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CRITICAL REVIEW

Cloud based manufacturing: A review of recent developments in architectures, technologies, infrastructures, platforms and associated challenges

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Abstract

Service-provider industries have used cloud-based technologies in recent years. Information technology (IT) led the development of electronic hardware and software technologies to enable cloud computing as a new paradigm. Other vanguard industries such as communications and financial services leveraged cloud computing technology to develop cloud-based platforms for their respective industries. Manufacturing industry is a relative newcomer to cloud technologies although it has used modern technologies on factory floor to boost production efficiency. Cloud manufacturing (CMfg) is one of the key technologies of Industry 4.0 (I 4.0) and the goal of CMfg is to develop cloud-based approaches in manufacturing that provide flexibility, adaptability, and agility also, reduces challenges caused by system complexity. In recent years, researchers evaluated cloud technologies and proposed initial solutions tailored to manufacturing requirements. However, there are challenges in implementing CMfg due to complexity of technologies, different types of products and wide range of requirements from mass production of consumer products to low-volume specialty products. This paper presents the advantages, challenges and shortcomings associated with applications of the latest technologies to drive transition to CMfg. This research examined cloud technologies proposed for implementation of CMfg such as architectures, models, frameworks, infrastructure, interoperability, virtualization, optimal service selection, etc. This research also studied the role of technologies such as the internet of things (IoT), cyber physical systems (CPS) robotics, big data, radio frequency identification (RFID), 3D printing and artificial intelligence (AI) in accelerating the adoption and future direction of CMfg.

Keywords Cloud computing · Cloud technologies · Cloud manufacturing · Intelligent manufacturing

Abbreviations

IT	Information Technology
CMfg	Cloud Manufacturing
IoT	Internet of Things
IIoT	Industrial Internet of Things
RFID	Radio Frequency Identification
AI	Artificial Intelligence
SME	Small and Medium Enterprises
MES	Manufacturing Execution Systems
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
3D	Three-Dimensional Printing
Web 3.0	Next Generation Worldwide Web
MaaS	Manufacturing as-a-Service
IaaS	Infrastructure as-a-Service
PaaS	Platform as-a-Service
DaaS	Data as-a-Service
XaaS	Anything as-a-Service
MCaaS	Machine Control as-a-Service
RCaaS	Robot Control as-a-Service
HaaS	Hardware as-a-Service

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TaaS	Technology as-a-Service
QoS	Quality of Service
PSA	Product-Service Architecture
SOA	System-Oriented Architecture
ISO	International Organization for Standardization
MOM	Manufacturing Operations Management
SCOS	Service Composition Optimal Selection
BOM	Bill of Materials
WSDL	Web Service Description Language
ERP	Enterprise Resource Planning
ASDI	Analysis Specification Design Implementation
MES	Manufacturing Execution System
VMES	Virtualization of Manufacturing Execution System
SOM	Service-Oriented Manufacturing
SoMS	Service-Oriented Manufacturing System
CBDM	Cloud-Based Design & Manufacturing
PCS	Product Configuration System
SME	Small & Medium Enterprises
SNA	Social Network Analysis
DFM	Design for Manufacturability
PA	Predictive Analytics
OEEE	Overall Equipment Effectiveness
SCM	Supply Chain Management
CMSS	Cloud manufacturing service system
GA	Genetic Algorithm

1 Introduction

Over recent years, financial globalization and globalization of manufacturing resources as two significant variables have compelled businesses to adapt their business processes in order to remain competitive. In addition, globalization has resulted in geographically dispersed suppliers around the world. The cloud manufacturing (CMfg) refers to a relatively new paradigm that enables ubiquitous, hassle-free, and on-demand network access to a shared pool of manufacturing resources that may be configured in a variety of different ways [1–4]. Entirety of an industrial chain ecosystem is possible to be covered by the use of CMfg [5, 6]. Cost reduction, data analysis improvement, higher efficiency and flexibility and forge stronger collaboration among manufacturers are the notable advantages of using CMfg [7–9]. However, allocation of appropriate resources for multiple tasks and taking the preferences and objectives of a large number of stakeholders involving in the manufacturing process into account are integral challenges in CMfg which is called Task Scheduling and Resource Allocation (TSRA) [10]. Involvement of computer networks in manufacturing by utilizing dispersed manufacturing capabilities, hardware and software is a new advancement in manufacturing using CMfg. Cloud computing, service-oriented, radio-frequency identification (RFID), and the Internet of Things (IoT) are the cutting-edge technologies that play an important part in the CMfg [11–20][21].

There is historic evidence indicating ancient peoples engaged in primitive form of manufacturing and built hand-made objects. Hand-made manufacturing skills improved throughout history until a radical change occurred in eighteenth century when early forms of textile production machines were invented. The change from hand-made to machine-made began in England and was called the "Industrial Revolution" [22]. The rate of industrialization continued until the mass production of steel, cars and other industries in nineteenth century which became known as the "Second Industrial Revolution" [23]. Some researchers believe that mankind is in the early phase of the "Third Industrial Revolution" which began in 1990's with invention of personal computer, internet and other new technologies [24]. Factories were first built in eighteenth century during the first industrial revolution. The number of companies in different industries that built factories increased over time. The manufacturing processes across various industries improved over time. The emergence of new technologies in second half of twentieth century helped factories in various industries to develop new production methods and more efficient manufacturing processes. Many productions related technologies and tools flourished such as six sigma, quality management, lean manufacturing, operations management, enterprise resource planning (ERP), etc. Latest revolution called as Industry 4.0 (I4.0), is characterized by a significant evolution in technologies integrating into all areas of smart manufacturing systems (SMSs) and encompassing the complete product lifecycle from the beginning to the end of the product's life, including design, development, cloud computing, sales, and services [25]. The concept of I 4.0 encompasses several crucial enabling technologies, such as cyber-physical systems (CPS), IoT, artificial intelligence (AI), big data analytics, and digital twins (DT). These technologies are widely recognized as significant contributors to the development of automated and digital industrial settings. The implementation of Fourth Industrial Revolution technology contributes to the attainment of sustainability in corporate operations [26]. The aim of these technologies was to improve the productivity, agility and scalability in a single factory or a network of factories within a company. To be able to drive I4.0 technologies, data-driven services and cloud-based manufacturing play an essential role toward smart factories that are more agile, more productivity and customized production. Previous approaches to mass customization simply reprogrammed individual machines to produce specific shapes [20, 27]. Existing monitoring systems are not capable of collecting large amount of real time data required to create

Fig. 1 Trends and design concepts in Industry 4.0 technology [30]

meaningful progress in manufacturing [28]. Figure 1, the digitization of manufacturing industries has enabled new production methods based on the major technological developments and design concepts of Industry 4.0 [20, 29, 30].

Is cloud-based approaches in manufacturing a new paradigm or old wine in new bottle? Based on comparison with other manufacturing systems, this paper provides supporting evidence to conclude that CMfg is definitely a new paradigm that will revolutionize manufacturing [31]. The modern manufacturing industry needs next-generation integration models to become truly interoperable, intelligent, adaptable and distributed [32, 33]. Cloud-based manufacturing is a new concept that applies cloud computing in manufacturing. The goal is to transition the manufacturing companies to a new paradigm such that production functions can be componentized, integrated and optimized globally [34]. In addition, Shi et al. [35], provided a number of potential as well as problems that are present in the area of edge computation. The term "edge computing" refers to the enabling technologies that make it possible for computation to be conducted at the edge of the network. This computation can be performed on downstream data on behalf of cloud services and on upstream data on behalf of IoT services. They envisioned that cloud computing would have an equally significant effect on their society as would edge computing [35].

Upcoming SMSs envisioned by I4.0, have the potential to reform our product design and manufacturing processes [36]. In order to achieve its success, cloud-based manufacturing plays an essential role to make manufacturing system agile, interoperable, programmable, manageable, adaptable, configurable, and protectable [37–43]. Also, cloud technologies provide flexibility and interactivity between users and providers in globally decentralized markets through standardization of resource integration and service models [34]. The key driver of CMfg is small and medium enterprises (SMEs) that attempt to lower production cost through outsourcing production operations and support functions [44]. The study conducted by Berrio et al. [45] examined the factors that influence the adoption of 4.0 technology in manufacturing SMEs in an emerging country. The primary contribution of their research lies in the identification of a novel variable within their investigation of factors that hinder or enable the adoption and implementation of Industry 4.0 technologies. Specifically, they shed light on the significance of financing challenges as a crucial variable in the endeavors of SMEs to enter the realm of Industry 4.0 [45]. One of the emerging demands placed on manufacturing organizations in the context of Industry 4.0 is the need for enhanced flexibility in response to changes in market demands. This necessitates the ability to swiftly and effectively adapt production capacities. In conjunction with the growing adoption of service-oriented architectures (SOA), the aforementioned necessity engenders a demand for flexible cooperation among supply chain stakeholders, as well as between various departments or subsidiaries of an organization [46].

Software-defined manufacturing (SDM) represents a novel paradigm that pertains to the manufacturing processes within the I 4.0 factory of the future. The proposed strategy necessitates a paradigm shift in cognitive processes and a complete overhaul of core business frameworks within the realm of production technology [47]. In their study, Yang et al. [48] introduced a novel manufacturing model called software-defined cloud manufacturing (SDCM), which leverages cloud and software-defined networking (SDN) technologies. This approach effectively shifts the control logic from physical automation resources to software-based systems. The importance of this shift lies in the software's ability to serve as the central component of the production system, allowing for seamless and efficient system reconfiguration, operation, and evolution. The time-sensitive data traffic control problem of a set of complicated manufacturing jobs was formalized by leveraging the virtualization and flexible networking capabilities of the Software-Defined Cyber-Physical Manufacturing (SDCM) system. This formalization took into account both subtask allocation and data routing path selection. The experimental findings demonstrated that the solution provided, which involved the integration of the genetic algorithm (GA), Dijkstra's shortest path algorithm, and a queuing algorithm, effectively mitigated network congestion and minimized the overall communication delay in the SDCM [48].

CMfg empowers manufacturing firms to respond rapidly to changing customer demands as well as global markets especially in Waste Electrical and Electronic Equipment (WEEE) where rework, remanufacture, recycle and recover are required [32]. An important goal of CMfg is the realization of full-scale sharing, open circulation and transaction as well as on-demand use of manufacturing resource and capabilities as a service [49]. Human factors are critical in enabling the successful adoption of CMfg due to the need to ensure safety and optimum user experience of participants [50]. It is challenging to perform the complex cost-vs-benefit analysis needed to justify the migration to CMfg [51]. Enterprises in CMfg networks share diverse business models, resources and 4 knowledge to offer manufacturing services to clients [52]. CMfg systems are quick to roll out, easy to customize and have the potential to boost adoption rates across resellers [53]. CMfg and Manufacturing Execution Systems (MES) virtualization will introduce "Smart" solutions in testing, management, product scheduling & design, batch planning, real-time manufacturing control and other stages of product life cycle [54]. There is urgency in reaching the targets for developed supplier quality, predicting accuracy and optimized inventory while minimizing cycle times in manufacturing. Since CMfg can be constructed quickly to fit a enterprises' needs, companies are bearing in mind it as a fast way to achieve production targets [55]. It is vital to building a methodical technique for assessing CMfg applications in order to enable factory managers to pick the best way from a number of methods. This may be accomplished by developing a system for evaluating CMfg applications. Hence, according to methodology, scholars proposed different flowcharts.

In recent years, there has been an increase in the incorporation of digital technologies into industrial systems, and their corresponding connectivity to the IoT, has made it possible to offer production services over the cloud, giving rise to a new production paradigm known as CMfg. Customers and providers of production services are able to meet on a digital platform thanks to this paradigm, which then paves the way for the creation of new business opportunities [56]. As a result, many companies that provide production services can form partnerships with one another. This allows these companies to improve the quality of the services they provide to their customers and even profit from their unused capacity by renting it out to other service providers. Because of these benefits, there has been a rise in interest in CMfg, which has resulted in the development of a diverse array of architectures and systems that support these interactions.

Each CMfg platform must include, at the very least, the capabilities necessary to allow connectivity among the many manufacturing resources available in the system, including the effective flow of the important information gleaned from the resources that are connected [57]. To connect these manufacturing resources, the CMfg platform converts actual resources into virtual ones. Using so-called "digital twins" is one method for logically virtualizing a physical resource [58]. In addition, a crucial function that any CMfg platform needs to carry out is the administration of the knowledge and large data generated by the system [59]. Consequently, this feature is vital to business collaboration and interoperability. As the cloud platform's resources and companies expand, the management of so-called "big data" should be regarded as a serious endeavor [60–63]. A CMfg platform is also anticipated to automatically discover services to fulfill customer requests. After the producer and the consumer have mutually agreed upon the product, the platform is required to dynamically create a system of virtual manufacturing by assembling collaborative services and integrating relevant resources [64, 65].

