-based systems. These challenges and their most appropriate solutions are addressed in Ref. [100].

With current advances in ICT, cloud computing can be considered as “the fifth utility,” along with water, electricity, gas, and telephone [101]. Because of its relative innovation and exploding development in recent years, a great deal of research has been conducted on cloud computing [102]. Table 4 [103–111] lists some typical applications of cloud computing.

As shown in Table 4, applications of cloud computing, from education and healthcare to manufacturing and transportation, have

Table 3
Typical applications of CPS.

Industries/companies	Aims	Improvements	Future research	Refs.
Power systems, USA and Canada	• CPS test bed implemented in RTDS and OPNET	• Providing a realistic cyber-physical testing environment in real time	• Studying CPS vulnerabilities in various power system models	[74]
Children keeper service, Korea	• Proposing a key design method for CPSs	• Designing CPSs with high-quality more feasibly and practically	• Data-driven CPS decision-making models	[75]
Water distribution networks, USA	• Integrated simulation method for reflecting the operation and interaction of CP networks	• Facilitating modeling CPSs	• Extending the models and techniques for other CPS domains	[76]
Civil structure, USA	• Developing and assessing CPSs for real-time hybrid structural testing	• Illustrating the feasibility of virtualizing CPS components	• Improving hydraulic actuator models • Quantifying further scalability of the proposed approach	[77]
Fire handling. China	• Developing a simulation model for emergency handling problems	• Obtaining optimal sensing and robot scheduling policies	• Increasing computational time for more complicated scenarios	[78]
Autonomous vehicles, USA and Germany	• Proposing a parallel programming model for CPSs	• Guaranteeing timeliness for complex real-time tasks	• Addressing the dynamic nature of CPSs in the proposed model	[79]
Intelligent manufacturing, Sweden and USA	• Associating a CPS with holons, agents, and function blocks • Using CPS to digitalize pneumatics with applications	• Ease of system implementation in decentralized or cloud environment • Maximized flexibility and advanced condition monitoring • Self-adjusting and self-adopting subsystem	• Practical in dynamic manufacturing with uncertainty • Time-sensitive networking for synchronized motion control • Distributed decision-making and self-organization between (sub)systems	[71,72,80]
Healthcare, Brazil	• Model-based architecture for validating medical CPSs	• Providing enough information to perform medical tests	• Proposing architecture for other medical device models	[81]
Communication, China	• Analyzing the features of machine-to-machine, wireless sensor networks, CPS, and the IoT • Reviewing home machine-to-machine networks	• Outlining the challenges related to CPS design	• Future design of CPSs	[82]

RTDS: real-time digital simulator; CP: cyber-physical.

Table 4
Typical applications of cloud computing.

Industries/organizations	Aims	Improvements	Future research	Refs.
Business, France	• Proposing a method for cloud business applications	• Reducing the technical knowledge for provisioning cloud applications	• Integrating a discovery approach and semantic matching in the components discovery phase • Adding a negotiator module	[103]
National Natural Science Foundation, China	• Presenting a hybrid information fusion approach	• Achieving multilayer information fusion • Identifying global sensitivities of input factors under uncertainty	• More comprehensive information fusion approach	[104]
Business and healthcare, UK	• Developing cloud computing in the life sciences	• Introducing cloud models to life-science business	• Identifying major issues	[105]
IT and business, UK	• Highlighting aspects and uniqueness of cloud computing	• Examining the true benefits and costs of cloud computing	• Application extension in other industries	[106]
Manufacturing, Iran	• Proposing a service-oriented approach	• Adopting a layered platform (LAMMOD) for distributed manufacturing agents	• Upgrading the XMLAYMOD layers' procedures and structures	[107]
Education, India	• Outlining the benefits of using cloud computing for students	• Providing opportunities for students to test, learn, experiment, and innovate	• More cloud-based education applications	[108]
ICT, China	• Proposing a forensic method for efficient file extraction	• Efficient location of large files stored across data nodes	• Researching the parallel extraction method for a Hadoop distributed file system • Researching the analysis method on EditLogs	[109]
ISO-New England, USA	• Developing cloud-based power system simulation platform	• Security schemes • Cost savings	• Real-life applications of this system	[110]
Transportation, China	• Formulating a new entropy-cloud approach	• Solving the railway container station reselection problem	• Study, design, and plan for the transferring network	[111]

been widely reported. With the right middleware, a cloud computing system can perform all the applications that a normal computer can run. Everything from generic word processing software to customized business programs designed and developed for an organization can potentially perform on a cloud system. Cloud computing has been credited with increasing competitiveness through greater flexibility, cost reduction, elasticity, and optimal resource utilization.

