1 Introduction

Over the past more than 200 years, technologies have been playing a dominant role in increasing industrial productivity, which was demonstrated by the previous three industrial revolutions, i.e., mechanization (powered by steam engines in the 1800s), mass production (powered by electricity and the assembly line in the early 1900s), and automation (powered by computers in the late 1900s) [1]. Nowadays, information and communication technology—in particular, the Internet and embedded systems technologies—is undergoing rapid development, which has given rise to a number of novel technologies, such as cyber-physical systems (CPS), the Internet of things (IoT), cloud computing, and big data analytics. The advent of these new technologies enables the creation of a smart, networked world, in which “things” are endowed with a certain degree of intelligence, and moreover, being increasingly connected to each other. In the manufacturing field, the widespread deployment of sensors and the extensive application of software in industrial production bring together the physical and virtual worlds, giving rise to CPS. Moreover, with the help of the internet, a great variety of manufacturing things and “services” can be connected to create the things and services Internet, i.e., IoT and Internet of services (IoS). All these transformations mark the transition of current industrial production to the fourth stage—Industry 4.0, which is characterized by smartness and networking [1].

Apart from industrial revolution, there is another way for describing the different development stages of industrial production—advanced manufacturing. Almost starting from the same time as the third industrial revolution, various advanced manufacturing models and technologies have been proposed [2]. However, there are some drawbacks with existing advanced manufacturing models and technologies, which make them unable to meet the increasing sharing and collaboration requirements of manufacturing enterprises. In recent years, cloud computing has created a brand new way for delivering computing resources [3]. The ingenious combination of cloud idea and method with manufacturing has given rise to a disruptive manufacturing paradigm—cloud manufacturing [4].

Industry 4.0 and cloud manufacturing constitute the two major efforts of taking advantage of information technologies to promote the further development of the manufacturing industry in the manufacturing community. Since their inception, they have drawn enormous attention of people from both academia and industry. Several hundreds of articles have been published (Fig. 1). Note that the keywords for the retrieval of literature on Industry 4.0 are “Industry 4.0” and “Industrie 4.0,” and the literature with any one of the keywords in the titles, keywords, or abstracts was included. According to their current rapid development trend, it can be envisioned that these two concepts have great potential to transform the manufacturing industry in the future. However, to date, they
have largely been addressed in isolation. The fact is that, although being proposed from different perspectives and embracing different ideas, they each have some key features that can benefit one another. In order for their better future development, there is a need to compare these two concepts and clarify their relationship. To this end, this paper first presents basic ideas of Industry 4.0 and cloud manufacturing, then gives a detailed overview of their current research status, and finally conducts a detailed comparative analysis of them from different perspectives.

This paper is structured as follows: In Secs. 2 and 3, we give brief introductions to Industry 4.0 and cloud manufacturing, respectively. Their current research status is also presented therein. Based on Secs. 2 and 3, Sec. 4 conducts a detailed comparative analysis of the two concepts. Section 5 concludes the paper followed by some discussions.

2 Industry 4.0

2.1 Definition, Concept, and Technologies. Reference [5] presented a definition of Industry 4.0: “The term ‘Industry 4.0’ stands for the fourth industrial revolution, the next stage in the organization and control of the entire value stream along the life-cycle of a product. This cycle is based on increasingly individualized customer wishes and ranges from the idea, the order, development, production, and delivery to the end customer through to recycling and related services. Fundamental here is the availability of all relevant information in real-time through the networking of all instances involved in value creation as well as the ability to derive the best possible value stream from data at all times. Connecting people, objects and systems leads to the creation of dynamic, self-organized, cross-organizational, real-time optimized value networks, which can be optimized according to a range of criteria such as costs, availability and consumption of resources.” Hermann et al. defined Industry 4.0 as “a collective term for technologies and concepts of value chain organization. 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. Over the IoT, CPS communicate and cooperate with each other and humans in real-time. Via the IoS, both internal and cross-organizational services are offered and utilized by participants of the value chain” [6]. Both of the definitions above deem Industry 4.0 as the next stage of value chain organization and management.