From a commercial point of view, CMfg platforms fulfill the function of a market in which cloud service providers can sell their products and clients can purchase them. As a result, it is essential to cultivate a commercial setting in which both purchasers and vendors are capable of managing commercial concerns such as negotiations and the formation of contracts. Creating a "social network" in which materials, capital, and information flow is one method to foster greater collaboration among cloud users. This so-called "social network" has the potential to potentially serve as a means of coordination among the many users of the platform [66, 67]. Finally, a CMfg platform needs to have a customizable user interface that caters to each type of user as well as each role. There is consensus that strong security and privacy are essential for any organization, so it should also provide end users with customizable security policies. A positive user experience is extremely valuable since it boosts productivity and alters the perspective that end users have of the entire system. In this context, a CMfg platform needs to offer dynamism, which enables producers to offer idle production capacity while also allowing for the offer to change over time. The platform needs to be able to immediately react to these changes in capacity in order to reorganize resource allocations in an effective manner for new customer orders as they come into the system. Capabilities in information processing and integration are absolutely necessary for this purpose. Because it strives to optimize the firms' whole production process, a CMfg platform can boost the competitiveness of the companies that use it by making their manufacturing procedures more efficient [56].

Evaluating the performance of IoT services is challenging because it is dependent on the performance of a large number of individual components in addition to the performance of the technologies that are used beneath them. Similar to other systems, the IoT must continuously develop and enhance its services to satisfy customer demands It is necessary to monitor and evaluate IoT devices in order to provide consumers with the best possible performance at an affordable price. The performance of the IoT can be evaluated using a wide variety of criteria, such as the processing speed, the connection speed, the device form factor, and the cost [68]. The idea of an IoT, in which the sensing and actuation functions seamlessly fade into the background and new capabilities are made feasible by access to rich new information sources, is coming closer to reality as a result of the proliferation of devices that are capable of both communicating and acting upon information. Gubbi et al. [69] proposed a user-centric cloud paradigm using private and public clouds to achieve this purpose. They proposed a framework that is supported by a scalable cloud in order to provide the capability to make use of the IoT. This will allow for the essential flexibility to fulfill the varied and often competing needs of different industries. The system allows for storage, computing, networking, and visualization themes to be kept separate, which enables independent progress in each sector while simultaneously complementing each other in a shared environment. A comprehensive picture of the integration and functional elements that can produce an operational is provided as a result of the consolidation of multinational initiatives, which is quite clearly driving progress toward an IoT [69]. Both cloud computing and the IoT are now commonplace, but they are quite distinct technologies. It is anticipated that their adoption and utilization will become increasingly widespread, and these technologies will play a major role in the future internet. Foreseen that a novel paradigm in which cloud and IoT are combined will be disruptive and enable a vast array of application scenarios. Botta et al. [70] studied Cloud and IoT integration, which they refer to as the Cloud IoT paradigm. The next significant step forward in the development of the future internet will be the combination of cloud computing with the IoT As a result of the paradigm of Cloud IoT, day-to-day living and activities have the potential to be improved for everyone [70].

The utilization of deep learning in service clustering for manufacturing networks has been identified as a highly successful approach for facilitating service discovery and service management within the manufacturing industry. The utilization of manufacturing service clustering presents a viable solution for addressing the challenges associated with service selection and composition within the context of cloud-based manufacturing. Zhu et al. [71], suggested a clustering methodology called deep manufacturing cloud service clustering methodology using pseudo-labels (DSCPL). This model integrates graph topology and node properties to effectively cluster nodes that possess comparable attributes. The conducted experiments provide extensive evidence that the clustering effect of their method surpasses that of existing advanced deep clustering algorithms on both public datasets and simulated datasets. Furthermore, Chen et al. [72] conducted a study on cloud-edge cooperation in manufacturing task scheduling in CMfg (CETS) with the aim of optimizing customer satisfaction and achieving production balance. The Cloud-Edge Task Scheduling (CETS) system enhances manufacturing services by integrating cloud-based and factory-level processes. It effectively allocates jobs based on real-time production data from the edge side and manufacturing service information from the cloud side. The authors presented an attention-based deep reinforcement learning (DRL) approach to address the challenges provided by the dynamism and complexity of state information in CETS. The findings of their study confirm the efficacy of their proposed algorithm in efficiently addressing the CETS problem [72].

The aforementioned studies were conducted by many researchers from around the world. These studies present a vision of CMfg as an early-stage emerging industry. As an example of how researchers are trying to apply CMfg to solve production problems, an interesting study was conducted in Taiwan. This research went beyond theoretical concepts and simulated the actual production operations in a semiconductor wafer manufacturing factory. The preliminary results showed that proper implementation of CMfg can reduce production costs in semiconductor manufacturing [73]. It seems the continued development of cloud-based approaches in manufacturing platforms in the next several years will transform the nascent CMfg into a critical capability for cost-effective production of innovative future products in the twenty-first century [58, 74–76].

1.1 Quantitative Assessment

There was no clear trend in the number of publications involving technologies for cloud-based manufacturing. very few articles are found before 2011. It seems interest in cloud-based approaches in manufacturing technologies started to increase in 2011. There was a wave of papers published from 2018 to 2023 period as presented in Fig. 2(a). In Fig. 2(b), it is shown that most of the published documents are from China then United States and United Kingdom has second and third highest number of published documents respectively [77].

1.2 Impact of Cloud-based Manufacturing

High production efficiency, CMfg can streamline production and key operations in a company which can free up more time and money to invest in new products and marketing. Distributed Manufacturing, CMfg enables distributed manufacturing which will reduce costs and allow rapid prototyping of new products. Strong focus on customers, real-time data on critical operations will improve responsiveness to customer requirements and allows for quick changes in operations to meet changes in customer demand. Intensive Collaboration, CMfg tools and technologies are developed specifically to drive collaboration. Optimized for SME, CMfg's pay-as-you-go business model is especially useful for SME enterprises that lack resources to invest in the latest manufacturing technologies to improve operations. Advantages of cloud-based manufacturing on SME are shown in Table 1.

The IMD [86] ranked countries' capability to adopt digital technologies that are essential for digital transformation in government business models, practices and society. The rankings are presented in Table 2.

For manufacturing enterprises in all countries with a strong global value chain, the benefits of new technologies such as CMfg is understandable. Market occasions for customized products enhanced with digital services that attracts new customers. As CMfg services cannot be provided by manufacturers that has traditional IT services and traditional processes, new technology integration becomes critically important [85, 87–90]. In their study, Liu et al. [91] introduced a hybrid group recommendation technique (HGRA) as a potential alternative to conventional methods. In order to tackle the issue of group recommendation in CMfg systems, the researchers initially divide the entire process into three consecutive components. These components consist of an improved user similarity model, the K-medoids clustering technique, and a weighted rank aggregation model. The experimental findings indicate that the utilization of HGRA has the potential to significantly enhance the quality of group suggestions. Additionally, it has been seen that there is a certain degree of improvement in the level of group satisfaction [91]. In addition, Deloitte [92] intended to direct manufacturing enterprises toward cloud-based manufacturing integration by providing a cloud strategy, cloud-based manufacturing principles. Cloud-based manufacturing strategy should be between IT of enterprise and management of enterprise to accomplish cloud-based-service portfolio that are associated each other to enhance manufacturing with a hybrid cloud system.

Literature search showed increasing sophistication and higher technical content in relatively recent published papers. Also, there is more interest in taking advanced digital technologies from other industries and using them in CMfg. As a novel manufacturing paradigm, cloud-based manufacturing uses big data, internet of things (IoT), and cloud computing technologies to integrate different manufacturing resources and provide on-demand manufacturing services. This approach can revolutionize manufacturing method by increasing efficiency, scalability, and flexibility. Nonetheless, corporations have found the transition to digital transformation to be very difficult for a number of reasons. A comprehensive grasp of Industry 4.0's enabling technologies and design concepts is required for the development of an implementation strategy. Hence, this paper aims to evaluate and investigated cloud-based manufacturing technologies architectures, software frameworks, different approaches, virtualization, digital transformation, simulation platform, benefits, and challenges which can give an overview of cloud-based manufacturing technologies.

2 Cloud-based Manufacturing Implementation Technologies

From traditional view, manufacturing is a highly-centralized process, with huge production lines and factories applied for specific product lines or products. However, of the development of new technologies such as IoT and cloud computing has made it possible to decentralize manufacturing and move it closer to consumption point [16, 93–96]. This made manufacturers more sensitive in responding to the variations of

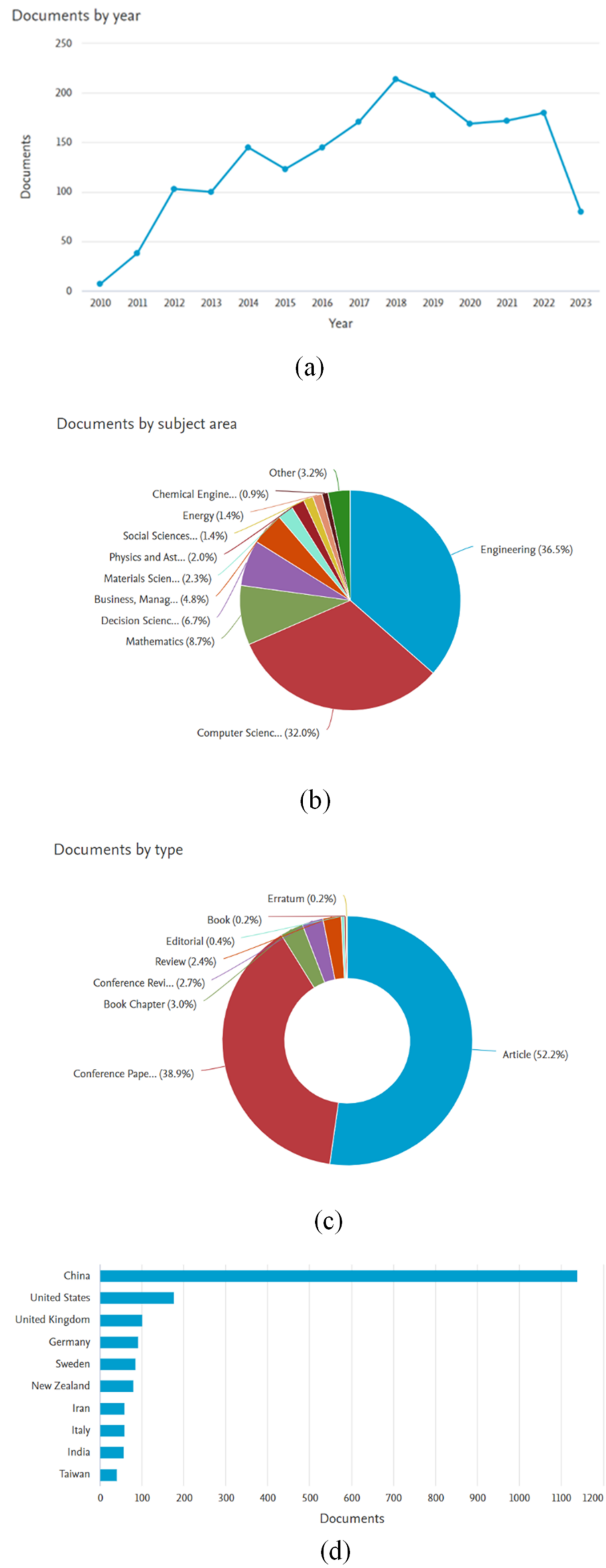


Fig. 2 Statistics from Scopus database (Search keywords: ("Cloud Manufacturing"), Date: 11 July 2023): **a** Published documents per year; **b** Published documents by subject area; **c** Published documents by type; **d** Published documents by country/territory [77].