3.4. Big data analytics

With an aggressive push toward the Internet and IoT technologies, data is becoming more and more accessible and ubiquitous in many industries, resulting in the issue of big data [112]. Big data typically stems from various channels, including sensors, devices, video/audio, networks, log files, transactional applications, the web, and social media feeds [113]. Under these circumstances, a "big data environment" has gradually taken shape in the manufacturing sector. Although the advancement of the IoT (e.g., smart sensors) has streamlined the collection of data, the question remains of whether this data can be processed properly in order to provide the right information for the right purpose at the right time [114]. In a big data environment, the datasets are much larger and may be too complex for conventional data analytic software [115]. Therefore, for organizations and manufacturers with an abundance of operational and shop-floor data, advanced analytics techniques are critical for uncovering hidden patterns, unknown correlations, market trends, customer preferences, and other useful business information.

Research in academia and industry shows that retailers can achieve up to a 15%–20% increase in return on investment by introducing BDA technologies [116]. In most industries, putting customer relationship management (CRM) data into analytics is considered to be an effective way to enhance customer engagement and satisfaction [117]. For example, an automobile company can launch a "face-lift car" that will satisfy customers more than before, by mining history orders and user feedback [118]. Moreover, a deeper analysis of various data from machines and processes can realize the productivity and competitiveness of companies [119]. For example, in the production flow of biopharmaceutical production, hundreds of variables must be monitored to guarantee the accuracy, quality, and yield. By processing big data, a manufacturer can discover critical parameters that have the greatest impact on quality or yield variation [120]. To investigate the application of BDA in various industries, Table 5 [112,118,120–124] lists typical application cases.

Now that BDA technologies have matured for a few years, Table 5 shows that pioneers such as the Internet giants (e.g., Google) or giant retailers (e.g., Tesco) are not the only ones to have benefited from BDA. An increasing number of manufacturing firms (e.g., General Electric (GE)) are also committed to optimizing production or maintenance processes in a big data environment. The majority of the applications listed here are related to manufacturing businesses, although there are far more cases in various industries. For manufacturers that are keen to apply BDA and obtain significant value from it, numerous applications from e-commerce companies and financial investment institutes can be provided as starting references.

3.5. Information and communications technology

ICT refers to an extended IT that highlights unified communications and the integration of telecommunications, as well as other technologies that are able to store, transmit, and manipulate data or information [125]. ICT covers a wide range of computer science and signal-processing techniques such as wireless systems, enterprise middleware, and audio-visual systems. It focuses on information transferring through various electronic media such as wired or wireless communication standards, and is crucial in intelligent manufacturing, where production operations and decision-making heavily rely on the data. ICT has been found to have a distinct impact on firm organization, such that better ICT for plant managers and workers is associated with more autonomy and a wider span of control [126]. For example, ICT is regarded as one of the successful factors in Europe's manufacturing competence, since it helps companies to improve their business agility, flexibility, and productivity.

For an SME, ICT has been proved to be essential for competitiveness, since it enables quick responses to a dynamic market. The use of ICT facilitates the handling of information resources and results in cost reduction and the increase of client compliance [127]. In the modern manufacturing era, billions of digital devices have access to Internet-based networks. This rapid growth has caused ICT to become a keystone of manufacturing systems, where the rapid and adaptive design, production, and delivery of highly customized

Table 5
Typical applications of BDA.