Industry 4.0 is characterized by the integration along three dimensions: vertical integration together with networked manufacturing systems, horizontal integration through value networks, and end-to-end digital integration of engineering across the value chain of a product’s life-cycle. Smart factory is a core concept component as well as a key feature of Industry 4.0, which is where the vertical integration takes place. Horizontal integration refers to the integration of multiple smart factories through value networks, occurring both within a smart factory and across different smart factories. Vertical and horizontal integration enables the end-to-end integration across the entire value chain. Smart product is another critical concept component in Industry 4.0’s concept system. In a smart factory, products and machines communicate with each other, cooperatively driving production. Smart products can refer to objects, devices, and machines that are equipped with sensors, controlled by software and connected to the Internet [5].

Industry 4.0 will give rise to novel CPS platforms geared toward supporting collaborative industrial business processes and the associated business networks. CPS platforms are where the specific requirements for horizontal and vertical integration of CPS, applications, and services arise in business processes (Fig. 2) [1]. It should be noted that Industry 4.0 stands for the fourth industrial revolution, which necessitates the consideration of many other issues that may occur in the upcoming new era, including standardization, safety and security, resource efficiency, new social infrastructure, work organization and work design, training, regulatory framework, etc. [1].

Technologies of nine aspects that power the transformation of the current industrial production to that of Industry 4.0 have been identified, which more or less have something to do with CPS [7] (Fig. 2). CPS provide a critical support to the vertical and horizontal system integration. The combination of CPS and the industrial IoT enables the creation of the IoT and IoS. CPS will surely bring about the cybersecurity issue. Moreover, the widespread application of CPS means the generation of industrial big data, which requires cloud technology and big data analytics for storage and analysis. The virtual world of CPS consists of a great variety of models of the production facilities, for which simulation can play an important role. Augment reality technology is required for operators to interact with CPS. Additive manufacturing and robots are essential parts of the CPS-based manufacturing systems of Industry 4.0 [7].

Figure 3 shows the principle of Industry 4.0. Within a smart factory, all the physical production elements in the physical world have a cyber twin (i.e., model) in the virtual world. The physical and virtual worlds as well as the physical assets and cyber twins in them are seamlessly connected to achieve the global optimization of production within a smart factory. Moreover, within a value network, multiple factories are horizontally integrated, i.e., the physical assets and the cyber twins are, respectively, integrated to enable optimized decision-making across the value network. The integration through the value network will give rise to CPS platforms, within which things, services, “data,” and “people” are connected over the Internet.

2.2 Current Research Status. Many research works on Industry 4.0 have been published (Fig. 1). In the following, we will give a brief overview of the current research, focusing on the critical issues, such as CPS, smart factory, big data and its analytics, service, and cloud, etc.

- CPS: Current research on CPS in the area of Industry 4.0 focuses on discussions of the concept, technologies, architecture, challenges, and emerging directions of CPS (or cyberphysical production systems (CPPS)) [8–10]. In particular, Wang et al. presented the latest status and advancement of CPS in manufacturing [10]. Lee et al. proposed a unified five-level architecture as a guideline for implementation of CPS in Industry 4.0, including smart connection level, data-to-information conversion level, cyber level, cognition level, and configuration level [11].

- Smart factory: Radziwon et al. defined a smart factory as “a manufacturing solution that provides such flexible and adaptive production processes that will solve problems arising on a production facility with dynamic and rapidly changing boundary conditions in a world of increasing complexity” [12]. That is, a smart factory should be a network of adaptive and self-organized production units which allows production processes to be globally optimized and is able to be adaptive to unexpected changes. Shrouf et al. presented reference architecture for IoT-based smart factories [13]. Wang et al. constructed a general architecture of the smart factory that incorporates industrial wireless networks, cloud, and fixed or mobile terminals with smart artifacts, such as machines, products, and explored the operational mechanism from the perspective of control engineering [14]. Munera et al. discussed how to achieve control missions into a smart factory through distributed services [15]. Some works discussed the issue of interfactory integration, such as horizontal integration in collaborative networks and end-to-end digital integration [16], and management of innovative production networks of smart factories [17].

