# From Digital Manufacturing to Cloud Manufacturing

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**Abstract:** Digital manufacturing and cloud manufacturing are the newly emerged manufacturing models that represent important paradigms to improve the competitiveness of manufacturing enterprises and enable them cope with the global market turbulence, and therefore the two models have been widely accepted and also gained more and more attention from the academia and industry. After a brief summary of the development changes occurred in manufacturing and the main concept, this paper discusses the connotation, scientific and technological system, and framework of the two manufacturing models, and summarizes that both them are the new service-oriented and networked manufacturing model which is developing toward being agile, informatized, intelligent and green. In addition, the two models also improve and extend the connotation of manufacturing informatization and cloud computing in terms of the manufacturing resource sharing, manufacturing business model and strategies, and manufacturing informatized technologies. A survey of the recent advances and application cases in different domains is also introduced. Finally, the relationships between digital manufacturing and cloud manufacturing, as well as their development prospect, are given and concluded at the end of the paper.

***Key-Words:*** *Digital manufacturing, cloud manufacturing, theory, key technologies, framework, application cases*

## 1. Introduction

During the last decade, a new competitive environment for manufacturing enterprises has been developing due to the rapid development of advanced manufacturing technology, information and communication technology, network and computer technology, management technology, etc., which is also facing a set of new changes to operation and management of manufacturing enterprises. There are three grand changes in such competitive environment [1-5]:

The 1st is from traditional 'small manufacturing' changes to global 'large manufacturing'. The traditional small manufacturing mainly focuses on the machining operation of products and the whole production process that transfers the materials into products only locates at a small area. Hence, it features as a small workshop or a small manufacturer. On the other hand, the global large manufacturing extends the production processes and activities of manufacturing enterprises to a global area, and the 'large' characteristics of such manufacturing model feature as: the large range of production activities and processes that covers the whole product lifecycle, the large space boundary of manufacturing activities that covers the area from a factory level to an enterprise level and to a globalization level, and the huge covering surface of manufacturing industries types, for instance, the discrete manufacturing covering machine industry and electronics industry, the process manufacturing covering oil industry and petrochemistry industry, the hybrid manufacturing covering iron and steel industry and food industry, etc.

The 2nd is from a certain stable domestic market changes to a dynamic and changeable global market. In traditional manufacturing model, the enterprises operate within a certain stable domestic market, which offers specified market targets

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and be of a low market competition. However, nowadays the fierce global competition and rapid technology development faced by manufacturing industry have been forcing enterprises to evolve at an unprecedented rate. In order to survive and succeed in such a turbulent and dynamic environment, enterprises are striving to improve their competencies to meet the requirements for rapid response to different market opportunities, and realize the goal of PTQCSKES, e.g. customized **P**roduct, shortest development **T**ime, highest **Q**uality, lowest **C**ost, best **S**ervice, plenitudinous **K**nowledge, cleanest **E**nvironment and harmonious **S**ociety.

The 3rd is from a local process manufacturing informatization changes to a whole product lifecycle manufacturing informatization. Manufacturing informatization is a complex system engineering which aims at integrating and optimizing three factors, including people and organization, management, and technology, and four flows, including information flow, material flow, value flow and knowledge flow, in order to improve the production efficiency and enable the enterprises to achieve the PTQCSKES goal. The traditional manufacturing model mainly focuses on the local process informatization during the production period and therefore results in the "information island" problem. In order to conquer this, manufacturing informatization is developing towards to a deep convergence of industrialization and informatization, and intends to encompasses the whole product lifecycle, which is from market analysis to design and production, and to testing, training, usage, and maintenance and finally to dismantlement. Furthermore, manufacturing informatization enables the enterprises operate in a collaborative manner so that improve their competencies and competitiveness within the global market environment.

Facing to the aforementioned changes in manufacturing industry, new business models, new organizational structures, new manufacturing theories, processes and technologies are required to allow enterprises to achieve a differentiated competitive advantage in very competitive climate, and to cope with the challenges of market turbulence. In this context, some new manufacturing forms emerge and aim at enabling enterprises to tackle the changes and the corresponding challenges, for instance, the digital manufacturing (DM) [6] presented in 2001 and the cloud manufacturing (CM) [7] recently presented in 2010.

Digital manufacturing is firstly proposed based on the concept of 'digital earth' and originated from the technologies of numerical control (CN/CNC) and CNC machine [6,8], and relies on the intersect of multiple disciplines, including network, computer, automation, intelligence, biology, materials, cybernetics, etc., together with manufacturing engineering and mechanics, to support its theory foundation. Digital manufacturing is a manufacturing process realizing product in a digital space which built on the digital description for various production processes. It synthesizes partial attributes of networked manufacturing, intelligent manufacturing, virtual manufacturing, etc., and emphasizes on the digitized technologies, such as digital modeling, digital machining, digital equipment, digital resource and resource description, digital maintenance, digital factory, etc. The realization of digital manufacturing is based on the knowledge convergence in manufacturing process and features as the digital modeling, simulation and optimization. Moreover, it utilizes the methods of digital quantitiveness, description, storage, processing and control, to support the overall performance optimization during the enterprise operation and the whole product lifecycle.