Industries/companies	Aims	Improvements	Future research	Refs.
Google, USA	• Refining its core search and ad-serving algorithms	• Searching patterns and recommended searches based on what others have searched, external events, and etc.	• Studying the algorithm	[121]
Retailers, UK and USA	• Tesco: precise promotions and strategic segmentation of customers • Amazon: accurate recommendations for customers • Wal-Mart: supply-chain optimization	• Mining customer data from loyalty program • Recommendation engine based on collaborative filtering • Enabling vendor-managed inventory based on big data	• Reducing potential risks of sharing data • Avoiding using sensitive personal information • Protecting IT infrastructure from cyber attacks	[112]
Biopharmaceutical industry, USA	• Reducing process flaws • Eliminating yield variation	• Making targeted process changes according to statistical analysis • Increasing its vaccine yield by more than 50%	• Making a long-term investment in systems to collect more data • More advanced analytics	[120]
Remote monitoring application for heavy-duty equipment vehicle, USA	• Assessing and predicting the health of the diesel engine component	• Utilizing classification model to detect analogous engine behavior • Fuzzy logic-based algorithm for remaining life prediction	• Predictive manufacturing process • More comprehensive big data environment	[122]
Tata Motor, India	• Driving quality and reducing cost in manufacturing process • Increasing customer satisfaction level	• Utilizes process excellence and Six Sigma principles • Analytics of CRM system data	• Combination of optimization, emotion, and empathic use of data	[118]
Premier Healthcare Alliance (vendor: IBM), USA	• Improving patient outcomes • Reducing expenditure	• Collecting data from different departmental systems and sending to central data warehouse • Generating reports to help users recognize emerging healthcare issues by data processing	• Developing efficient unstructured data analytical algorithms and applications	[123]
General Electric (Global Software and Analytics Center), USA	• Boosting industrial product sales • Reducing after-sale maintenance cost	• Optimizing the service contracts and maintenance intervals for industrial products	• Integration with data processing in production process	[121]
Aerospace industry, USA	• Predicting number of returns in the future • Minimizing product escapes	• Combining large datasets (manufacturing and repair) together • Using predictive algorithm to analyze data in aerospace test environments	• Automated process of datasets combination	[124]

products are enabled by support from digital and virtual production, modeling, simulation, and presentation tools [128].

ICT applications have been widely reported in a large number of areas such as education, tourism, manufacturing, social science implementations, telecommunications, healthcare, telemedicine, and clinical applications. Table 6 [129–137] presents several typical applications of ICT.

It can be seen from Table 6 that ICT applications in various industries have a longer history than other technologies such as BDA. This is because ICT is an extension of computer technologies that have been in use for several decades. Current applications of ICT mainly focus on integration with other technologies such as cloud computing and the IoT, so that the existing information systems in industry can be combined with cutting-edge technologies. Using ICT has resulted in significant improvements in a large number of real-life cases. Thus, companies in industry are seeking various ICT-based solutions to address their current issues. Under Industry 4.0, it can be foreseen that ICT will be further relied on to integrate emerging technologies in order to address future challenges in various industries.

4. International efforts

This section provides an overview of the major ongoing intelligent manufacturing plans and projects around the world in the context of Industry 4.0.

4.1. The European Union

In 2013, Germany launched its Industry 4.0 plan, the name of which refers to the Fourth Industrial Revolution in which manufacturing industries occupied by intelligent machines and products create intelligent systems and networks that are able to communicate with each other autonomously [138]. Germany is focusing on research into the underlying technologies for manufacturers, such as intelligent sensing, wireless sensor networks, and CPSs. For example, Siemens' digital cloud service platform, Sinalytics [139], can provide secure communication and the integration and analysis of large amounts of machine-generated data, thereby improving monitoring and optimization capabilities for various facilities (e.g., gas turbines and medical systems) through data analysis and feedback.

Under Industry 4.0, IMSs are able to generate massive amounts of data in real time. Such data are essential to the realization of intelligent analysis and decision-making in order to transform a production mode into intelligent manufacturing, cloud-based collaborative manufacturing, and customization production. The aim of Industry 4.0 is to achieve the "smart/intelligent factory" by making full use of CPS technologies and principles. For example, manufacturing machines will have real-time sensing capabilities by the integration of different sensors with precise process control. A series of technologies, such as the IoT or cloud computing, are used for production management. These technologies constitute a service cloud and provide physical equipment with information perception, network communication, precise control, and remote coordination capabilities [140]. Strong standardization efforts in all these activities are a core of the German initiative, which include the efforts of ZVEI on the RAMI 4.0 model, or the "administration shell" on devices [35,36].