Table 1 Impact of cloud-based manufacturing

Impact	Remarks	Refs
High Production Efficiency	• Accelerated new product launch • Unify all Mfg locations worldwide • Cloud integration expertise	[53]
Distributed Manufacturing	• Cost reduction • Improved resource sharing • Rapid prototyping	[44]
Strong Focus on Customers	• Customers select web services • Customers can ramp up/down quickly	[78]
Intensive Collaboration	• Improved organization skills thru distributed collaboration • Collaboration mechanisms and tools already in place via cloud	[79]
Optimized for SME	• Reasonable size of cloud facilities • Affordable for SME	[80]
Efficient Resource Sharing	• Dynamic sharing of resources in manufacturing	[81]
Enhanced Performance	• Cloud utilized to guide continuous improvement in manufacturing	[82]
Increased System Availability	• Provide flexible and advanced manufacturing	[83]
Improved Virtual Platforms	• Utilization of digital twin technology in manufacturing	[84]
Service Quality	• Personalized services covering the entire life cycles of pro- ducts	[85]

Table 2 Country rankings to adopt and explore digital technologies toward transformation [86]

	Knowledge			Technology			Future Readiness		
	Talent	Training & education	Scientific concentration	Regulatory framework	Capital	Technological framework	Adaptive attitudes	Business agility	IT integration
Australia	7	29	13	7	19	17	7	35	11
Austria	12	8	14	25	34	31	29	25	15
Canada	13	7	2	17	10	27	17	16	13
China	19	37	9	20	32	32	24	1	41
Denmark	6	6	17	10	27	8	1	10	1
France	24	28	12	8	18	22	36	39	19
Germany	25	14	4	27	17	40	16	11	17
Greece	53	60	34	52	52	49	41	60	50
Hungary	47	43	45	35	46	19	62	53	37
India	38	47	28	55	3	62	54	29	56
Italy	44	57	23	44	53	46	35	31	34
Netherlands	3	36	19	6	5	10	9	7	3
New Zealand	11	34	26	11	15	25	13	32	10
Norway	16	17	21	3	7	6	5	23	9
Russia	45	9	18	40	57	39	40	54	43
Spain	29	40	20	34	33	23	25	38	25
Sweden	8	2	3	5	4	12	8	13	12
Switzerland	2	15	7	14	16	9	11	14	7
Thailand	40	50	35	33	21	29	58	30	51
Turkey	52	63	43	38	56	50	38	44	48
UAE	5	41	56	1	2	5	20	4	8
United Kingdom	17	23	8	18	22	18	10	26	14
USA	14	25	1	19	1	11	2	2	5

market and customer demands, reduced costs and increased efficiency.

Cloud-based manufacturing has some main categories, but there might also be other specific services and applications which fall under various categories. This section reviews some research works performed on cloud platforms, architectures, manufacturing, and software by several researchers. The illustrative and descriptive examples of representative works are provided in Figs. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, and 16 and discussed in more detail below.

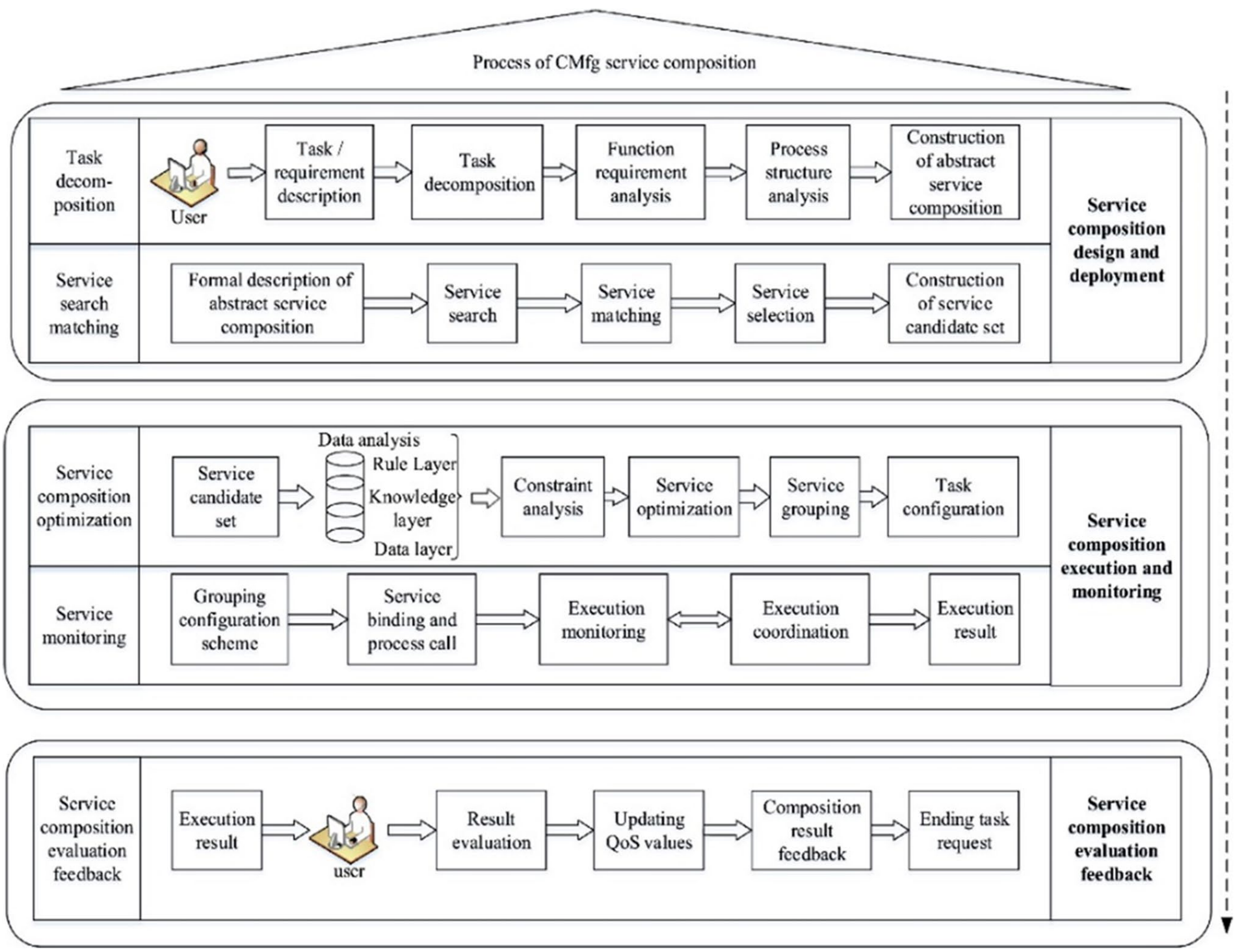


Fig. 3 CMfg service composition procedure [110]

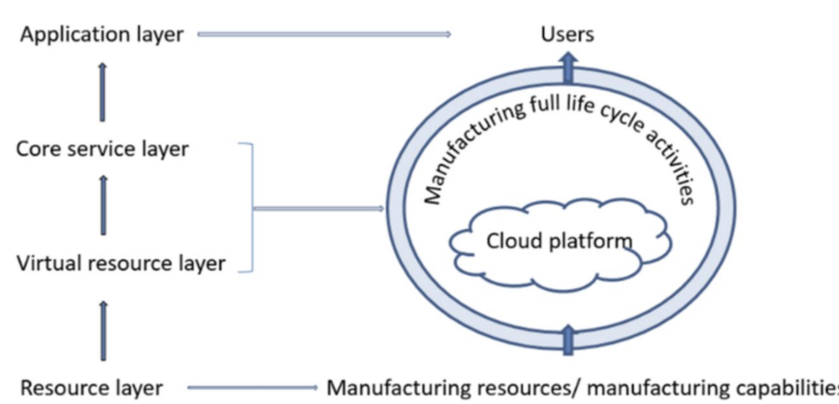


Fig. 4 Basic architecture components of the CMfg [90]

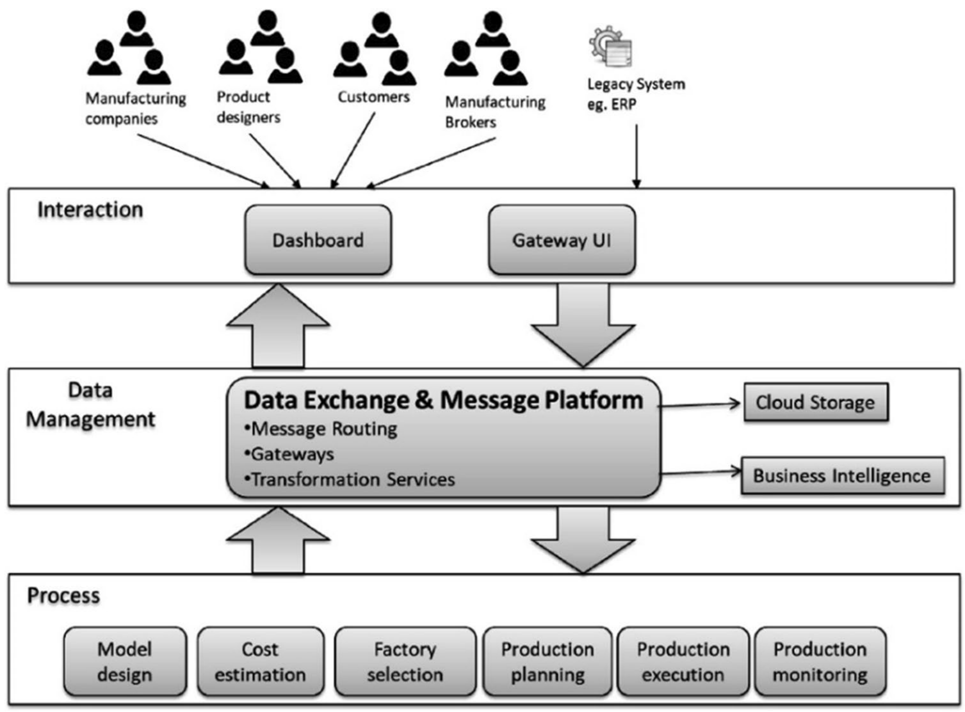


Fig. 5 The architecture components of Cloud-Ecosystem [5]

In recent years, many researchers worked in different areas of cloud-based manufacturing technology [82, 97–103] [104–109]. Yuan et al. [110] proposed a cloud-based manufacturing service composition model and approach. The composition of CMfg services is a vital component of the overall functioning of the CMfg platform and an efficient method for realizing on-demand resource allocation and consumption. The composition procedure is dependent on the mode of the task. Figure 3 depicts the CMfg service composition procedure. In addition, 100 out of 512 schemes were chosen at random to determine the objective function *f* and validate the efficacy of the suggested composition optimization approach based on the gray relational analysis method. In another study, Lim et al. [90] reviewed and evaluated the cloud-based manufacturing theory, supporting technologies, and application analysis. Manufacturing resources and manufacturing capabilities, cloud platform, manufacturing life cycle activities, and the users are basic components of CMfg architecture that enable the complete transaction operation of CMfg. Figure 4 depicts the connections between the basic

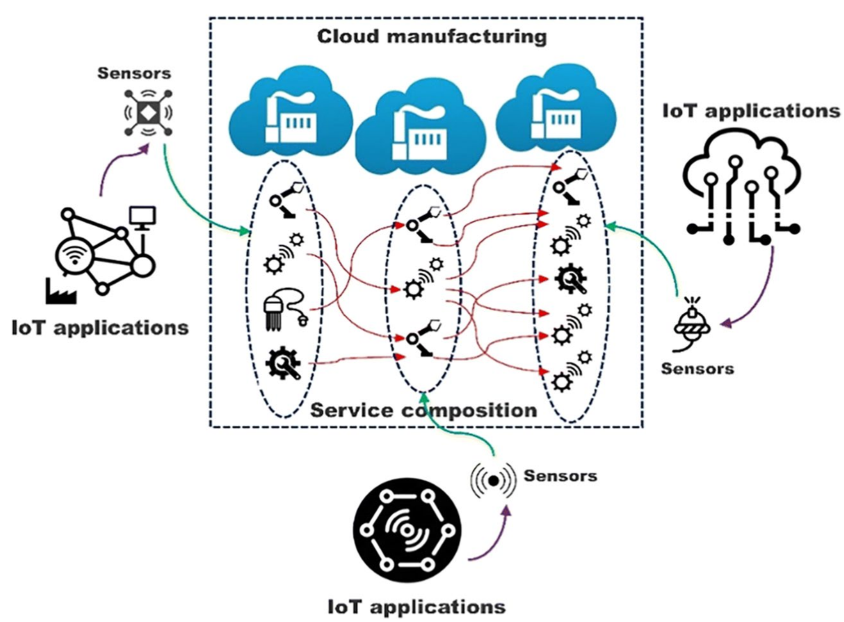


Fig. 6 The composition of cloud-based manufacturing services in IoT applications [111]