Cloud manufacturing is proposed based on the concept of 'smart earth' and originated from the cloud computing technology. Cloud manufacturing is a new networked and smart manufacturing model that features as service-oriented, knowledge based, high performance, and energy efficient. It also integrates the technologies such as cloud computing, informatized manufacturing, Internet of things, semantic Web, high-performance computing, etc., to offer secure, reliable, high quality, and on-demand services with low cost for production, during the whole manufacturing lifecycle [9,10]. In such model, manufacturing resources and capabilities are virtualized towards service provision, and then the pervasive and efficient sharing and coordination of such services cloud be realized by the unified and centralized intelligent management in the manufacturing systems. The services are trade on a “pay-per-use” basis in a secure and intelligent manner, so that the economic incentives lead to the cost reduction for service users and the profits up for service providers, and also a more competitive market.

Both digital manufacturing and cloud manufacturing aim at developing manufacturing enterprises being integrated, digital, intelligent, agile, networked, green and service-oriented, and also to achieve a sustainable development. The two novel manufacturing models introduce new conceptions, new organizational structures, and new theories, processes and technologies into manufacturing informatization. Through one decade development, digital manufacturing has been widely accepted and adopt in a number of manufacturing fields [7,11-13]. On the other hand, due to the great potential benefits to manufacturing industry and the successful operation of cloud computing in different business fields, cloud manufacturing has attracted more and more attention from both academic and industrial circles in recent years [2,14-16], and the research projects related to cloud manufacturing have been carried out in EU and China in order to support its development and push the applications in industrial areas [17,18]. Although digital manufacturing and cloud manufacturing have their own unique characteristics, there are still close relationships between them, and therefore a detailed description and discussion, including characteristics, connotation, scientific system and technological system of the two manufacturing models, are presented in this paper, as well as the application cases.

## 2. Characteristics

As aforementioned introduction, in general, digital manufacturing and cloud manufacturing are new service-oriented manufacturing models which are developing toward being intelligent, agile, informationalized, networked and green. In the models, state-of-the-art manufacturing technologies, such as computer aided and network based design (CAD), computer aided process planning (CAPP), computer aided engineering (CAE), simulation, enterprise resource planning (ERP) and computer integrated manufacturing (CIM), and also the information technologies, such as cloud computing, Internet of things, semantic Web, knowledge-based intelligence, high-performance computing and embedded system, are integrated and further improved. Besides advanced manufacturing technologies, semantic Web technology offers the foundation of knowledge-based intelligence in manufacturing processes, sensor networks and RFID technology realize the identification of manufacturing resources, Internet of things technology achieves the extensive interconnection among the physical things, and embedded system technology also promotes the realization of the above information technologies in manufacturing processes. By the efforts of such technologies, digital manufacturing and cloud manufacturing are able to provide dynamically scalable virtualized manufacturing resources and capabilities as unified services, and a large-scale service information pool can be formed for users to access such services, relying on a networked digital manufacturing platform or a cloud manufacturing platform, so as to efficiently implement the various manufacturing activities in the whole manufacturing lifecycle.

Although digital manufacturing and cloud manufacturing have a set of similar characteristics as a manufacturing model, they also own their unique characteristics. Considering from the conception of a manufacturing model, networked manufacturing is the global realization of digital manufacturing, digital factory and digital product in virtual manufacturing is a digitized realization of digital manufacturing, agile manufacturing and e-manufacturing is a dynamic alliance of digital manufacturing, computer integrated manufacturing is the integrated model and technology basis of digital manufacturing, and green manufacturing is the environment-friendly representation of digital manufacturing. Combining the theories, technologies and research achievements in multiple disciplines, such as mathematics, biology, informatics, cybernetics, management, etc., the scientific supporting system, digital manufacturing science, has formed for digital manufacturing [1,19,20], and the technological system of digital manufacturing mainly refers to the various digitized technologies existing in the whole manufacturing lifecycle, including the information technologies in manufacturing process and manufacturing system, the digital environment-aware and resource-aware technologies, and the representing technologies for digital products, etc.

By integrating multiple concepts of tangible and intangible assets, including resources and capabilities, owned by each individual enterprise and offering them as services in cloud environment, enterprises in cloud manufacturing are able to easily achieve the required services by paying only for what is consumed, and utilize various collaboration mechanisms in a transparent manner to carry out the production. Therefore, the cloud enterprises benefit from the inherent mechanisms embedded in such manufacturing model which in terms of lower production cost, higher resource utilization, and more efficient energy and environment use of various manufacturing resources and capabilities. In addition, cloud manufacturing also has the characteristics [2,7]: (i) interoperability and collaboration, it means cloud manufacturing supports the interoperability between the manufacturing resources and capabilities, and realizes seamless collaboration among users to solve large scale and complex manufacturing tasks, (ii) heterogeneous target integration and rapid service, it means cloud manufacturing supports the integration of distributed and heterogeneous manufacturing resources and capabilities, and realizes the rapid service to respond the users' requests, and (iii) the whole lifecycle of smart manufacturing, it means cloud manufacturing supports the cloud services for the whole manufacturing lifecycle, and utilizes intelligent and informatized manufacturing technologies to realize the smart manufacturing.