In the wake of Germany's Industry 4.0 initiative, the European Union launched its biggest ever research and innovation program,

Table 6
Typical applications of ICT.

Industries/companies	Aims	Improvements	Future research	Refs.
Nigerian national policy analysis, Nigeria	• Examining the ICT impacts on education • Determining suitable policy for ICT potential in the Nigerian education system	• Integration in teaching and learning • Improving teachers' professional development	• Maximizing ICT potential • Proper ICT implementation and monitoring	[129]
Foresight processes, Delphi, Germany	• Identifying the channels for ICT in foresight • Determining the focus on foresight processes using ICT	• More precise strategic decision-making • Increasing product variety in ICT-based foresight tools	• Insights concerning specific tools • Expanding the scope	[130]
Job satisfaction evaluation, USA	• Examining the association between ICT factors and job satisfaction • Examining technology orientation impacts	• Improving sales and job satisfaction • Integrating ICT tools in daily professional activities	• ICT-enabled training • Educational influence of ICT	[131]
Tourism, Hong Kong, China	• Establishing the process of ICT in tourism	• Improving hospitality in tourism • Improving tourism services	• Industry applications • Incorporating ICT into business missions	[132]
Water and soil monitoring, Taiwan, China	• Using ICT to efficiently improve monitoring systems • Classifying the focal area into different agricultural environmental risk zones	• Improving environmental assessments and environmental management decisions • Increasing awareness of ecosystem services	• Collecting data analytics • Increasing the potential of environmental monitoring coverage	[133]
Nursing education, Australia	• Examining e-learning with ICT • Finding the impact of ICT changes on nursing education	• Improving learning efficiency • Increasing motivation for learning	• Learning-quality evaluation • Preregistration nursing curricula	[134]
Women's primary healthcare, Brazil	• Analyzing the ICT incorporation in primary care • Identifying different aspects associated with better quality in the care	• Improving women's healthcare • Improving ICT resources utilization	• Incorporation and the quality of primary healthcare • Policies implementation	[135]
Emergency medical services, China	• Storing and interpreting data • Building an ICT system for emergency medical services	• Improving emergency medical rescuing processes • Increasing data access	• Applying standard data models • Short value chain	[136]
ICT-enabled manufacturing landscape, Germany	• Examining industry decision-making using ICT	• Improving decision-making efficiency • Improving product quality • Decreasing time-to-market	• Allocating production capacity within a value chain • Establishing a heterogeneous tool environment	[137]

Horizon 2020 [141], with nearly €80 billion of funding available over seven years (2014–2020). Under Horizon 2020, the new contractual public-private partnership (PPP) on Factories of the Future (FoF) will build on the successes of the European Union's 7th Framework Program for Research and Technological Development (FP7 2007–2013) FoF PPP. The FoF multi-annual roadmap for the years from 2014 to 2020 sets a vision and outlines routes toward high added-value manufacturing technologies for the factories of the future, which will be clean, high performing, environmentally friendly, and socially sustainable. These priorities have been agreed upon within the wide community of stakeholders across Europe, after extensive public consultation.

4.2. The United States

In 2012, GE introduced the concept of the Industrial Internet of Things (IIoT), suggesting that intelligent machines, advanced analytics, and connected people are the key elements of future manufacturing in order to enable smarter decision-making by humans and machines. The three major components of the Industrial Internet are intelligent equipment, intelligent systems, and intelligent decision-making [142]. The most prominent organization identified with the IIoT is the Industrial Internet Consortium (IIC) [143], which was formed in 2014 with the support of GE, AT&T, Cisco, Intel, and IBM. The IIC aims to provide resources, ideas, pilot projects, and activities about IIoT technologies—and about the security of these technologies.