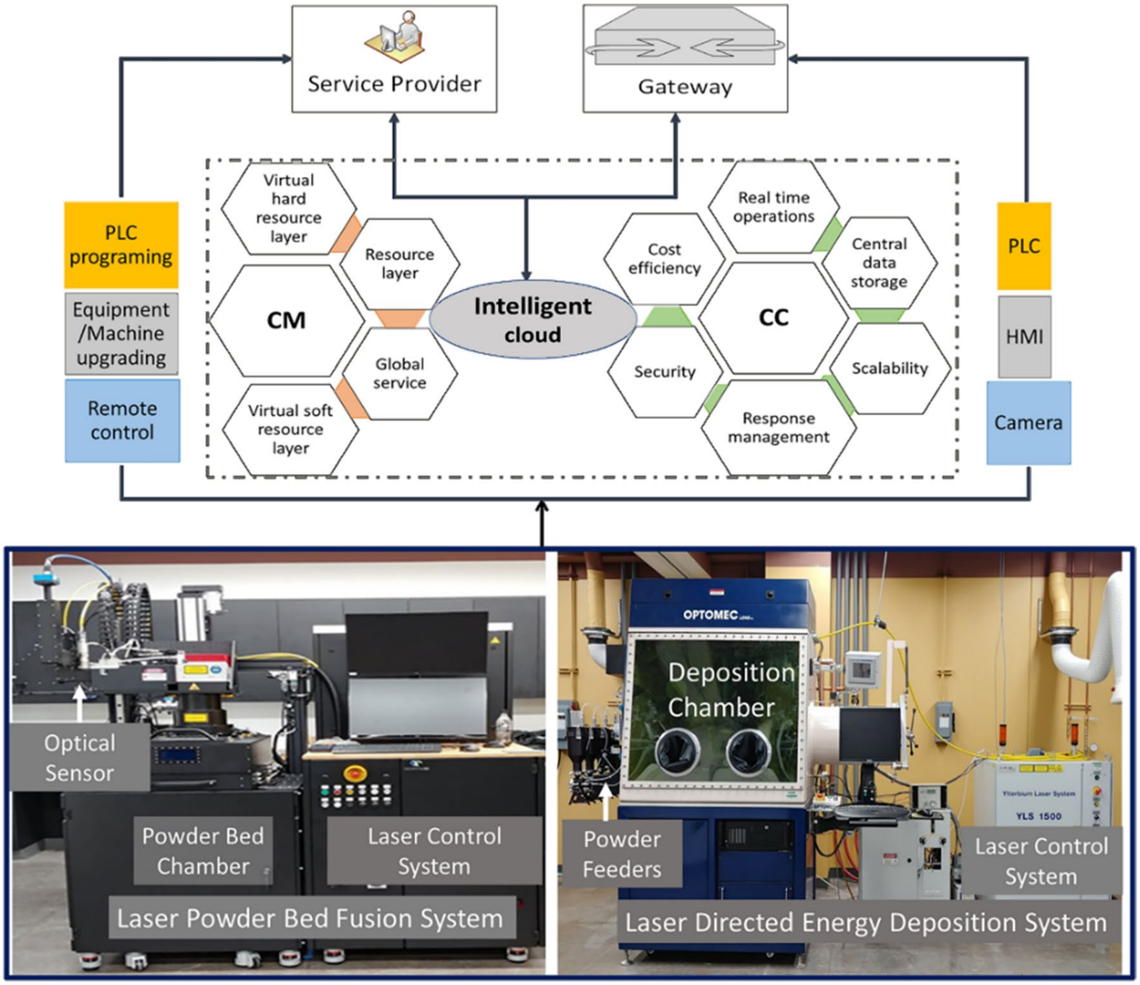
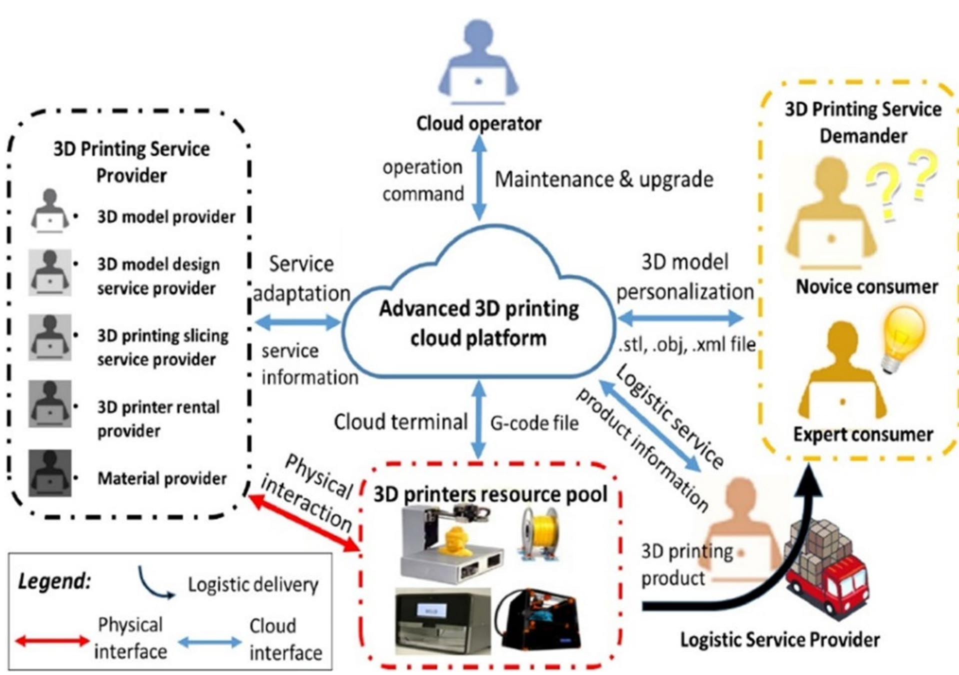


Fig. 7 AC integration with intelligent cloud [115]

Fig. 8 Advanced 3D printing cloud model [116]



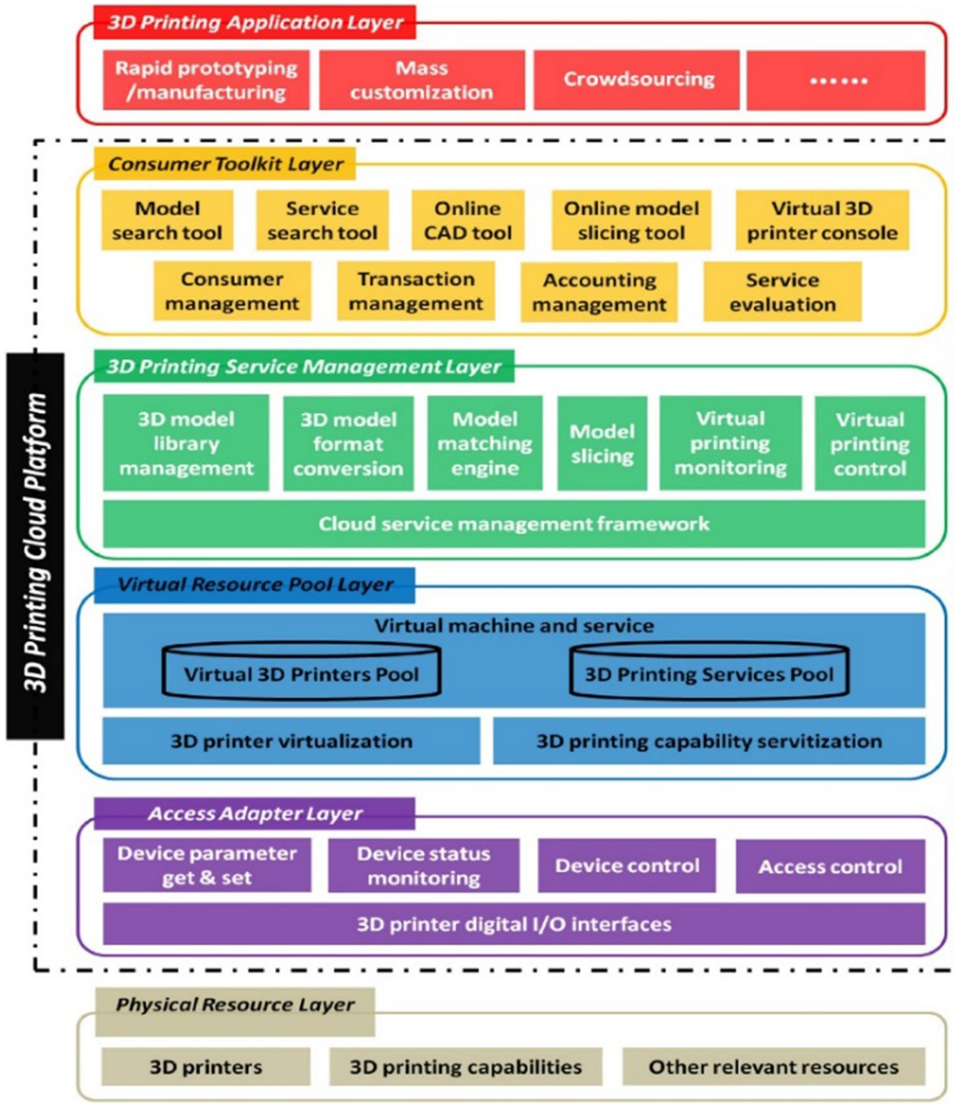


Fig. 9 Architecture of 3D printing cloud platform [116]

components of CMfg architecture and the same layers (the resource layer, the resource virtualization layer, the core service layer, and the application layer).

Helo et al. [5] conducted more research on cloud-based manufacturing ecosystem analysis and design. Depending on the design of the supply chain, they identified three distinct portal types for cloud-based approaches in manufacturing ecosystems. Figure 5 explains the architecture described in their research. Moreover, Fig. 6 depicts a conceptual model for cloud-based manufacturing service composition technique for IoT applications provided by Souri and Ghobaei [111]. Existing actuators, sensors, and RFID tags are utilized to collect aggregated data, which is then transmitted to cloud-based production. In another study, Lin et al. [112] examined the efficient container virtualization-based digital twin (DT) simulation of smart industrial systems. The vast need for on-demand DT-based simulation, a particularly valuable and sustainable tool for assisting with decision-making, is a direct result of the immense potential of DT in supporting smart industrial systems. Thus, a technique of container virtualization-based simulation as a service (CVSimaaS) was proposed in their research. Furthermore, in the study conducted by Wang et al. [113], the obvious characteristics of multi-user-oriented manufacturing service scheduling (MSS) were investigated by contrasting them with the multi-task-oriented MSS problem. Following this, a multi-user-oriented MSS mathematical model was developed in order to accommodate the needs of multiple users in a practical setting. To enhance the quality of solutions, an improved NSGA-II (INSGA-II) was created by combining the k-means algorithm and local search method. Besides, Tan et al. [114] suggested a novel service level agreement approach by combining blockchain and Smart Contract (SLABSC). The solution suggested in their work realizes the complete functionality of SLABSC, promotes data security and can be used to oversee cloud