## 3. Connotation

The connotation of the two manufacturing models, digital manufacturing and cloud manufacturing, is very plentiful, and the theory system connotation is developed from many other related theories. It can be noticed that there are close relationships between digital manufacturing and cloud manufacturing, and the two models also have a set of common aspects of connotation as follows:

### 3.1 Manufacturing resource sharing

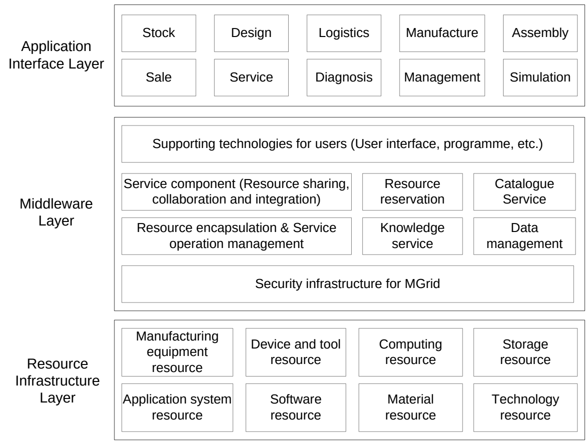



Fig. 1 Manufacturing Resource Sharing Model of MGrid

Manufacturing resource sharing is the first common aspect of the connotation of digital manufacturing and cloud manufacturing. Digital manufacturing relies on manufacturing grid (MGrid) [5,21] to realize the sharing of manufacturing resources. MGrid is one of the emerged collaborative forms and offers new business models, business strategies, and technological capabilities allowing the enterprises involved in manufacturing to improve their competencies in a form of virtual enterprises (VE). It federates a wide variety of geographically distributed manufacturing resources and enables large scale and dynamic collaboration among the enterprises. By the efforts of an MGrid platform, all kinds of manufacturing resources, located in highly heterogeneous and distributed systems, can offer users abundant manufacturing services in a transparent manner [22], and thereby enable users to achieve complete sharing of resources in a collaborative environment. The business model of MGrid is typically project-oriented in which the users involved in that project can have certain amount of resource services from other organizational members to deal with the business opportunities. In other words, MGrid focuses on integrating the existing resources owned by different enterprises to achieve the common goals. The resource sharing model of MGrid is illustrated in Fig. 1 [5,23].

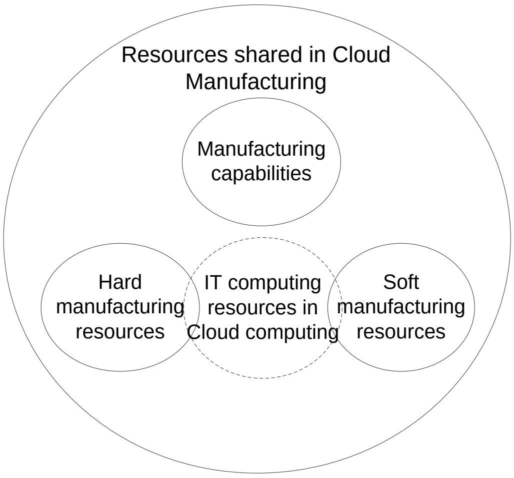



Fig. 2 Manufacturing Resource Sharing Model of Cloud Manufacturing [2]

Cloud manufacturing realizes the sharing of manufacturing resources using the operation model of cloud computing, and the manufacturing resource sharing model is shown in Fig. 2. From the figure, it can be seen that the manufacturing resources shared in cloud manufacturing mainly consist of (i) IT computing resources in cloud computing, (ii) hard manufacturing resources, such as digital machine, machining tool, manufacturing centre, computing equipment, simulation equipment, testing equipment, etc., (iii) soft manufacturing resources, such as product model, data, software, information, knowledge, etc., and (iv) manufacturing capabilities, such as design, production, simulation, testing, management, integration, demonstration, etc. [24]. For the operations of cloud manufacturing in such resource sharing framework, the manufacturing resources are virtualized and move towards service provision, and then pervasive and efficient sharing and coordination of manufacturing resources can be realized by the unified and centralized management and operation with intelligence in the whole manufacturing lifecycle. In this manufacturing model, consumers rely on cloud providers to supply their needs for the services. On the other hand, cloud providers consider and satisfy different requirements of each consumer through the negotiations. All the requests for services are regarded as equally important by the providers. Finally, a consumer can simply pay for the services on a "pay-per-use" basis, and therefore the economic incentives for both consumers and providers result in the cost reduction for users and the profits up for service providers.

### 3.2 Emphasizing on manufacturing service

Emphasizing on manufacturing service is the second common aspect of their connotation. Digital manufacturing and cloud manufacturing are able to provide the manufacturing services in terms of the consumer's request, and realize the services of interoperability and collaboration for users in the whole manufacturing lifecycle. However, the two manufacturing models also have their own emphasizes on manufacturing services.

Digital manufacturing utilizes MGrid to realize the resource service management and to achieve the goal of TQCS, in which means, the shortest product development **T**ime, the optimum product **Q**uality, the minimum **C**ost, and the best **S**ervice. The TQCS goal represents the requirements for manufacturing resource services in digital manufacturing, and a TQCS market model of manufacturing resource service management is presented in [25]. In addition, digital manufacturing also focuses on the rapidly re-configurable manufacturing (RRM) in order to cope with the dynamic market changes. The RRM uses the rapid design (RD), rapid prototyping (RP) and rapid manufacturing (RM) to constantly enhance product development, improve product quality and reduce cost, so as to survive and succeed in turbulent market. Nowadays, a mass of computer-aid technologies and digital technologies have been adopted in the whole lifecycle of product design, product manufacturing, product maintenance, product response and marketing to achieve the TQCS goal and facilitate the RRM in digital manufacturing.