The IIoT is a circulation of data, hardware, software, and intelligence that enables their interaction by storing, analyzing, and visualizing data acquired through intelligent machines and networks for final intelligent decision-making [144]. The maximal potential of the Industrial Internet will be realized through the holistic integration of its three components: intelligent equipment, intelligent systems, and intelligent decision-making. With a network of machines, materials, workers, and systems, the IIoT will ultimately achieve the smart factory in Industry 4.0.

The emphasis in the United States is predominantly on the IT aspects of the top layer, such as cloud computing, big data, and virtual reality (VR) [145]. Predix, an IIoT platform (i.e., a cloud-based platform-as-a-service platform) [146], was developed by GE. It is claimed to enable industrial-scale analytics for asset performance management and operations optimization by providing a standard way to connect machines, data, and people. Built on Cloud Foundry open-source technology, Predix provides a microservices-based delivery model with a distributed architecture (cloud and on-machine) [147]. It includes four core parts: the security monitoring of networked assets; industrial data management; industrial data analysis; and cloud applications and mobility. These parts connect all types of industrial devices and suppliers to the cloud, thereby providing asset performance management and operations optimization services [148].

4.3. Japan

In 2015, Japan commenced its Industrial Value Chain Initiative (IVI) [149], which corresponds to Germany's Industry 4.0 initiative, in order to connect businesses via the Internet. Thirty Japanese companies, including Mitsubishi Electric, Fujitsu, Nissan Motor, and Panasonic, form part of the initiative. The IVI is a forum to design a new society by combining manufacturing and information technologies and to create a space in which enterprises can collaborate. In order to bring linked factories and connected manufacturing into reality, representatives of IVI member companies bring current situations in real industrial scenes into discussion in order to identify issues and determine ideal situations to be pursued [150]. The forum actively discusses how human-centric manufacturing will change with the IoT. The IVI puts aside the competitive advantages of individual firms and aims at building a mutually connected system architecture based on scenarios in which companies naturally collaborate. It is based on two principles: connected manufacturing and the loosely defined standard. The former aims to purge overburden, waste, and unevenness through digitally connected companies and factories, and to create smart value chains that are based on both automation and human ability. The latter promotes an adaptable model rather than a rigid one. It adopts a pragmatic reality-based approach, and starts from the state of the art today to develop the next level of manufacturing, thus increasing the value of each enterprise by means of cyber-physical production systems [151].

4.4. China

In 2015, China's State Council unveiled a 10-year plan to upgrade the nation's manufacturing capacity to allow it to catch up with production powerhouses such as Germany and the United States. The Ministry of Industry and Information Technology (MIIT) in China led the creation of the Made in China 2025 initiative [143]. This initiative aims to ① increase innovative capability in national manufacturing, ② promote a deep fusion of information and industrialization, ③ strengthen the basic industrial capacity, ④ boost Chinese quality brand-building, ⑤ promote environmentally friendly manufacturing, ⑥ enable breakthroughs in key sectors, ⑦ press further restructuring of the manufacturing industry, ⑧ advance service-oriented manufacturing and manufacturing-related service industries, and ⑨ increase international involvement in manufacturing. To support the manufacturing transformation, the Chinese government has also proposed the following strategic plans: Guidance of the State Council on Promoting Internet+ Action, Guidance of the State Council on Deepening the Integration of Manufacturing and the Internet, and the 13th Five-Year Plan on the National Program for Science and Technology Innovation [6].

Cloud manufacturing, as a first attempt at a new form of intelligent manufacturing, was first proposed in China [25]. Its achievements have been widely referred to and applied in many academic works [144]. Moreover, in certain specific areas of intelligent manufacturing, such as high-end computerized numerical control (CNC) machine tools, industrial robots, intelligent instruments, and additive manufacturing, China has made significant contributions and has established an initial intelligent manufacturing standard system [145]. Through the development of the intelligent manufacturing industry in China, the network infrastructure has reached a higher level and breakthroughs have been achieved in high-performance computing, networking communication equipment, intelligent terminals, and software, forming a series of mobile Internet, big data, and cloud computing leading enterprises that support the development of intelligent manufacturing [145].