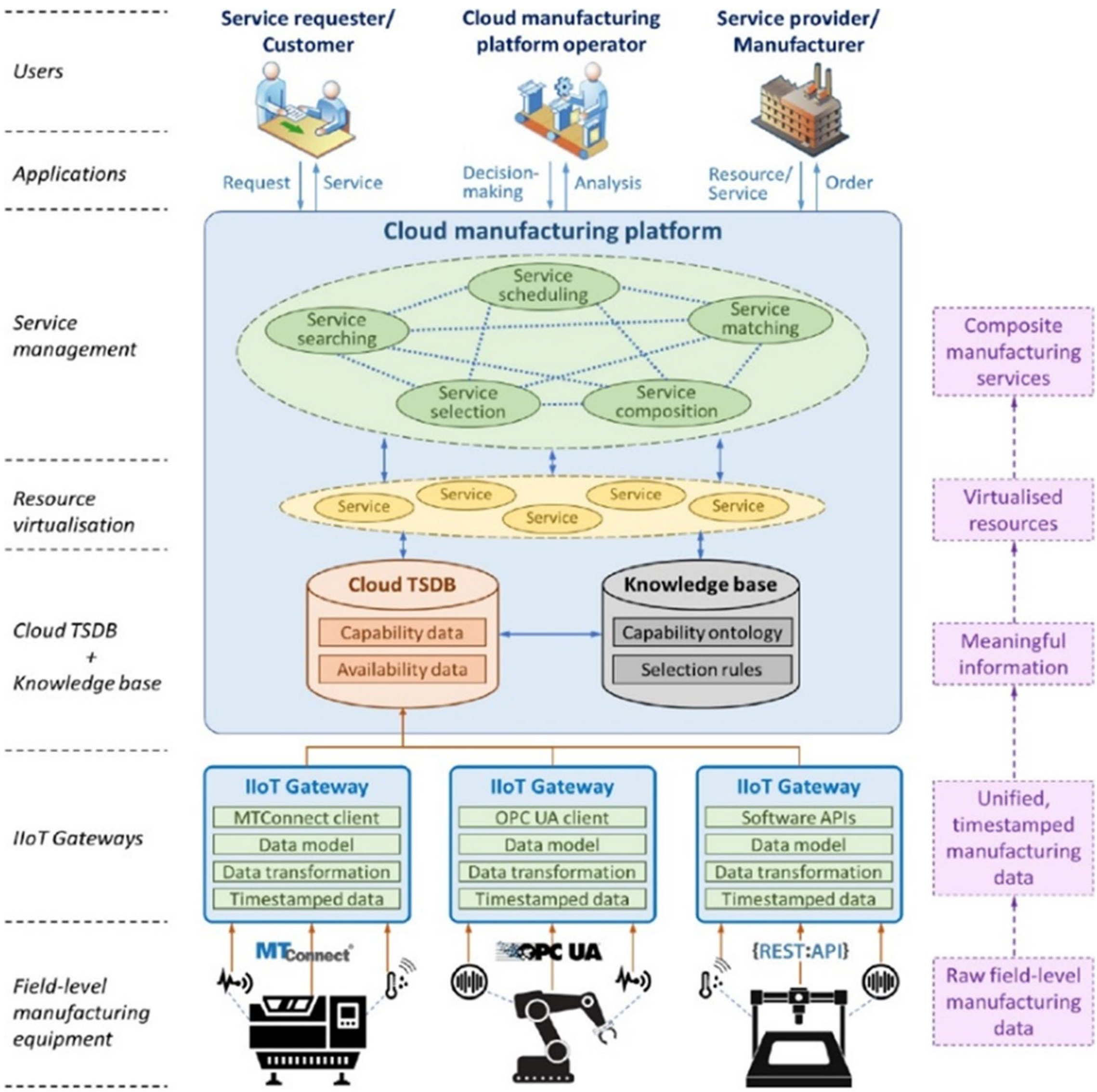


Fig. 10 System architecture of IIoT-supported cloud-based manufacturing [117]

service providers (CSP) in order to improve service delivery. Experiments were undertaken to determine if the combination consensus algorithm has superior performance and is more secure than the Delegated Proof of Stake (DPoS) method by comparing the DPoS algorithm to the new algorithm combining DPoS and the practical byzantine fault tolerance (PBFT). Their first experiment consisted of timing how long it takes for a consensus to be reached regarding the DPOS algorithm and the combination algorithm. Their second experiment consisted of simulating a bifurcation attack in order to research the safety of the DPOS and combination algorithm. Additionally, their third experiment consisted of simulating 50 nodes in the blockchain. Their experiment findings demonstrate that the proposed model's performance is valid and efficient.

Haghnegahdar et al. [115] proposed the integration of AM with the intelligent cloud by depicting in graphic form. Sustainability and efficiency of the manufacturing across the production cycle could be improved by using CM which is an intelligent and knowledge-based platform. Figure 7 illustrates the proposed visual of an integrated AM with the intelligent cloud. Also, Cui et al. [116] investigated AM in cloud- based manufacturing environment. In their study, two common AM models, the basic and advanced AM cloud models are presented and compared with each other. The advanced cloud model for AM depicted in Fig. 8. Moreover, Fig. 9 shows the architectural design of an AM cloud platform, which is mainly planned to support the advanced AM cloud model suggested in this study. Furthermore, Liu et al. [117] utilized the emerging Industrial Internet of

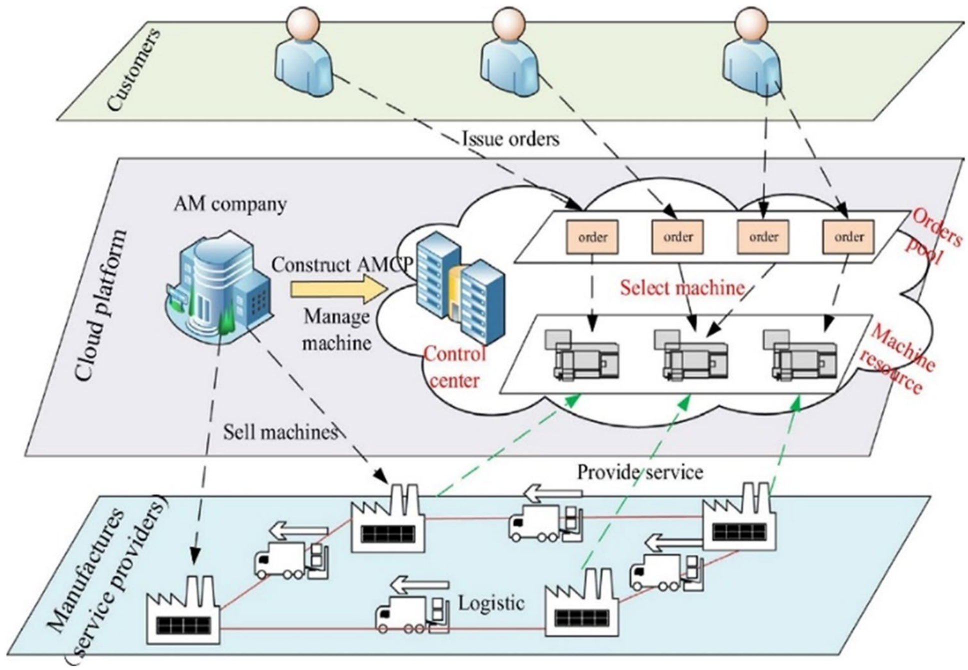


Fig. 11 The structure of AMCP [119]

Things (IIoT) technologies in a cloud-based manufacturing system. A service-oriented plug-and-play (PnP) IIoT gateway explanation based on a general cloud-based manufacturing system architecture supported by IIoT is suggested. In the context of cloud-based manufacturing, Fig. 10 depicts how Industrial Internet of Things (IIoT) technologies may be utilized to build the connectivity between field-level manufacturing equipment and the cloud-based manufacturing platform. Moreover, the additive manufacturing cloud platform (AMCP) is a typical application case for CMfg online scheduling [118]. Hence, Wu et al. [119] proposed a more realistic model including online scheduling as opposed to offline scheduling, in which tasks come at random. In accordance with the scenario, a mixed integer linear programming model of multiple 3D printing tasks based on the AMCP is developed with the objective of lowering the average cost per volume of material. Their study was based on a Chinese AM company specializing in the manufacture of 3D printing machines. Their simulation demonstrated that the suggested method may successfully tackle the online scheduling problem for 3D printing. Figure 11 illustrates the structure of the proposed AMCP.

Wu et al. [120] presented a combination of supplier assignment and third-party logistics to develop centralized scheduling on the cloud-based manufacturing platform as one of the most recent research concentrating on logistics CM scheduling issues. Meanwhile, Salmasnia and Kiapasha [121] investigated the Integration of sub-task scheduling and logistics in CM systems with setup time and varying task arrival timings. Their findings demonstrated the significance of factoring in job arrival time, logistics time/cost, and setup time/cost for more practical solutions. Due to the geographically dispersed nature of the firms participating in the cloud-based manufacturing system, the time/cost of traveling among the enterprises must be considered. The Scheduling process structure in cloud-based manufacturing is depicted in Fig. 12. Moreover, manufacturing services monitoring is useful in ensuring that the cloud-based manufacturing service system (CMSS) in the uncertain cloud environment operates normally. Hence, Zhang et al. [122] proposed a method for assessing the functional significance of manufacturing services based on a complex network and evidentiary reasoning (ER) rule. Prioritizing the distribution of monitoring resources to essential services is a viable strategy. The experimental findings of vertical elevator design services demonstrate that their proposed method is better than those now in use and is able to successfully identify the essential manufacturing services. Figure 13 depicts the domain-specific customization of the CMSS.

2.1 Cloud-based Manufacturing Implementation Architectures

Cloud-based manufacturing relies on a distributed architecture, where internet is used to connect different manufacturing resources which can be controlled and accessed remotely. These resources include tools, machines, other equipment, and human resources such as technicians and engineers. Cloud-based manufacturing architecture also contains a software layer and applications to make it possible to manage and coordinate these resources.

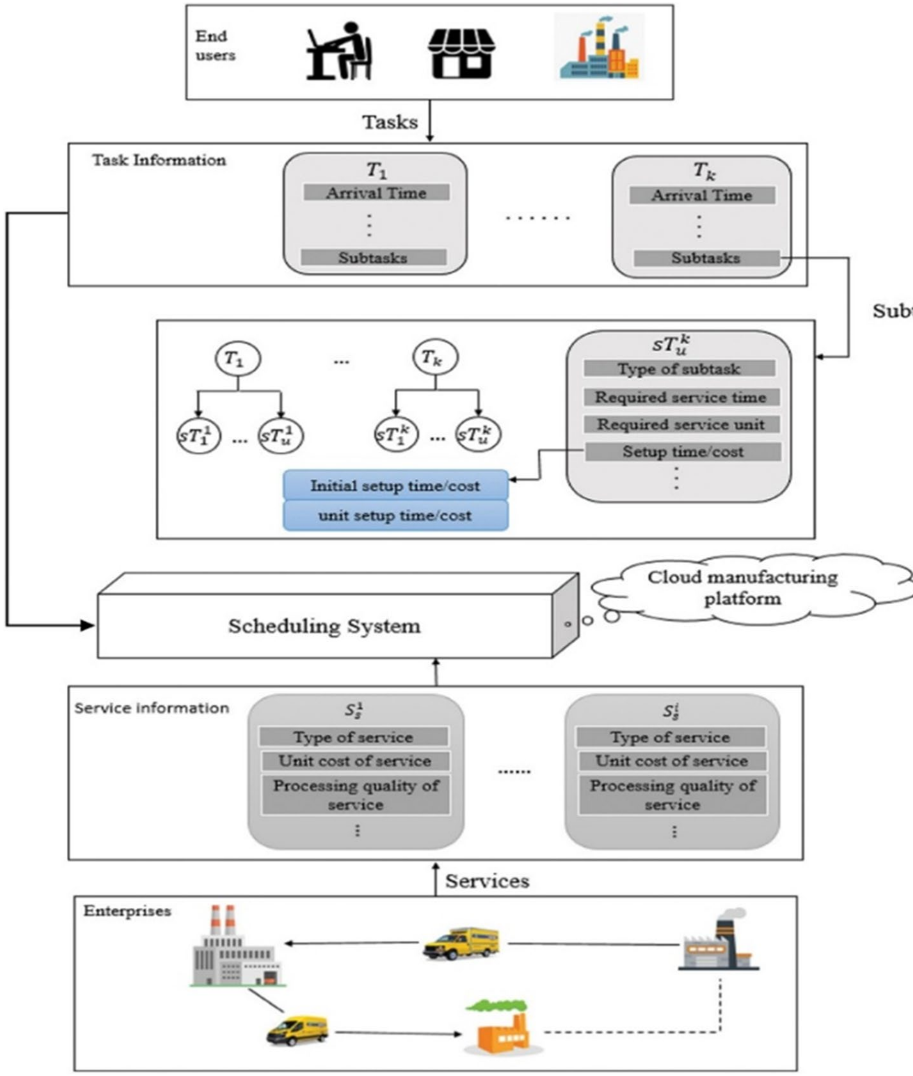


Fig. 12 Scheduling process framework in cloud-based manufacturing [121]

Using this architecture, manufacturers can access and use the resources they require in real-time and across various locations to improve their scalability, flexibility, and efficiency. However, security is still a key aspect of this architecture, since the systems and data should be protected from security breaches.

Multi-layer system architectures and modular solutions are studied by cloud researchers and those studies are summarized in Table 3 to highlight that most researchers recommend multi-layer system architectures and modular solutions for building CMfg platforms.

2.2 Implementation Software Frameworks

Typical manufacturing business process management software currently in use are not optimized for cloud-based applications. Therefore, there is a need to define and develop software frameworks optimized for CMfg so that production volume can be quickly scaled up or ramped down depending on customer demand. Existing software frameworks for cloud-based manufacturing are listed in Table 4.