In cloud computing, every computing resource is treated as a service, such as Software as a Service (SaaS), Platform as a Service (PaaS) and Infrastructure as a Service (IaaS). Besides the services offered in cloud computing, cloud manufacturing emphasizes more on the manufacturing resources and capabilities in the whole manufacturing lifecycle and treats them as services in a cloud environment, such as the conception of Manufacturing as a Service (MaaS) in [17]. The manufacturing services in cloud manufacturing can also be further classified as: Argumentation as a Service (AaaS), Design as a Service (DaaS), Fabrication as a Service (FaaS), Experiment as a Service (EaaS), Simulation as a Service (SaaS), Management as a Service (MaaS) and Integration as a Service (IaaS). Users pay for the services on a "pay-per-use" basis, and thus the usage-based pricing scenario enables cloud manufacturing to be more potential for revolutionizing the business models in manufacturing in terms of it making better economic sense for the enterprises. Manufacturing enterprises are able to transparently access the required resources in clouds to scale up as demand requires, and to pay for only what they actually use to reduce both time and cost burdens in business practices.

### 3.3 Integrating multiple disciplines and technologies

Integrating multiple technologies and disciplines is the third common aspect of digital manufacturing and cloud manufacturing. Digital manufacturing relies on the supporting technologies, e.g. virtual reality, computer network, rapid prototyping, information processing, database, multimedia, etc., to collect the resource information in terms of user's requirements, and then perform the analysis, planning and reorganization of the collected information, such as product information, technique information and resource information, so as to realize product design, function simulation and prototype manufacturing, and further achieve the product manufacturing process which can meet the user's requirements. Moreover, digital manufacturing also integrates the recent research achievements from multiple disciplines, e.g. mathematics, biology, informatics, cybernetics, management, etc. and in particular the results from information science and control science, to develop its scientific supporting system. Meanwhile, the ideas from information theory, control theory, system theory and biological evolution theory are also considered in the development of digital manufacturing.

While cloud manufacturing mainly integrates the new technologies which are from cloud computing, Internet of things, service-oriented technology, intelligent system, high performance computing, informatized manufacturing, etc. For the new technologies the model, cloud computing provides the new business model operated in cloud manufacturing and the enabling technologies for the soft manufacturing resource service in cloud. Internet of things offers the enabling technologies for the interconnection between things in manufacturing, and also realizes the smart manufacturing in the whole product development lifecycle. Service-oriented technology provides the enabling technologies for operating the virtual environment of manufacturing services. In addition, intelligent science and technology offers the enabling technologies for the intelligence of manufacturing resources and capabilities, and the high-performance computing provides the solutions to complicated manufacturing issues, as well as the enabling technologies for operating the large-scale collaborative manufacturing.

## 4. Scientific and Technological System

This section provides the systems, including theory support system and technology support system, of digital manufacturing and cloud manufacturing.

### 4.1 Theory support system

The scientific system of digital manufacturing is formed by multi-disciplinary, which involves the subjects such as [1]: (i) computer system, computer networks, distributed computing, high-performance computing, etc. in computer field, (ii) system control, process control, intelligent control, etc. in automation field, (iii) information representation, information transfer and security, etc. in information field, (iv) mechanical design and manufacture, modeling and simulation of product, electromechnical system, etc. in mechanical engineering field, (v) manufacturing system re-configuration, industrial process, enterprise recombination, enterprise management, etc. in management field, (vi) biological mechanics in biology field. At present, the scientific system, digital manufacturing science (DMS), which providing the theory basis and supporting the operation of digital manufacturing is established in [1,20], and the theory support system is illustrated in Fig. 3.

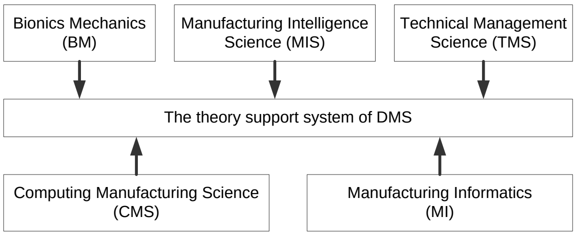



Fig. 3 Theory Support System of Digital Manufacturing Science [19]

As shown in the figure, the theory support system of digital manufacturing science consists of five parts, including computing manufacturing science (CMS), manufacturing informatics (MI), bionics mechanics (BM), manufacturing intelligence science (MIS) and technical management science (TMS) [19]: here the CMS part concentrates on the establishment of all kinds manufacturing computing models, theories and methodologies, and thus provides the digital expression, digital quantitative reasoning and digital formula treatment to the problems occurred in manufacturing processes; the MI part focuses on the scientific issues related to information expression, optimized allocation and effective operation in manufacturing process and manufacturing system [26], and this part consists of the principle and attributes of manufacturing information, measure and materialization of manufacturing information, and self-organization and combination of manufacturing information; the BM part is the result of the combination of digital manufacturing science and biological science due to there are a number of similar aspects between them, and the theories and technologies inspired from biological science can significantly facilitate the production capabilities in manufacturing; the MIS part relies on artificial intelligence (AI) tools and the intelligent computing methods to handle the problems occurred in manufacturing process, e.g. the expert system, neural networks, fuzzy logic, genetic algorithm, etc., and the TMS part is the result of the combination of digital manufacturing science and management science, in order to improve the efficiency of enterprise operation and management during the whole manufacturing life-cycle and enhance their competitiveness in the market turbulence.