- Big data and its analytics: Big data and associated analytics play a significant role in optimizing production quality, saving energy, and improving equipment service in the context of Industry 4.0 [7,18]. The collection and comprehensive evaluation of data from many different sources—production
Fig. 2  Core concept map of Industry 4.0 and technologies that enable its implementation

Fig. 3  Principle of Industry 4.0
equipment and systems as well as enterprise- and customer-management systems—will become standard to support real-time decision-making. However, the five versus of big data (i.e., volume, variety, veracity, velocity, and value) pose many challenges, such as new requirements of hardware and software for processing the data, the urgency of online detection/processing ability, and the necessity for interdisciplinary approaches [19]. Industry 4.0 is a new production paradigm of autonomous and decentralized control which involves a new level of data integration and data processing in industrial production. In the context of Industry 4.0, there are many explicit and implicit data-processing requirements regarding data that need to be processed (e.g., data model, data integration, and data content) and the processing of the data (e.g., decision processing, knowledge processing, and real-time processing) [20].

- **Services and IoS:** Industry 4.0 aims to achieve IoS so that service vendor can offer their services over the Internet. In Industry 4.0, as more software and embedded intelligence are integrated in industrial products and systems, predictive technologies can further intertwine intelligent algorithms and lead to the transformation of manufacturing services, such as predicting product performance degradation, and autonomously managing and optimizing product service needs [18]. Apart from the product-related services, factories can go one step further and offer special production technologies instead of just production types as services that can be used to manufacture products or compensate production capacities [6]. Industry 4.0 can use the cloud-based manufacturing for creating, publishing, and sharing the services that represent manufacturing processes [21].

- **Cloud:** Cloud technologies can be widely used in Industry 4.0 for increased data sharing across company boundaries, improved system performance (such as increased agility and flexibility), and reduced costs through bringings systems online. As a consequence, the integration of cloud technologies with industrial CPS becomes increasingly important [22]. Many vendors have begun to offer cloud-based solutions to manufacturing execution systems (MES). However, factories are comprised of different subsystems, modules, devices, and machines that operate with various communication protocols and interfaces. There is a need for a unified connection between the technological layer (in the context of Industry 4.0, the technological layer consists of CPS and smart products) and the higher layer of the industrial hierarchical model. Zolotova et al. proposed an industry IoT gateway for connecting physical devices and higher layers and thus supporting the communication with a cloud (such as MES services in the cloud) [23]. Sensing network and cloud computing technologies are also utilized to provide an advanced manufacturing solution to Industry 4.0 [24]. However, there are some problems with current enterprise resource planning (ERP) and MES solution in supporting a shared cloud-based approach in distributed manufacturing [25].

- **Other issues:** Schuh et al. discussed the mechanisms contributing to raising productivity in Industry 4.0 [26]. The other issues that have arose the interests of researchers include augmented reality applications [27], knowledge [28], communication [29,30], agent technology [31], standardization [32], energy [33], human–machine interaction (HMI) [34], training and learning [35,36], etc.

### 3 Cloud Manufacturing

#### 3.1 Definition, Concept, and Technologies

Li et al. coined the term “cloud manufacturing” and defined it as “a new networked manufacturing paradigm that organizes manufacturing resources over networks (manufacturing clouds) according to consumers’ needs and requirements to provide a variety of on-demand manufacturing services via networks (e.g., the Internet) and cloud manufacturing service platforms” [4]. Subsequently, Xu defined cloud manufacturing as “a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction” [37].