5. Future perspectives

Future research perspectives for intelligent manufacturing in the Industry 4.0 era are believed to be in the following areas: a generic framework for intelligent manufacturing, data-driven intelligent manufacturing models, IMSs, human-machine collaboration, and the application of intelligent manufacturing.

5.1. A generic framework for intelligent manufacturing

Given the deep integration of Industry 4.0, a generic framework for intelligent manufacturing is important, since manufacturing science and technology, ICT, and sensor technology will be highly integrated in the future. This generic framework will cover large areas that will be used in different enterprises so that the implementation of intelligent manufacturing can be guided and standardized. Typical technologies such as advanced sensors, wireless communication standards, big data processing models and algorithms, and applications will be placed within this framework. Thus, an intelligent hierarchical architecture will be worked out as a basis for Industry 4.0. One such area is the smart grid, which is designed as an ecosystem in which different elements can be extensively combined in order to work in a highly effective manner [152].

In order to fully implement intelligent manufacturing, platform technologies such as networks and the IoT, virtualization and service technology, and smart objects/assets technology should be focused on, since increasing amounts of customized requirements from customers will increase the cost of manufacturing. Platform technology is able to reduce cost by making full use of flexible and reconfigurable manufacturing systems through intelligent design, production, logistics, and supply-chain management. Multiplex platform technology, especially for design and development, will provide a novel solution to address the issue of highly customized products [153]. A more open innovative framework is required to integrate collaborative efforts in manufacturing for additional downstream and upstream activities. Thus, service-oriented concepts for intelligent manufacturing will be key components in Industry 4.0.

Fig. 2 presents a framework of the Industry 4.0 IMS, in which research topics are categorized into smart design, smart machines, smart monitoring, smart control, and smart scheduling.

- **Smart design.** With the rapid development of new technologies such as VR and augmented reality (AR), traditional design will be upgraded and will enter into a "smart era." Design software such as computer-aided design (CAD) and computer-aided manufacturing (CAM) is able to interact with physical smart prototype systems in real time, enabled by three-dimensional (3D) printing integrated with CPSs and AR.
- **Smart machines.** In Industry 4.0, smart machines can be achieved with the help of smart robots and various other types of smart objects that are capable of real-time sensing and of interacting with each other. For example, CPS-enabled smart machine tools are able to capture real-time data and send them to a cloud-based central system so that machine tools and their twinned services can be synchronized to provide smart manufacturing solutions.
- **Smart monitoring.** Monitoring is an important aspect for the operations, maintenance, and optimal scheduling of Industry 4.0 manufacturing systems. The widespread deployment of various types of sensors makes it possible to achieve smart monitoring. For example, data and information on various manufacturing factors such as temperature, electricity consumption, and vibrations and speed can be obtained in real time.
- **Smart control.** In Industry 4.0, high-resolution, adaptive production control (i.e., smart control) can be achieved by developing cyber-physical production-control systems. Smart control is mainly executed in order to physically manage various smart machines or tools through a cloud-enabled platform. End-users are able to switch off a machine or robot via their smart phones.
- **Smart scheduling.** The smart scheduling layer mainly includes advanced models and algorithms to draw on the data captured by sensors. Data-driven techniques and advanced decision architecture can be used for smart scheduling. For example, in order to achieve real-time, reliable scheduling and execution,