The scientific system of cloud manufacturing also involves multiple disciplines and covers a set of theory domains. However, cloud manufacturing pays more attention on the business models, business strategies, business processes and activities, etc. In cloud manufacturing, distributed manufacturing resources and capabilities over networks are virtualized and then encapsulate into cloud services which are managed in a centralized manner. A cloud manufacturing service platform performs the searching, intelligent mapping, scheduling, recommendation, execution and optimization of a cloud service, and cloud users can utilize the cloud services, which ranging from product design, simulation, manufacture, testing, management and all other stages of the manufacturing lifecycle, according to their requirements.

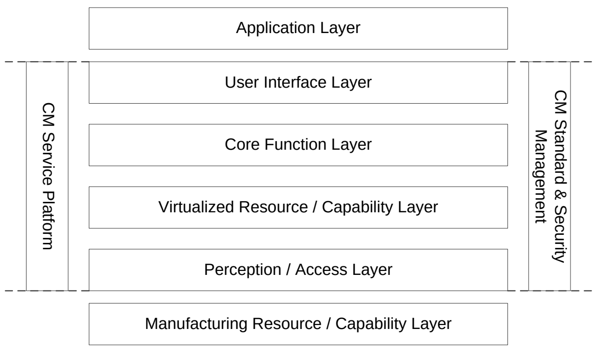



Fig. 4 Layered System Framework of Cloud Manufacturing

Fig. 4 illustrates the layered system framework of cloud manufacturing [2,7], in which containing the manufacturing resource/capability layer, perception/access layer, virtualized resource/capability layer, core function layer, user interface layer and application layer, and the functions of each layer are

[2,14]: the manufacturing resource/capability layer encompasses the manufacturing resources and capabilities required during the product development lifecycle, the perception/access layer realizes the intelligent perception for various manufacturing resources and capabilities, and also enables the smart access of such resources and capabilities, the virtualized resource/capability layer is to identify the resources and capabilities, and virtualized them, and finally encapsulate them as cloud manufacturing services, the core function layer offers the most important realization functions of cloud services, such as service deployment and registration, service searching and matching, service composition and scheduling, service operation and fault tolerance, service monitoring and evaluation, service cost and pricing, etc., the user interface layer provides a interface between the users and manufacturing resources/capabilities, as well as a official Web platform for the users and managers to implement their manufacturing activities, and the cloud manufacturing applications are carried out in the application layer.

### 4.2 Technology support system

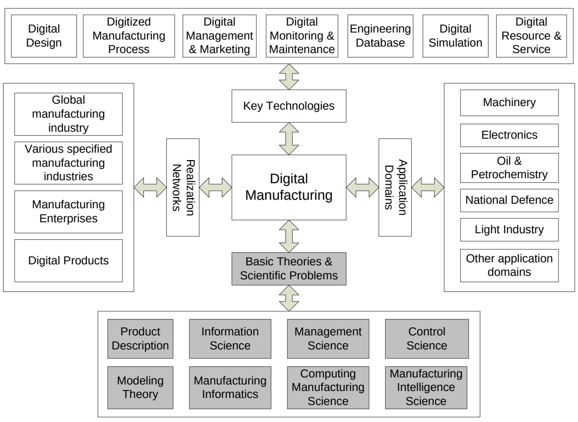



Fig. 5 Technological System of Digital Manufacturing

The technological system of digital manufacturing is shown in Fig. 5. The key technologies involves digital design, digitized manufacturing process, digital management and marketing, digital monitoring and maintenance, engineering database, digital simulation, digital resource and service, etc. The realization network for such technologies is composed by the global manufacturing industry, various specified manufacturing industries, manufacturing enterprises and digital products. Meanwhile, the application domain for such technologies involves machinery, electronics, oil and petrochemistry, national defence, light industry, etc. On the other hand, in [1,19], the technology support system of digital manufacturing science is formed by four aspects, such as all kinds of digital technologies in the whole product life-cycle, digital environment-aware and resource-aware technologies, information technologies in manufacturing system and process, and technical characteristics of digital product. The detailed content of each aspect is also described in such above references.