Figure 4 shows the core concepts and technologies of cloud manufacturing. The core concepts of cloud manufacturing are closely related to its operational mode (Fig. 5). In the cloud manufacturing mode, providers supply their manufacturing resources, which will be transformed into services and then pooled into the cloud manufacturing platform. In line with the market economy theory, operators are introduced to manage the platform so that high-quality services can be guaranteed and provided. Customers can submit their requirements to the platform for requesting services ranging from product design, manufacturing, testing, management, and all other stages of a product life-cycle.

The core of cloud manufacturing lies in the establishment of the cloud manufacturing platform, which relies on many technologies. A cloud manufacturing platform has a multilayer architecture, including resource layer, virtual resource layer, global service layer, application layer, and interface layer [37], as shown in Fig. 5 (for the sake of brevity, layers such as security layer, knowledge layer, and communication layer are not shown).

The implementation of different layers requires different technologies. IoT, virtualization, and servitization technologies are needed to sense manufacturing resources and transform physical resources into virtual resources in the virtual resource layer. The core technologies for global service layer are cloud computing, service-related technologies (including service-oriented technologies and service management-related technologies), and semantic Web technology. In the interface, it is the human–machine interaction technology that plays an important role. Certainly, the high-performance computing technology and advanced manufacturing model and technology are also essential. Many other supporting technologies such as big data are also necessary for the complete implementation of a cloud manufacturing platform [38].

#### 3.2 Current Research Status

Since its inception, the concept of cloud manufacturing has attracted much attention of researchers, and a large number of papers have been published (Fig. 1). Existing research on cloud manufacturing mainly revolves around the discussion of the cloud manufacturing concept itself, as well as the architecture and function implementations of a cloud manufacturing platform, including resources and services issues, cloud manufacturing system operation, and other relevant issues, such as security [39–41]. In the following, we focus on the fundamental issues with cloud manufacturing instead of giving a complete review (for a complete picture of the research on cloud manufacturing, readers can refer to the review papers [39–41]).

Li et al. systematically introduced the concept of cloud manufacturing in 2010 [4]. Afterward, many works devoted to clarifying the concept, definition, connotation, and characteristics [42–47]. The key characteristics of cloud manufacturing include the Internet of manufacturing resources (or Internet of manufacturing things) and ubiquitous sensing, virtual manufacturing society and flexible manufacturing system on demand, service-oriented manufacturing and whole life-cycle capability provisioning, efficient collaboration and seamless integration, knowledge-intensive manufacturing and collective innovation, and toward future social manufacturing [45].

In cloud manufacturing, manufacturing resources can be categorized into physical manufacturing resources and manufacturing capabilities [48,49]. Physical resources can be “hard” or “soft.” Manufacturing capabilities are intangible and dynamic resources that represent an organization’s capability of undertaking a
specific task or operation with competence. In cloud manufacturing, all the manufacturing resources are virtualized and encapsulated as manufacturing cloud services to achieve the Internet of manufacturing services [50].

Cloud manufacturing platforms can be built for small-medium size enterprises (SMEs) or group enterprises [51,52] and can be integrated based on the federation mode [44]. As with cloud computing, there are four deployment modes for cloud manufacturing, i.e., private cloud, community cloud, public cloud, as well as their conglomeration (i.e., hybrid cloud) [53].

4 A Comparative Analysis

This section presents a comparative analysis of Industry 4.0 and cloud manufacturing based on their concepts and current research status.

Industry 4.0 is named after the industry revolution, while cloud manufacturing follows from the advanced manufacturing models and technologies. Therefore, Industry 4.0 needs to be able to describe the landscape of the manufacturing industry in the upcoming era and present solutions to issues that need to be dealt with (such as the resource and energy efficiency, urban production, and demographic change). Industry 4.0’s CPS-based manufacturing systems are capable of providing effective means for solving the problems. Cloud manufacturing is an advanced manufacturing business model that focuses on issues that are directly related to manufacturing (i.e., resource sharing and collaboration in the cloud) and pays less attention to issues like urban production and demographic change, etc.