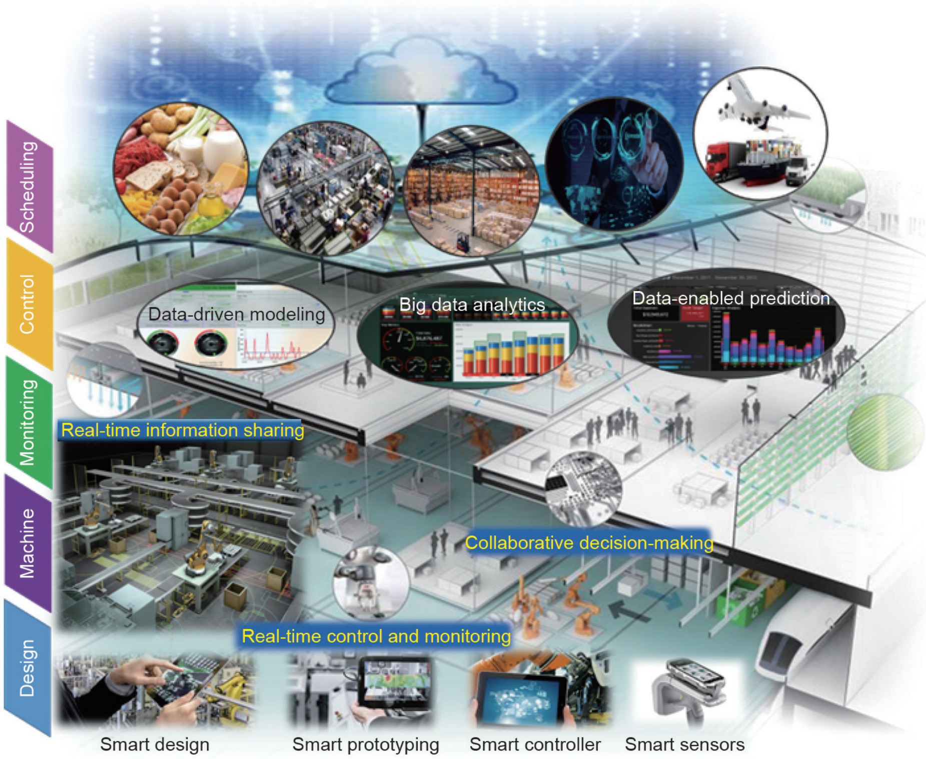

Fig. 2. A framework of the Industry 4.0 IMS.

distributed smart models using a hierarchical interactive architecture can be used.

5.2. Data-driven intelligent manufacturing models

With the large increase of digital devices carrying RFID and/or smart sensors in manufacturing, enormous amounts of data will be generated. Such data carry rich information or knowledge that can be used for different decision-making situations [154]. Therefore, the effective usage of data not only involves improving manufacturing efficiency, but also drives greater agility and deeper integration with other parties such as logistics and supply-chain management entities. For example, the chip maker Intel used a data-analyzing approach on its data from manufacturing equipment to predict quality issues. This usage greatly cut down on the number of quality tests and improved the production speed. The data-based model uses 5 TB of machine data per hour to work out the quality predictions.

Dynamics in a production system will significantly influence quality and efficiency. Data-driven models are able to make full use of historic or real-time data for system diagnosis or prognosis, based on information or knowledge integration, data mining, and data analytics [155,156]. For example, a two-stage maintenance framework using a data-driven approach was utilized for degradation prediction in the semiconductor manufacturing industries [157]. It is clear that in the future, data-based or knowledge-driven models and services will be largely adopted for intelligent manufacturing. One key research area is the integration of cloud services with knowledge management in a platform that is able to provide enterprise services such as intelligent design and manufacturing, production modeling and simulation, and logistics and supply-chain management. This platform will accumulate a vast amount of production data from various manufacturing objects equipped with smart sensors or digital devices, in order to combine human, machine, material, job, and manufacturing logics. An intelligent workshop operation center over the cloud may use self-learning models to build more advanced or intelligent models and algorithms for advanced decision-making in manufacturing systems.

5.3. Intelligent manufacturing systems

The design and development of IMSs require more and more collaboration across the whole range of enterprises and industry. Collaborative manufacturing models or mechanisms such as a cloud-based manufacturing resources/objects management system will centrally control the large variety of production objects so that IMSs are able to work properly and effectively [158]. In the context of Industry 4.0, IMSs are the basis for any enterprise that plans to deploy advanced technologies to create more value-adding processes and services, as has been shown with the digitalization of pneumatics [71,72]. A key research area in the future involves decentralized control service, from whence each intelligent component in the system can make self-adaptive decisions. For example, intelligent components operating in each stage of an assembly line can seamlessly cooperate with moving pieces and other lines to maintain the synchronized production rhythm.