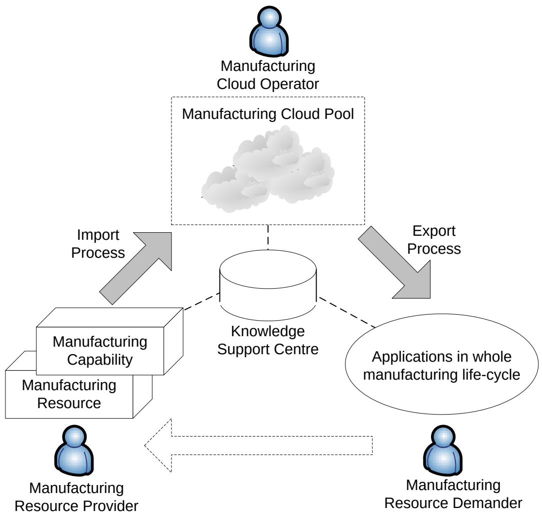



Fig. 6 Technological System of Cloud Manufacturing [9]

Fig. 6 illustrates the technological system of cloud manufacturing and also shows its operation principle [9]. The technological system consists of manufacturing resources and capabilities, manufacturing cloud pool, and whole manufacturing life-cycle applications. Meanwhile, it also involves one knowledge support centre, two operation processes, such as import and export for the cloud pool, and three kinds of users, such as cloud service provider, cloud service demander and cloud service operator. In this system, manufacturing resources and capabilities are virtualized and then encapsulated as cloud services within the import process. The cloud services are registered and stored in the cloud pool. Depending on the requirements from manufacturing resource demanders, the cloud services are combined to form a manufacturing cloud, so that provide diverse services to the whole manufacturing life-cycle applications, and this process is named as export process. Knowledge support centre performs a key role in supporting the entire operation of such system, and facilitates the system functions, such as service searching and matching, service composition and scheduling, service operation and fault tolerance, service monitoring and evaluation, service cost and pricing, etc.

## 5. Application Cases

### 5.1 Application cases of digital manufacturing

#### 5.1.1 Networked NC system using embedded technology

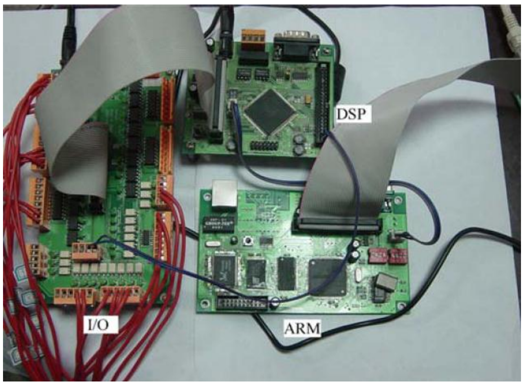



Fig. 7 The Hardware of the Basic System with Common NC Functions [27]

Currently, the traditional computer numerical control (CNC) systems usually face the problems, e.g. the insufficient use of resources, the lack of tailorability, and the complexity of interconnections using parallel interfaces, etc. Meanwhile, in modern production processes, the requiring for interoperation of modules locating in different places and for flexible configuration of various functions introduces great challenges to such traditional NC systems. In order to conquer this, a lot of works, which focusing on the networked NC system using embedded technology, have been carried out by the authors' research group, and the novel embedded-based modular NC systems in networked environment are presented in [27], as well as a set of related research works in [28-30]. By taking advantages of the advanced embedded technology, these systems adopt a flexible modular structure and consist of a number of embedded-based modules, and two kinds of such systems, including a basic system with common NC functions and a network NC system with an NC core server module, were developed.

(a) Milling machine used in functional tests

(b) Punching machine used in functional tests

Fig. 8 The Functional Tests for the Embedded-based NC System [27]

The basic system consists of a number of embedded-based modules, e.g. NC operations and management, machining control, position/speed servo controllers, I/O interface, and display and keyboard, and each of the embedded-based modules performs a certain function in such system. The basic system hardware is shown in Fig. 7. The functional tests in milling machine and punching machine, as illustrated in Fig. 8, demonstrate the embedded-based NC system is able to replace the traditional industrial PC-based CNC systems for product machining and also achieves a perfect operation performance.

Moreover, the networked NC system uses the embedded-based multi-machine NC operations & management server, which acts as an NC core server module, to realize the sharing and sufficient use of the NC resources. The core server module is responsible for the management of a number of NC machine tools that implement common and non-time-critical NC functions. The structure of the networked NC system is shown in Fig. 9.

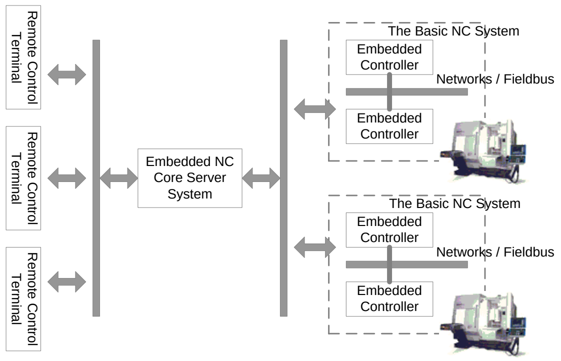



Fig. 9 The Structure of the Networked NC System using Embedded Technology

### 5.1.2 Condition digit monitoring for large-scale machines

The working condition of critical components determines the ultimate efficiency of a large-scale machine, such as turbine, aircraft engine, and other large-scale mechanical production equipments. They have to usually work under harsh conditions, operating in high temperatures environment while being subjected to large thermal and mechanical stresses. Fatigue cracking and deformation can occur on critical components in both new and aging machines. This becomes more critical for large-scale machines for a safety reason.

Machine performance monitoring has been introduced to reduce fatal machine failures and to meet very rigorous satisfy demands. The online condition monitoring system has been proved to be very effective in providing early warning of ongoing or impending failures, thus in practice reducing unscheduled delays and more serious machine failures. However, for large-scale machines, the widely used electric sensors are not suitable for the online condition monitoring of large-scale machines, in particular the large rotating machines such as aircraft engine, gas turbine, etc., because of their singleness of data collection and the poor anti-interference capability, as well as bulk size and heavy weight. Therefore, it is a challenge to acquire data from critical components working under a harsh environment.