In terms of concept system, Industry 4.0 encompasses both vertical integration and horizontal integration, but cloud manufacturing concentrates on the integration in the cloud manufacturing platform in the form of service composition (integration in the cloud corresponds to the horizontal integration concept in Industry 4.0). At the factory end, cloud manufacturing is more concerned with how to connect the manufacturing resources into the cloud manufacturing platform and pays less attention to the issue of internal organization and operation (e.g., vertical integration) within a cloud manufacturing factory. But this does not mean that the implementation of the cloud manufacturing factory is unimportant. Exploring the requirements of the cloud manufacturing factory and building it are important future research issues in the area of cloud manufacturing. In this aspect, the CPS-based smart factory of Industry 4.0 can provide important reference. Based on the analysis above, we can conclude that Industry 4.0 is a broader concept system than cloud manufacturing in terms of the issues involved and the completeness of the concept systems (Fig. 6).

Industry 4.0’s fundamental idea is to integrate manufacturing systems of different smart factories along a value chain (or a value network) in the form of CPS so that real-time data and information across the entire value chain can be obtained, which enables real-time and accurate decision-making. Industry 4.0’s CPS-based manufacturing systems have high flexibility, adaptiveness, real-time capability, and can achieve the transparency of production processes. Industry 4.0 is therefore capable of producing increasingly individualized products (of even batch size one) with higher quality, lower costs, and high productivity, etc. (Fig. 6). Cloud manufacturing’s fundamental idea is to connect and integrate manufacturing resources of different factories (or enterprises) into the cloud so that large-scale resource sharing and collaboration can be realized in the form of services and their composition (Fig. 6). Cloud manufacturing’s cloud-based resource sharing method can also bring enormous benefits and advantages to enterprises, such as financial flexibility, business agility, and instant access to innovation [53]. Both Industry 4.0 and cloud manufacturing converge to better meeting increasingly customers’ individualized requirements (Fig. 6). In fact, Industry 4.0 represents a highly digital and networked manufacturing paradigm that satisfies enterprises’ digital manufacturing and collaboration requirements between them and business partners, while cloud manufacturing can effectively satisfy the sharing and collaboration requirements of enterprises in a convenient and agile way [54]. The technologies shown in Figs. 2 and 4 are closely related to the core ideas of Industry 4.0 and cloud manufacturing. Overall, the technologies for Industry 4.0 have something to do with CPS, while the technologies for cloud manufacturing are mainly for the implementation of a cloud manufacturing platform.

As far as the interfactory integration is concerned, Industry 4.0 relies on CPS platforms, and cloud manufacturing relies on cloud...
Fig. 5 Principle of cloud manufacturing

Fig. 6 Comparison between concepts of Industry 4.0 and cloud manufacturing
manufacturing platforms (Fig. 6). These two types of platforms are different in the aim, core technologies, operational mode, and platform architecture.

- **Aim:** Cloud manufacturing platforms aim to support full sharing and efficient collaboration of social manufacturing resources through centralized management and operation. Cloud manufacturing platforms are open that allows enterprises to freely join or exit. CPS platforms also aim to provide support for collaborative industrial business processes and the associated business networks for all the aspects of smart factories and smart product life-cycle [1].

- **Core technologies:** For a CPS platform, it is certain that CPS and IoT are core technologies. Depending on business objectives of CPS platforms, other technologies may also be needed. While for cloud manufacturing platforms, the core technologies include IoT, virtualization and servitization, cloud computing, service-related technologies, etc. (Figs. 4 and 6).