2.3 Infrastructure

Traditional data exchange solutions on factory floors are not built for CMfg application. The current Computer Aided Design (CAD) and Computer Aided Manufacturing (CAM) reside on local manufacturing site. There is a need for a secure cloud infrastructure to simultaneously enable CMfg and also protect the client's design and manufacturing trade secrets that are stored on CAD/CAM tools today. Infrastructure services for cloud-based manufacturing are presented in Table 5.

CMfg software provides manufacturers full control over sales order management, material requirement planning, inventory control, production planning, organized workflows and business intelligence. These software solutions are accessible anywhere and with any device connected

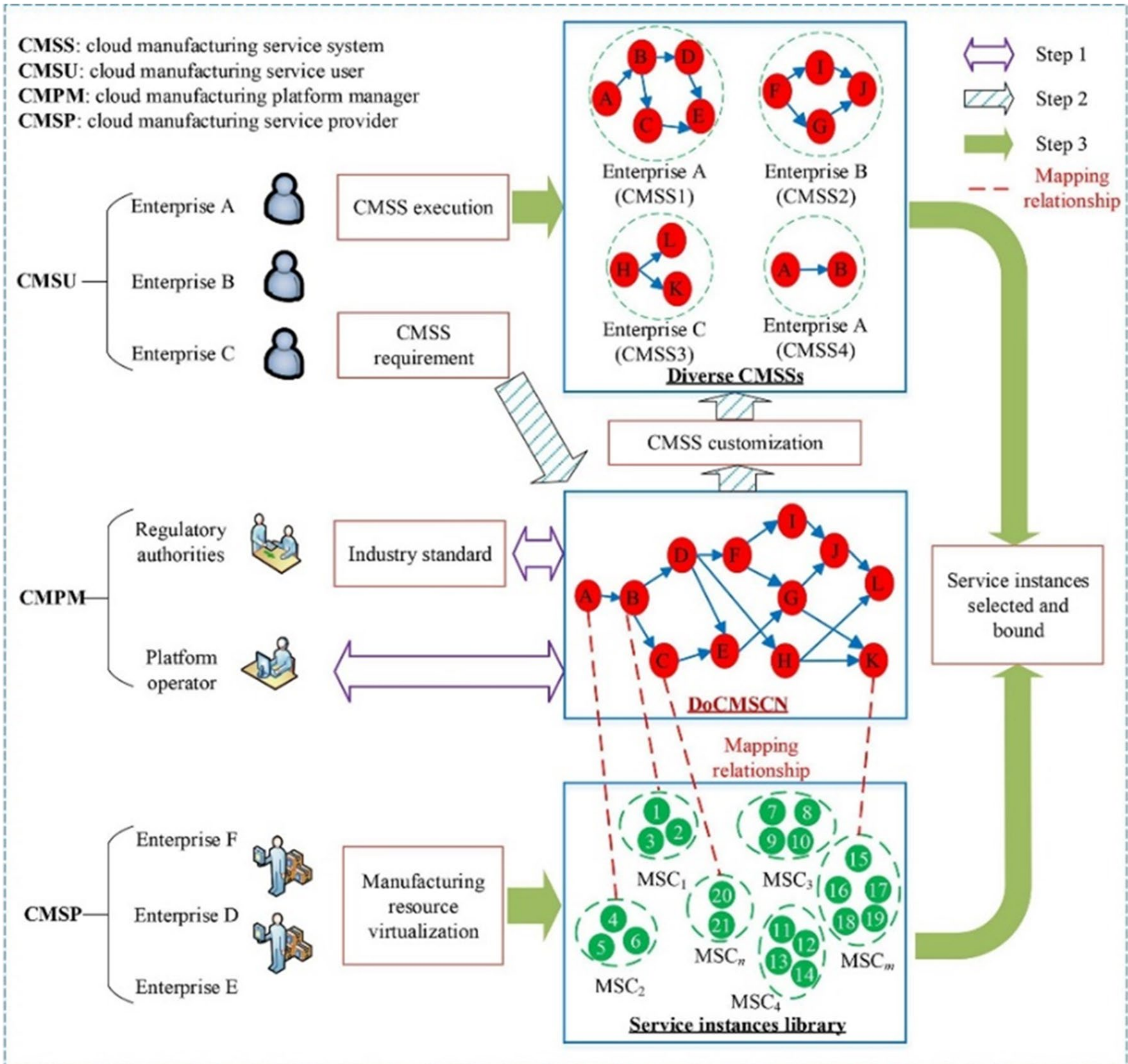


Fig. 13 Domain-oriented customization of CMSS [122]

to internet. Cloud-based software solutions are listed in Table 6.

2.4 Virtualization

The ability to integrate the physical and virtual worlds is one of the first challenges encountered when implementing a CMfg system. The virtualization of resources is a critical component of any cloud-based system [36]. In a manufacturing environment, virtualization translates physical assets into cloud-based services to be offered to customers. For CMfg to achieve its future potential, highly efficient virtualization technologies will be required to map the physical assets into virtual resources.

The term "Cyber–Physical Systems" (CPS) refers to a group of essential technologies whose primary function is to manage interconnected systems in terms of both their physical assets and their computing capabilities [146, 147]. Recent interest in CPS has increased due to its tremendous potential for integrating cyber technology into physical processes for intelligent systems of the next generation [148–150]. Digital Twins (DT) are a concept that has been developed based on the capability of the CPS to virtualize the various components of a manufacturing system. DTs are a new technology that has developed in order to virtualize various elements of a factory's physical world, creating a digital copy of the physical element. Over the years, DTs have gained increasing significance and attracted the attention of numerous scholars [56].

By combining sensor data acquired from the physical world with virtual or simulation-based models, virtualization permits the replication of a DT of the entire value chain [151]. For instance the smart factory's virtual twin would allow process engineers and designers to improve current

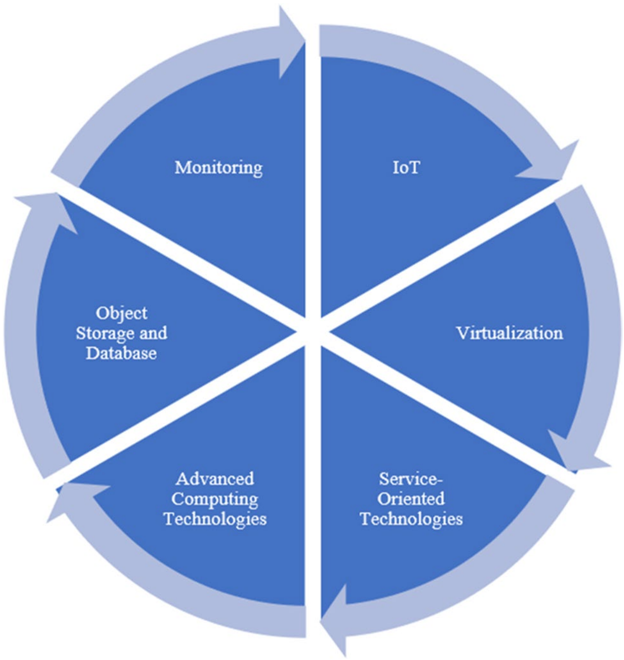


Fig. 14 Cloud computing concept, adapted from [165, 166]

processes or improve the functionality of production lines without affecting the physical processes in the smart factory [152]. On the other hand, a smart product's DT would give manufacturers a full digital footprint of their new or current products for the entirety of their lifecycle. Not only would this make it possible to have a better grasp of how the product functions once it has been consumed, but it would also make it possible for businesses to virtually analyze the system that is used to manufacture the product [153, 154]. Virtualization has a significant dependence on the availability of real-time capabilities. Real-time capability is heavily supported by internet of everything, which is why Industry 4.0 is centered on cumulative, real-time, real-world data across an array of dimensions such as smart warehouses, smart factories, smart products, and smart business partners [146, 155, 156]. The term "real-time capability" refers to more than just the act of gathering data; it also encompasses real-time data processing, real-time decision-making in light of newly discovered information [157], and even real-time detection of cyber-security attacks [158]. Cecil et al. [159] described the functional parts of IoT-based CPS. They came up with the phrase IoT-based CPS to refer to the development of collaborative systems that include both cyber and physical components and make use of IoT-based principles in order to share data, knowledge, and information. Such a framework for printed circuit board assembly has been created, including the construction of digital mockup environments using the Unity 3D engine and other software applications. Users can explore and interact with the Vive™ Virtual Reality system in Unity-based environments. The development

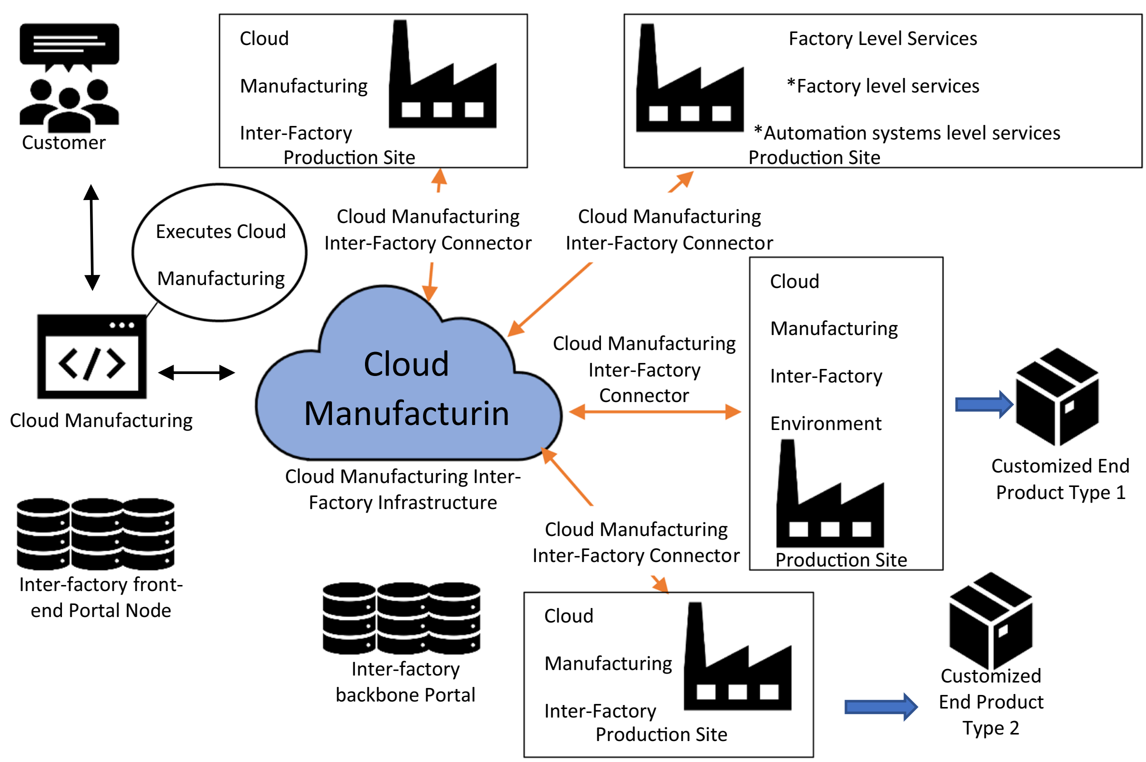


Fig. 15 Cloud-based manufacturing infrastructure ecosystem, adopted from [168]