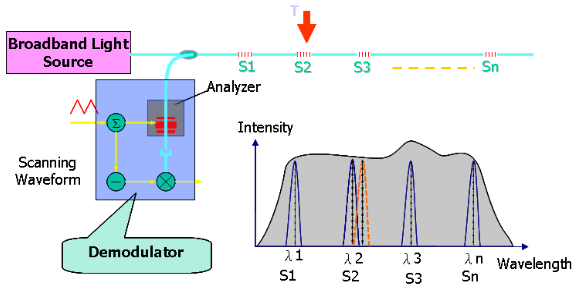
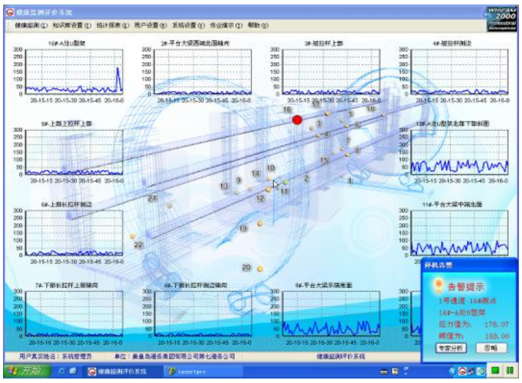



Fig. 10 Distributed Monitoring Method using FBG Sensors

To address the aforementioned challenges, new fiber Bragg grating (FBG) sensors have been developed and used for online condition monitoring of large-scale machines to improve operation safety and reduce maintenance cost. The fiber grating sensors holds several compelling advantages compared to other sensing elements in terms of miniature dimensions, electrical passivity, anti-electromagnetic interference and safety in corrosive or explosive environments. In addition, a number of sensing gratings can be etched on a single optical fiber to perform the distributed measurement function and multi-parameter collection, as shown in Fig. 10. Moreover, the sensing data can be transfer into the digital form by fiber optic sensing demodulation devices, and thus the digital online condition digit monitoring could be achieved. The unique advantages of utilizing fiber optic sensors in condition digit monitoring for a large-scale machine can be concluded as: detection and diagnosis of multi-type defects, increased measurement capability in areas currently inaccessible, reduced measurement uncertainty and lower development costs for large-scale and complex machines, and reduced component life prediction uncertainty and part consumptions. The authors' research group has carried out a lot of research works in this area, and the detailed theories, technologies and systems are presented in [31,32], as well as the open issues and challenges. Currently, as shown in Fig. 11 the digital online condition digit monitoring systems using fiber optic sensing have been adopt in a harbor to monitor the operation and perform the heath assessment of a large-scale rotating dumper.

(a) The rotating dumper in a harbor

(b) The developed fiber optic sensors



(c) Online condition monitoring interface

(d) Expert health assessment interface

Fig. 11 Online Condition Digit Monitoring and Health Assessment System for Rotating Dumper

## 5.2 Application cases of cloud manufacturing

### 5.2.1 The COSIM-CSP platform

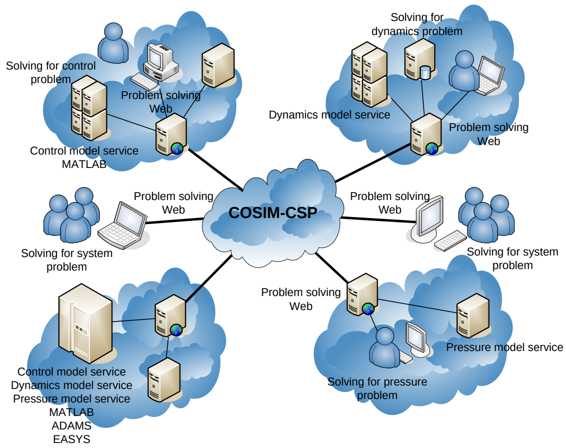
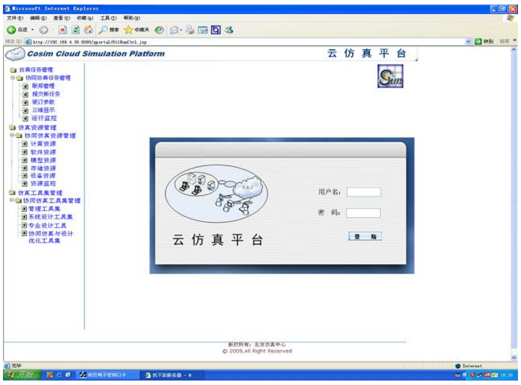


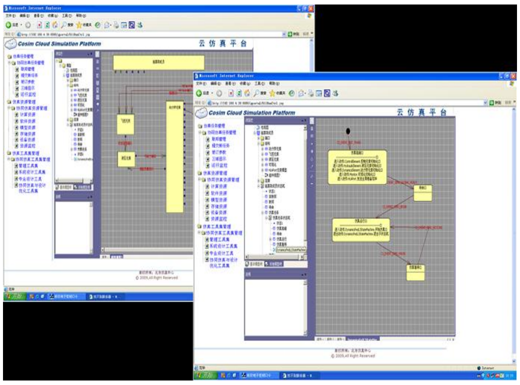

Fig. 12 The Structure of the COSIM-CSP Platform [33]