- **Operational mode and business model:** The operational mode of the CPS platform in Industry 4.0 is an open problem and there is little discussion about it [1]. By contrast, the operational mode of a cloud manufacturing platform has been explicitly defined [4]. Nevertheless, there are some common issues to be solved regarding these two types of platforms in terms of business model, such as dynamic pricing, fair benefit sharing, broader regulatory requirements, intellectual property and know-how protection, monitoring of business processes, legal issues, as well as safety and security issues.

- **Architecture:** To date, there has been no specific discussion with respect to the architecture of the CPS platform, whereas the cloud manufacturing platform adopts layered service-oriented architecture, on which researchers have largely reached a consensus [39].

The common parts between CPS platforms and cloud manufacturing platforms lie in the implementations of IoT, IoS, Internet of devices (IoD), and Internet of platforms (IoP), (or the Internet of users (IoU)) (Fig. 6) [1,38]. Moreover, service is an important concept for both Industry 4.0 and cloud manufacturing. There are some differences in the meaning of services in these two concepts. In Industry 4.0, services are closely related to CPS. The most frequently mentioned service concept in Industry 4.0 is product-related services (such as condition monitoring and preventive and predictive maintenance) [18,55]. Cloud manufacturing embraces the concept of manufacturing-as-a-service, taking everything (including manufacturing resources and processes encompassed in the entire product life-cycle) as services. This is the broadest service concept (including the product- and process-related services in Industry 4.0). Hence, the scope and connotation of services in cloud manufacturing are much broader than that in Industry 4.0.

Although much research has been done on both Industry 4.0 and cloud manufacturing, it is still in the very early stage. Existing research on Industry 4.0 is more about CPS, smart factories, big data, etc. Although interfactory networking and integration (i.e., horizontal and end-to-end integration) are also key constituents for the concept of Industry 4.0, the related studies are actually scarce. In this regard, only a couple of works discussed the issue of interfatory integration [16,17]. In contrast, cloud manufacturing research mainly focuses on how to implement a cloud manufacturing platform and its associated technologies, among which the large body of work addressed resource and service-related issues, such as resource classification, perception and connection, virtualization, and servitization [39].

## 5 Conclusion and Discussion

In this paper, we discussed and compared the two significant concepts—Industry 4.0 and cloud manufacturing—based on their fundamental ideas and research status. Industry 4.0 stands for the fourth industrial revolution, and cloud manufacturing is a service advanced manufacturing model. Industry 4.0 is a more comprehensive concept than cloud manufacturing as it encompasses both vertical and horizontal integration, whereas cloud manufacturing concentrates on the integration in the cloud. Their core ideas are different, but they both aim to meet customers’ individualized requirements through IoT, IoS, IoD, and IoP. We also compared the CPS platform and the cloud manufacturing platform from the perspectives of aim, core technologies, operational mode and business model, and architecture.

Industry 4.0 follows from the digital manufacturing concept and method. Digital manufacturing has been around for several decades, and now with the help of the internet and other newly emerging technologies, it is evolving toward a networked version with a higher level of digitization (i.e., CPS). At the same time, servitization, cloudization, and worldwide collaboration of manufacturing businesses are also unstoppable trends nowadays. In the future, how to achieve the seamless integration of these trends is an important research issue for the manufacturing industry.

Both Industry 4.0 and cloud manufacturing are evolutionary concepts. In the future, Industry 4.0 can resort to the “manufacturing-as-a-service” concept of cloud manufacturing and its operational mode to achieve the larger scale business collaboration, and cloud manufacturing may also need to borrow the concept of smart factory in Industry 4.0 for the building of cloud manufacturing factories to facilitate resource perception and connection.

Nowadays, we are entering an increasingly smart, networked world. Industry 4.0 and cloud manufacturing enable the networking of manufacturing things, services, data, and people over the internet in the manufacturing field, which constitutes part of the smart, networked world. It can be envisioned that Industry 4.0 and cloud manufacturing will unleash the full potential of the manufacturing industry in the coming new era of industrial production.

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