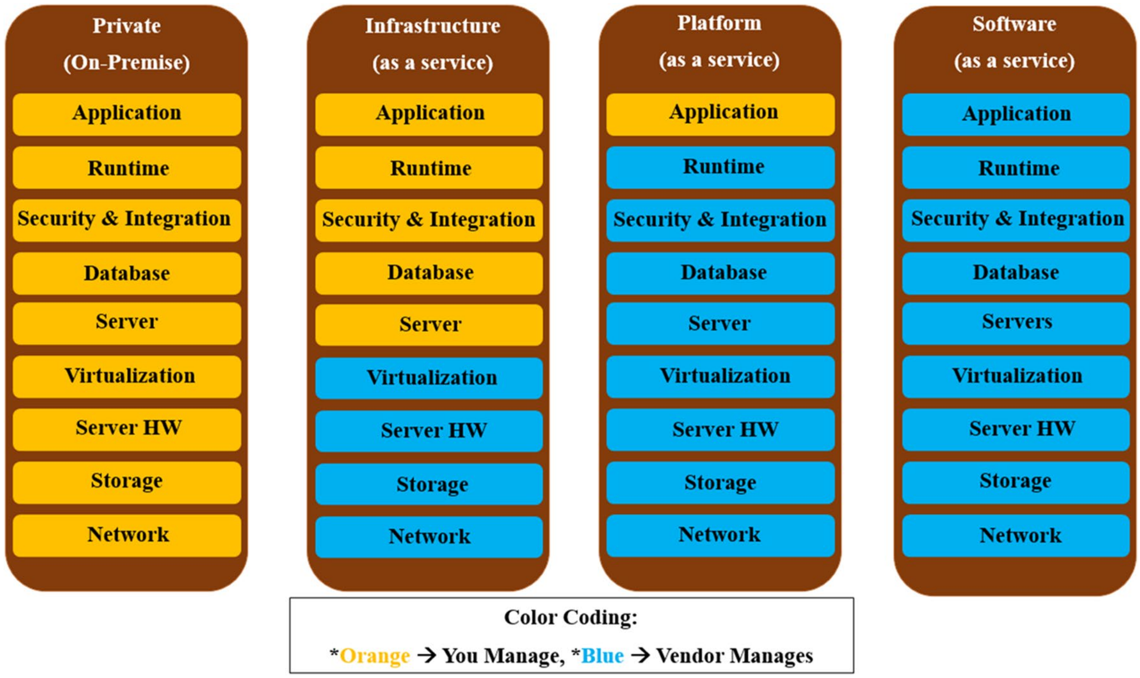


Fig. 16 Infrastructure outsourcing to cloud based vendors, adapted from [201]

Table 3 Implementation architectures for cloud-based manufacturing

Type	Remarks	Refs
CMfg	•Seven-Phase Implementation Proposal for CMfg • Two CMfg Service Platforms: Private & Public	[123]
MES	• Advanced Cloud & Ubiquitous Manufacturing • Open Architecture for Advanced MES System	[124]
RIA	• Rich Internet Applications (RIA) Cloudlets • Support for Emergent Interactive Web 3.0	[125]
CMfg	• Dynamically Generated CMfg System • Product Configurator for CMfg • Prototype Implementation of CMfg	[126]
MFG	• Distributed Mfg Collaboration • ISO 10303 (STEP) Standard • XMLAYMOD Platform for Distributed CMfg	[127]
SOM	• 3 Core Components for Constructing CMfg System • SOM Resources, Cloud Services, Manufacturing Cloud • Six-Layer Architecture	[128]
PSA	• Emerging Product-Service Architecture (PSA) • Grid of Services in Parallel to Main Mfg Process	[129]
PCS	• Impact of CMfg on Product Customization • Product Configuration System (PCS) Architecture	[130]
SOA	• Collaborative e-Manufacturing • System-Oriented Architecture (SOA) • Cloud Services for Mfg-as-a-Service (MaaS)	[131]
Architecture	• Software-Defined CMfg for I4.0 • CMfg Agility, Flexibility and Adaptability	[37]
Architecture	• The model is related to product platform that can draw on high-precision equipment, senior experts, design knowledge • Improve the utilization of resources	[83]
Architecture	• Configurable digital assets	[84]

Table 4 Software frameworks for cloud-based manufacturing

Type	Remarks	Refs
Framework	• Distributed Software Resource Sharing Platform • Focused on Small & Medium Size Companies	[132]
SCOS	• Service Composition Optimal Selection (SCOS) • CMfg Intelligent Algorithm Called FC-PACO-RM	[133]
MOM	• Rise in CMfg Software Adoption Rates • Manufacturing Operations Management (MOM)	[134]
CMGF	• Requirements for CMfg Process Enactment • Concept for CMfg Software Framework • Manufacturing Data-as-a-Service	[135]
DTDF	• Dynamic Tolerance Design Framework • Focus on Complex Customized Products	[136]
Framework	• Semantic Information Services Framework •Ontology Approach: Integrate Life Cycle Information	[137]
Framework	• Hypernetwork-Based Solution Framework • Dynamic Supply–Demand Matching	[138]
CMfg	• Interoperability as Key Enabler of CMfg • Framework for Heterogeneous Manufacturing System	[139]
Framework	• Advanced Cognitive Decision Making • Framework for Smart Monitoring of Machining	[140]
Framework	• Contemporary Cloud Manufacturing-as-a-Service (CMaaS)	[84]
Framework	• Connection of hierarchical gateways to manage manufacturing	[82]

Table 5 Infrastructure services for cloud-based manufacturing

Type	Remarks	Refs
Infrastructure	• Manufacturing as-a-Service Technologies • Flexible Service Composition for Production	[27]
Infrastructure	• Service-Oriented Interoperable Cloud System • Customer Cloud User & Enterprise Cloud User	[34]
MCAAS	• Machine Control Infrastructure • Machine Control-as-a- Service (MCaaS)	[141]
IT	• IT Infrastructure for Manufacturing IT • Product Tracking, Process Monitoring & Control	[142]
ERP	• Cloud ERP Platform for Enterprise Customers • Web-based ERP Service Customization Process	[73]
CAD	• Secure Infrastructure for Cloud-based Mfg • Feature-based Data Exchange for CAD Models	[143]
Services	• Flexible Service Delivery Modes • PaaS • IaaS • SaaS	[144]
Planning	• Distributed Process Planning Services • Infrastructure with Industrial Applications	[80]
CPS	• Contemporary CMaaS • Web browser-based client middleware • Client interaction with digital twin	[84]
Infrastructure	• Optimal allocation of resources	[110]

of low-cost digital prototyping is an essential step toward the acceptance of cyber-physical practices [159]. In another study, Cecil et al. [160] discussed the design and implementation of an IoT-based CPS in the context of I 4.0 for the field of micro device assembly. The adoption of the global environment for network innovation (GENI) next-generation networking principles, which are used to support the collaborative virtual enterprise (VE)-based assembly analysis from dispersed locations, was a key component of their approach. Multiple partners are able to provide assembly plans based on their own proprietary methods or algorithms, which is one of the benefits of choosing a VE-based approach. The CPS manager is able to compare different sequences based on the least amount of time required for assembly in addition to the limits imposed by the process [160].

2.5 Digital Transformation

The transformation of organizations by digital means is no longer only an emerging trend; rather, it is now an absolute must for companies that want to expand and keep up with the competition in their respective markets [30]. Technologies Several emerging technologies are viewed by researchers as being the catalysts to drive digital transformation and accelerate the adoption of CMfg. These technologies include IoT, Industrial IoT (IIoT), RFID, AI, Big Data, Cybersecurity, Advanced Materials, Predictive Analytics, 3D Printing, Robotics & Collaborative Robots, next generation Web 3.0

Table 6 Software solutions that support cloud-based manufacturing infrastructures [145]

Software	Client OS	Cloud Infrastructure modules	Remark
Plex Cloud ERP	web	• Decentralization • Linked plants • Real-time information	Assists lowering costs while scaling flawlessly
Katana MRP	web	• Production • Inventory control • Organized workflows • e-commerce integration	Production management Raw material inventory control Organizes workflows
MRPEasy	web	• Production scheduling • Inventory control • Sales	A cloud-based software for small manufacturers
Acumatica ERP	web windows	• Financial management • Customer management • Manufacturing • Order management	A cloud ERP system for small and medium size markets
Odoo	cloud on-premises	• Business intelligence • E-commerce • Enterprise social network • HR operation management	A software used for small enterprises to large enterprises
NetSuite ERP	web	• Departmental finance • Operations • Sales & service	A cloud-based platform that provides a software-as-a-service (SaaS) service
OptiProERP	cloud on-premises	• Scheduling • Workbench • MRP • Inventory Management • MPS • Shop Floor Execution	ERP solution for small and medium size enterprises in discrete manufacturing & distribution
Sage 100	windows	• Finance • Business intelligence • Human resources • Customer relationship management (CRM) • eBusiness • Manufacturing and distribution	An innovative and flexible solution for developing enterprises to help increasing productivity
Rootstock Cloud ERP	Web	• Customer relationship management (CRM) • Order management • Inventory control • Purchase order tracking • Standard cost accounting	Software used for distribution, supply chain and manufacturing
Infor CloudSuite	Web windows	• Delivery order management • Planning and scheduling • Inventory control	A software that helps to accelerate production and meet customer demand in your business
SAP Business One	Windows	• Finance • Production • Project management • Supply chain management • Production process	Provides inclusive management capabilities for small and medium size companies
IQMS MES	Cloud On-Premises	• Production management • Quality management • Real-time tracking • Overall Equipment Efficiency (OEE)	A software that is a core component of the complete MES and ERP solutions and can be integrated with your existing ERP system to increase visibility and transparency in manufacturing operations
Epicor E10 ERP	Mac web Windows	• Entire business monitoring • Real-time tracking • Lean manufacturing • Enterprise performance management • Financial management	A global ERP solution that provides flexibility and agility to your business

Table 6 (continued)

Software	Client OS	Cloud Infrastructure modules	Remark
Bluestreak	Web	• Industrial additive manufacturing • Information visibility • Monitoring work in progress • Preventive maintenance • Delivery management • Quality management	A Service-Based solution integrated with MES and Quality Management System (QMS). Used in production floor
SYSPRO	Web windows	• Inventory management • Financial management • Planning and scheduling • Supply chain management • MES	An ERP solution considering complexity of businesses for manufacturers
xTuple	Mac Windows Linux	• Maintain inventory • Business management • Delivery management	xTuple is a management software used to grow business profitably
Fulcrum	Cloud Hosted	• Job scheduling and tracking • Production tracking • Quality control • Inventory management	Eestablished by Atlas Solutions for small and medium size enterprises to improve efficiency of your business
E2 Shop System	Windows Mac Web	• Scheduling • Order management • Contact management • Accounting	Provides effectively activity control and managing profitability
Global Shop Solutions ERP	Cloud on-premises	• Shop management • Scheduling • Inventory control • Accounting • Quality control	An ERP software provides the applications needed for quality and can be used from quote to cash
Dynamics 365 Business	Web	• Order management • Reporting • Project management • Inventory control	Provides financial management for small & medium size enterprises
Oracle Manufacturing Cloud	Web	• Supply Chain • Production • MES	Provides web services that allow integration with external systems such as development applications, producing execution systems, workplace devices, and mobile devices

[25, 161–164]. Cloud-based manufacturing is empowered by several technologies, (1) the traditional manufacturing process, (2) cloud computing, (3) Internet of Things, (4) service-oriented technologies, (5) advanced computing technologies and (6) virtualization [165, 166]. Also, concept of cloud computing presented in Fig. 14.

Besides, cloud-based manufacturing has differences and similarities compared to cloud computing. Cloud computing and cloud-based manufacturing are different from a service providing viewpoint [11]. Three service models are provided by CMfg; 1) Infrastructure as a Service (IaaS), 2) Platform as a Service (PaaS), and 3) Software as a Service (SaaS) [2, 89]. Computing resources are used as a resource in cloud computing, whereas In CMfg, critical manufacturing capabilities are encapsulated with resources and involved in the lifecycle of manufacturing to provide various services. In CMfg, manufacturing capabilities and resources utilized as services while in Cloud computing, services include computational software resources and capability services. CMfg services are more powerful compared to traditional services [133]. Basically, cloud computing emerges as one of the major enablers for the manufacturing industry as it can transform the business model and create intelligent networks that encourage effective collaboration within factors [97]. Moreover, various methods of using RFID carrying out on cloud-based manufacturing as a gradual transition is being made into I4.0 era [167]. Manufacturing infrastructure ecosystem is shown in Fig. 15.