The research group leaded by B.H. Li [2,7] is one of the pioneers that focus on the research field of cloud manufacturing. In order to demonstrate the feasibility of the concept, they investigated the cloud simulation technologies for a product design and consequently a typical cloud manufacturing application, which named the COSIM Cloud Simulation Platform (COSIM-CSP) [33], was developed. Fig. 12 shows the structure of the COSIM-CSP platform, and a set of advanced technologies, e.g. cloud service scheduling, visual pervasive portal interface, simulation resource virtualization, project management for complex products, semantic Web and knowledge, fault-tolerance, security and trust mechanisms, etc., are used to support the operation of such platform.

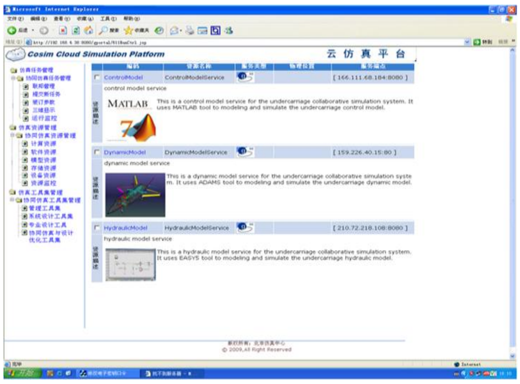
The COSIM-CSP platform has been used to perform the collaborative design of a virtual flight vehicle prototype, and the system operations are illustrated in Fig. 13. The practice results demonstrate that the COSIM-CSP platform can significantly improve the capabilities, such as simulation resource sharing and collaboration, migration of multi-granularity resources required by multiple users, fault tolerance, etc., and perform better than a grid-based simulation design system, particularly on the efficient utilization of resources.



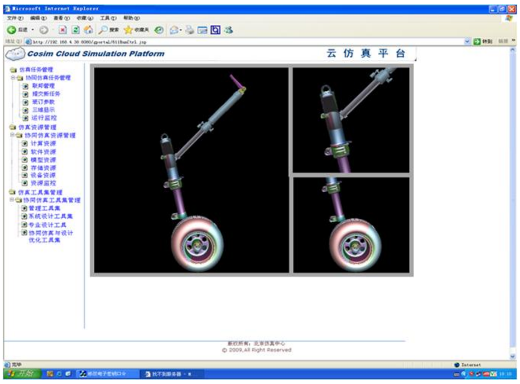

(a) Official Web portal



(b) Problem Solving environment




(c) Resource discovery




(d) Collaborative virtualization of a product

Fig. 13 Collaborative Design and Simulation using the COSIM-CSP Platform [33]

## 6. Conclusion

Nowadays, the conception and theories of digital manufacturing has been accepted in academic and industrial circles, and a number of research works have been continuously pushing the development of its technologies and subsystems. By such effective efforts, some characteristics of digital manufacturing are realized in practice, and the emerged new generation manufacturing systems based on digital manufacturing perform the characteristics as digitized, networked and globalized. Moreover, the digital manufacturing technologies are also widely adopt in various industries in order to improve the manufacturing system performance and production effectiveness, and therefore to enhance the enterprise competitiveness and be successful in market turbulence.

Cloud manufacturing is a new manufacturing model towards service-oriented, knowledge-based, digitized, high performance, and energy efficient, and also a strategic system engineering which has significant potential in academia and industry. The development of cloud manufacturing should rely on the joint efforts from academia, industry and government, and still need a gradual, long-term process. The future development of cloud manufacturing will face a number of challenges in both theories and technologies. In this context, the advisable solution is to use the service-oriented model to guide the cloud manufacturing system development, and then relies on the system development to result in the technology breakthrough. Using such new technologies, we can improve the functions of the cloud manufacturing system with new achievements, which could also be used for the service-oriented model development in cloud manufacturing. Furthermore, the establishment and operation of a service platform for manufacturing industries will significantly enable the cloud manufacturing to achieve a higher level of manufacturing informatization.

In summary, as the aforementioned description of the characteristics, connotation, scientific and technological systems, and application cases of digital manufacturing and cloud manufacturing, we can observe that digital manufacturing is a multi-disciplinary that covers the theories of manufacturing science, information science, control science and management science, and involves a set of technologies, such as computer networking technology, modeling and simulation technology, modern management technology, system engineering technology, etc. Since in the whole manufacturing lifecycle of cloud manufacturing, a number of digital manufacturing theories, technologies and systems have been used for the product development, digital manufacturing can be considered as the basis of digital manufacturing. While cloud manufacturing is a new service-oriented and knowledge-based manufacturing model, which also covers multiple disciplines and relies on the advanced technologies, such as informatized manufacturing, cloud computing, Internet of things, semantic Web, embedded technology, etc., and the digital manufacturing technologies also form the foundation of the cloud manufacturing technological system. In addition, cloud manufacturing emphasizes more on the business model, strategies, theories and technologies supporting the manufacturing enterprises to achieve the goal of PTQCSKES in a global market environment. Therefore, cloud manufacturing is the essential development trend of digital manufacturing.

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