Autonomous intelligent manufacturing units are very important for IMSs. They are based on more advanced embedded chips or sensors that can automatically recognize components, monitor online facilities, and move workpieces. Manufacturing executions based on this system will be more efficient with the help of advanced autonomous unmanned devices such as automated guided vehicles (AGVs). Key research in the future may focus on the enabling technologies for IMSs, such as AR and VR, for a safer production plant [159]. Advanced manufacturing processes and services will be easily integrated into IMSs, so an open platform will be beneficial for manufacturing companies, and particularly for SMEs.

5.4. Human-machine collaboration

Under Industry 4.0, humans and machines will work collaboratively by using cognitive technologies in industrial environments. Intelligent machines will be able to help humans to fulfil most of their work using speech recognition, computer vision, machine learning, and advanced synchronization models [160]. Thus, advanced learning models for machines such as robots are important so that humans and machines develop skills that complement each other under any working conditions. One future research direction is an approach for "human-in-the-loop" machine learning, which enables humans to interact efficiently and effectively with decision-making models. Thus, data-enabled machine learning mechanisms may provide pathways by using human domain expertise or knowledge to better understand the collaboration. For example, traditional machine learning systems or algorithms can be interjected with human knowledge so that a real-world sensing system can help improve human-machine interactions and communications. For example, Festo's Bionic Learning Network found many applications, such as a learning gripper that used AI for self-learning algorithms [161] and the BionicANT project that used multi-agent systems to enable robots to act in a self-organizing manner and solve a given task as a team [162].

Machine intelligence plays an important role in supporting human-machine collaboration, since machines will be providing assistance with every job, every role, and anything that is done in manufacturing sites where dynamic situations are present [163]. Safety issues may be a crucial research topic, as machines equipped with intelligent control systems begin to behave and act as humans in real-life manufacturing sites such as workshops. Such machines can easily communicate with workers through self-learning and evolutionary procedures. For example, intelligent human-machine integration for automating design can be realized from ontology-based knowledge management with local-to-global ontology transitions and the epistemology-based upward-spiral cognitive process of coupled design ideation [164]. Therefore, intelligent human-machine interactions can be implemented within a complex manufacturing environment in order to ultimately achieve manufacturing intelligence in the future.

5.5. Application of intelligent manufacturing

Intelligent manufacturing applications for entire enterprises or industries are significant in Industry 4.0, in which real-life companies can benefit from cutting-edge technologies. An agent-based framework for IMSs will be a suitable solution to the problem of production planning and scheduling, since manufacturing enterprises may involve many varied elements such as manufacturing process planning and scheduling, workshop monitoring and control, and warehouse management. Agent-based implementation is able to define workflows and follow manufacturing logics so that the decision-making related to these elements can be effectively facilitated [41]. Taking automation in manufacturing systems as an example, multi-agent technologies can be used to parallel-control robots that are enabled by an agent-based architecture with distributed agents, in order to ease the implementation of intelligent manufacturing [165].

Another future implementation of intelligent manufacturing is cloud-based solutions; these use cloud computing and SOA to share or circulate manufacturing resources. Several different cloud platforms will be established to make full use of IMSs so that manufacturing capabilities and resources can provide on-demand services to end-users. Key future research involves manufacturing resources modeling during the Industry 4.0 era, since typical resources with advanced sensors are equipped with intelligence and can react, sense, and even "think," given different manufacturing requirements or situations. The question of how to convert such resources into services and place them in a cloud-based platform is a challenging one.

6. Final remarks

As increasing attention is given to Industry 4.0, intelligent manufacturing is becoming more and more important in the advancement of modern industry and economy. Intelligent manufacturing is considered to be a key future perspective in both research and application, as it provides added value to various products and systems by applying cutting-edge technologies to traditional products in manufacturing and services. Product service systems will continue to replace traditional product types. Key concepts, major technologies, and world-wide applications are covered in this paper. Future research and applications are highlighted after a systematic review.

It is our hope that this paper can inform and inspire researchers and industrial practitioners to contribute in advancing the manufacturing industry forward. We also hope that the concepts discussed in this paper will spark new ideas in the effort to realize the much-anticipated Fourth Industrial Revolution.

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