Adam and Musah [169] proposed 4 phases for digital transformation of cloud computing for SME;

- The readiness of SMEs. Potential needs and system requirements
- The adoption of cloud computing in processes
- The use of cloud computing
- The impact of cloud computing

Table 7 Digital transformation technologies for cloud-based manufacturing

Type	Remarks	Refs
AI	• Artificial Intelligence Knowledge-based Planning • Hybrid Procedural and Knowledge-based Model	[170]
Predictive	• Principals of Predictive Manufacturing • Implementation by Coupled-Model Approach	[171]
Robotics	• Cloud Robotics Concepts & Technologies • Roadmap for Future Trends and Applications	[172]
AI	• Artificial Intelligence Applications • Reconfigurable SoMS Manufacturing Systems	[173]
IoT	• Intelligent Perception and Access • 5-layer IoT Structure for CMfg Resources	[61]
Web Service	• Appraisal of Web Service Composition Technology • Quality of Service (QoS) for User Requirements	[174]
3D Printing	• 3D Printing Services in CMfg • 3D Online Integration and 3D Model Library	[175]
AI	• Artificial Intelligence and Manufacturing • When Will Computers Become Self-aware?	[176]
RFID	• RFID-enabled Shop floor Logistics Big Data CMfg • RFID-Cuboid Model to Reconstruct Raw Data	[177]
Robotics	• Distributed Equipment Control in Cloud Domain • Robot Control-as-a-Service & Multi-layer Control	[178]
IoT	• Real-time Machine Status Monitoring • Captured data in use to enable production autonomously	[179]
IIoT	• Increase in IoT Solutions for Industrial Application • Security Important for Commercial Deployment	[180]
Digital Twin	• Increase in digital proliferation and improvement in virtualization	[84]
AI	• Big data driven services • Edge & cloud collaboration	[82]

Also, core technologies for cloud-based manufacturing toward digital transformation is presented in Table 7.

3 Simulation Platforms used in Cloud-based Manufacturing

Conceptual Simulation, conceptual modeling is used to compose various sub-system concepts to create a theoretical simulation of an entire cloud-based approaches in manufacturing system. Experimental Simulation, early phase physical construction of CMfg tools to demonstrate how the system can function. This can help to identify areas for continued development to improve the proposed system. Prototype Simulation, CMfg implementation prototype is built physically by using currently available cloud-based hardware and software components. Agent-Based Simulation, manufacturing agent-based simulation is the creation of theoretical models that simulate the actions and interactions of autonomous production components (i.e., agents) to determine modifying effects on the overall manufacturing system. Simulation models which applicable for cloud-based manufacturing are mentioned in Table 8.

4 Discussion

Research on cloud-based manufacturing has become diversified due to variety of research topics. CMfg has received attention from the inception of CMfg (Ex. concept, user interface, framework, resource-related issues, logistics, security, architecture, integration, interoperability, simulation, supply chain, process and energy consumption), Also CMfg has received attention from recently emerging topics (Ex. product, 3D printing and big data). Some authors, [1, 110, 189–195] give attention to service composition based models to validate their optimal selection scheme, thus lower operation and logistics costs in manufacturing systems. Similarly, Zhu et al. [196] studied pricing strategies for service providers and proved that the pricing strategies has significant effect on revenue generation for providers.

4.1 Benefits of Cloud-based Manufacturing

A main benefit of cloud-based manufacturing is on-demand manufacturing services. That is, manufacturers can easily and quickly scale down or up their production capabilities as required, without to the need for investing in expensive

Table 8 Typical simulation platforms for cloud-based manufacturing

Type	Type	Remarks	Refs
Conceptual Simulation	Model	• Network View Model • Function View Model • Running View Model	[181]
	WSDL	• Bilayer Manufacturing Resource Model • Web Service Description Language (WSDL) • Separate Platforms for Cloud End and CMfg End	[182]
	BOM	• Model for Product Bill of Material (BOM) • Portable Cloud Manufacturing Services • OASIS Topology and Orchestration Specification	[183]
	Evaluation Model	• Trust Evaluation Model for Resource Service Transactions • Third-Party Trust Evaluation Model Time Decay Factor	[184]
	ASDI	• Analysis Specification Design Implementation (ASDI) • ASDI-Onto Modeling Methodology: Mapping Users Providers	[185]
	Service Agent	• Cloud manufacturing simulation platform • Service agent integrates intelligence to the service in cloud manufacturing • Adapt itself to the environment	[186]
Prototype Simulation	CFMG	• Model for CMfg Task Ontology Construction • Task Sub-Ontology Matching Process • Prototype System in Cement Grinding Mill Assembling	[187]
Experimental Simulation	Machine Tool	• Model for Cloud-Based Machine Prognosis • Experimental Demonstration Using Machine Tool Data	[79]
	CMfg	• Model matching and service scheduling • A supply–demand matching hypernetwork of manufacturing	[64]
Agent-Based Simulation	CMfg	• Agent-Based Model to Simulate CMfg Ecosystem • Shorter Job Que Length & Lower Resource Idle Rate	[188]

facilities or equipment. In addition, cloud-based manufacturing can decrease cost by enabling manufacturers to share resources and eliminate the need for dedicated systems and facilities.

In addition, cloud-based manufacturing makes greater communication and collaboration among different departments and teams possible, improving product development and accelerating time-to-market. This allows manufacturers to access real-time analytics and data, for optimizing production processes and improving overall efficiency.

4.2 Challenges of Cloud-based Manufacturing

Despite cloud-based manufacturing potential benefits, several challenges exist that have to be addressed. These include data privacy and security, and the need for new regulations and standards for governing the application of cloud-based manufacturing. In addition, further research and development are required for improving the scalability and reliability of the cloud-based manufacturing technology. As mentioned above, a key concern is security, since manufacturers should ensure that their systems and data are protected from cyber-attacks. Furthermore, cloud-based manufacturing needs huge investment in technology and infrastructure, which can be considered as a barrier for lots of manufacturers, especially small and medium-sized enterprises (SMEs).

There are a variety of challenges for implementation of CMfg with respect to the proposed concepts, frameworks, models, etc. There is no general agreement on definition of what should be considered as a true challenge. A variety of challenges are reported depending on the researcher and type of CMfg or E-manufacturing system involved and how it compares to the known methodology of agile manufacturing. It is clear the industry is going through growing pains. The manufacturing implementation of cloud-based systems is continuing at faster pace as more firms develop cloud expertise. Based on this literature search, CMfg progress is very encouraging and adoption rate is growing fast.

CBDM Technical Communications, cloud-based design and manufacturing systems involves knowledge sharing among a great number of experts in a technical network to design and build various new products. CMfg system must facilitate efficient transfer of high volume of technical specifications and manufacturing data.

Web Services, one of the current CMfg challenges is the web composition of related web services based on their functional behaviors and non-functional behaviors. Web service must recognize and compose among dissimilar mixed systems.

Adapting to Changes, it is critical for any CMfg system to be able to provide fast responses against market changes

Table 9 Challenges of cloud-based manufacturing

Challenge	Remarks	Ref
Early Industry Phase	• Definitions & Implementations of Multi-tenant Virtualized Platforms • Complex Encapsulating of Integration, Collaboration, Changeability	[197]
CBDM Technical Communications	• What metrics to quantify collaboration • How to detect key actors in technical communities & network • SNA and HaaS implementation	[198]
Web Services	• Allocation of Web services among mixed dissimilar services • Difficult to recognize QoS for Web service composition	[174]
Adapting to Changes	• Deploy different cloud modes as requirements change • Hybrid cloud based on private cloud, community cloud, public cloud • Implementation of DaaS, DFM, etc	[199]
Cloud Security & Performance	• Secure data exchanges • Standardized input and output of data 14 • Availability of cloud knowledge base • PA analytics and closed-loop control	[188]
Dynamic Cloud Manufacturing Scheduling (DCMS)	• Breakdown due to unexpected actions • Breakdown and material shortage	[64]
Lack of Reconfigurability	• Big Data Analytics (BDA) and decision making cannot meet the requirements • Shop-floor disturbances and market changes cannot be adapted	[82]

that can increase or decrease customer requirements for production capacity.

Cloud Security & Performance, there is a significant challenge in CMfg to develop robust systems to protect vast amount of private data that will be exchanged between suppliers and customers. CMfg must also be designed to perform several key functions with rapid access and availability of services.

In this context, there are challenges of cloud-based manufacturing identified in Table 9.

4.3 Future Directions and Trends

In the near future, cloud-based manufacturing will continue to improve, as new and advanced technologies such as blockchain and AI are integrated into the manufacturing system and process. This will result in more flexible and efficient process, as well as new opportunities and business models for manufacturers. In the literature, CMfg main pillars, digital twin, big data analytics, cloud computing are directly related to I4.0 (Industry 4.0), even CMfg concept and approaches are comparable with I4.0. CMfg require the Industrial Internet of things (IIoT) integration into CMfg. CMfg fundamentality and extensive permeability should be paid more attention in further researches:

Cloud-based manufacturing concept is studied and there are many ongoing studies available. However, there is no clearly defined concept yet. Although there are on-going researches, each study defines CMfg concept from their own perspectives. Moreover, there is no reached consensus about the definition of CMfg concept by international CMfg community [98]. The uncertainty and unclear definition hinder the industrial implementation of CMfg. After clear definition of CMfg concept, implementation to industry should be focused.

Standardization is essentially important for implementation of cloud-based manufacturing as well as for academic research. This is because, defining the standards for core and enabling technologies, procedures/methods that are utilized in management and operation and M2M communication protocols are critically important for CMfg [200].

The literature search showed a trend for current manufacturers especially SMEs to shed internal manufacturing operations. SMEs are outsourcing more production functions to third party manufacturers. This trend is shown in Fig. 16

The literature review also showed adoption of the latest digital technologies to enable migration from physical assets to virtual assets as shown in Table 10.

5 Conclusions

Cloud-based manufacturing is a remarkable shift in manufacturing method and can revolutionize the industry. With its capacity of providing on-demand manufacturing services and reducing costs, it can increase the competitiveness of manufacturers and enable new business models. However, the real potential of this technology could be noticed completely when several important challenges are addressed. It is widely held that CMfg has the potential to be an excellent strategy for overcoming the obstacles connected with conventional manufacturing and facilitating a speedy transition to the capabilities of on-demand and dependable production.

Table 10 Future directions and trends in cloud-based manufacturing

Trends	Remarks	Refs
Software Applications	• TaaS, XaaS • Mobile reporting apps	[134]
Real-Time Scheduling	• Adaptive dynamic production scheduling • Big data multi-objective scheduling	[202]
3D Printing	• Transfer of physical product replaced with transfer of specialized 3D printing data • Distributed network of 3D printing labs	[203]
Machine Learning	• Predictive repair & maintenance • Overall Equipment Effectiveness (OEE) • Revolutionized supply chain management	[55]
Logistics Planning	• Decrease in operation and logistics costs	[1]
Pricing strategy on blockchain	• Rapid and safe global payments	[196]

The research overall provides an encouraging outlook for adoption of CMfg. Platforms for CMfg have arisen as a production paradigm that enables the full potential of the fourth Industrial Revolution to be realized. According to the research discussed in this article, there have been significant advancements in many of the architectures that facilitate CMfg. In this regard, the reviewed literature revealed that resource virtualization and data analysis have been one of the most important researched areas. In addition, data analysis is another key component of CMfg architectures. This is due to the fact that the connecting function of CMfg is achieved through the analysis of the data provided by the supplier of productive resources as well as the requirements of the customers.

Since CMfg's goal is to integrate resource providers with varied capacities into a single system, a better service composition will allow it to compete with other productive paradigms. Therefore, by having an integrated picture of them, it is feasible to develop synergy between these competencies, which will allow for the effective provision of integrated services. An impressive systematic and complete assessment of CMfg research can assist in fully comprehending and revealing the development direction of theory and technology and support its further application and implementation. Hence, the purpose of this study is to conduct an in-depth analysis of the state of CMfg. In addition to this, the study provides an insightful classification and analysis of the current state of the supporting technologies. This study carefully analyzes the application state of CMfg in many domains of manufacturing and explores the problems and hurdles that are present in existing CMfg applications.

There has been some discussion regarding the connections between CMfg and a few other manufacturing-related concepts, including cloud computing-based manufacturing, CPS, SMSs, I 4.0, and IIoT. This paper also reviewed the impact on manufacturing from emerging digital transformation technologies such as AI, IoT/IIoT, PA, Web 3.0, etc. This literature review reached the conclusion that manufacturing industry is entering an exciting period in its history. Manufacturing today stands to benefit from significant technology R&D investments made in other industries that are developing key emerging technologies. The historic transitions from man-made products to machine-made products is now ready for transition to hyper-advanced cloud era. Therefore, there is a tremendous opportunity for manufacturing researchers and practitioners to engage in a wide range of future research and development activities. As a future research, it is recommended to investigate AI applications across all manufacturing infrastructure from manufacturing service provider's factory floor to cloud service structure to manufacturing service user.

5.1 Compliance with ethical standards

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Qasim Zeeshan: Visualization, Investigation, Methodology, Review and Editing.

Zeki Murat Çınar: Data collection, Visualization, Methodology.

Saeid Sahmani: Data curation, Graphics preparation, Writing and Edition.

Mohammed Asmael: Conceptualization, Visualization, Investigation, Methodology, Writing and Edition were performed.

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