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# Cloud manufacturing: a computing and service-oriented manufacturing model

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**Abstract:** Combining the emerged advanced technologies (such as cloud computing, 'internet of thing', virtualization, and service-oriented technologies, advanced computing technologies) with existing advanced manufacturing models and enterprise 'informationization' technologies, a new computing- and service-oriented manufacturing model, called cloud manufacturing (CMfg), is proposed. The concept, architecture, core enabling technologies, and typical characteristics of CMfg are discussed and investigated, as well as the differences and relationship between cloud computing and CMfg. Four typical CMfg service platforms, i.e. public, private, community, and hybrid CMfg service platforms, are introduced. The key advantages and challenges for implementing CMfg are analysed, as well as the key technologies and main research findings.

**Keywords:** manufacturing system, cloud manufacturing (CMfg), service-oriented manufacturing (SOM), computing-oriented manufacturing (COM), cloud computing

## 1 INTRODUCTION

During the past two decades, many advanced manufacturing models and technologies have been proposed in order to realize the aim of TQCSEFK (i.e. fastest time-to-market, highest quality, lowest cost, best service, cleanest environment, greatest flexibility, and high knowledge) for manufacturing enterprise [1]. Typical examples are computer-integrated manufacturing (CIM), agile manufacturing (AM) [2], networked manufacturing (NM) [3], virtual manufacturing (VM) [4, 5], global manufacturing [6], application service provider (ASP), collaborative manufacturing network, lean manufacturing [7], digital manufacturing [8], industrial product-service

system (IPS<sup>2</sup>) [9], manufacturing grid (MGrid) [1, 10–13], and crowd sourcing [14].

Although each of the above-mentioned advanced manufacturing technologies or models has its own emphasis, they all centre on network, resource sharing, and cooperative work. These models and technologies have made great contributions to the development of manufacturing information [1]. However, how to further optimally allocate manufacturing resource, enhance resource utilization and reduce the resource and energy consumption, and to realize the transformation from production-oriented manufacturing to service-oriented manufacturing are still not effectively addressed. Some bottleneck problems need further research, such as:

- (a) effective models, standards, and criteria supporting free transaction and currency, and on-demand use of manufacturing resource, ability, and service;

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- (b) manufacturing knowledge management and innovative utilization;
- (c) intelligent perception and connection into the internet of various physical manufacturing resources and abilities;
- (d) virtualization and service encapsulation of manufacturing resource and ability based on knowledge;
- (e) reliable security solutions and technologies under the wider internet environment, and so forth.

These bottlenecks have hindered the practical application and development of the above-mentioned manufacturing models.

At the same time, some new technologies have emerged [15], and have been widely applied in various fields, such as advanced computing models and technologies (e.g. cloud computing [16, 17], high-performance computing (HPC), ubiquitous computing), service-oriented technologies (e.g. service-oriented architecture (SOA) [18], web service, semantic web, ontology), virtualization, internet of thing (IoT) [19], intelligent embedded system and technologies, and so forth. These technologies are the enabling force for effectively addressing the above bottlenecks in manufacturing.

In this short communication, combining the above-mentioned new technologies and existing theories and technologies of current enterprise information, a computing and service-oriented manufacturing model, i.e. cloud manufacturing (CMfg), is discussed based on the authors' previous work [1]. The concept, architecture, core enabling technologies, and typical

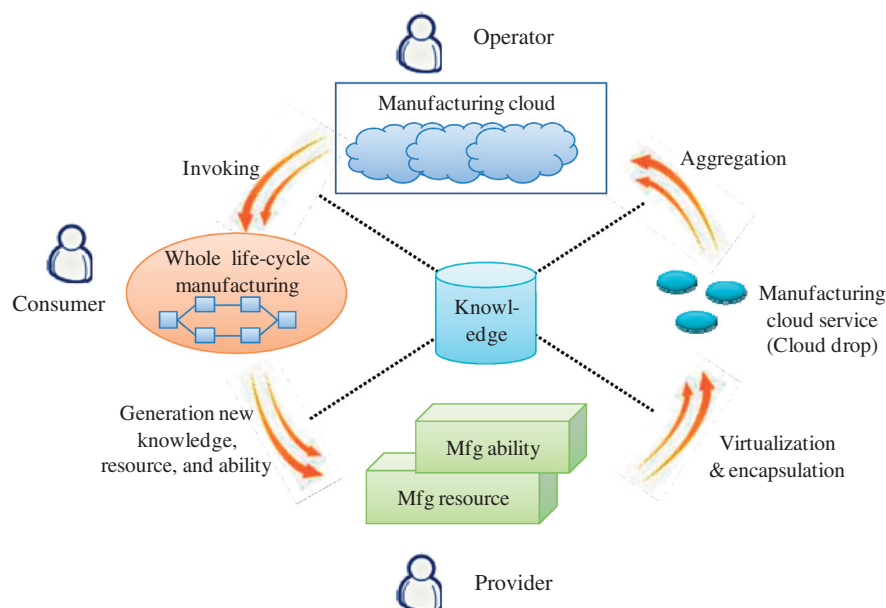
characteristics of CMfg are studied. Four typical CMfg service platforms, namely the public, private, community, and hybrid CMfg service platforms, are investigated. The key advantages and challenges for implementing CMfg are analysed, as well as the key technologies and main research contents.

## 2 CONCEPT AND ARCHITECTURE OF CLOUD MANUFACTURING

### 2.1 Concept of cloud manufacturing

Cloud manufacturing is a computing and service-oriented manufacturing model developed from existing advanced manufacturing models (e.g. ASP, AM, NM, MGrid) and enterprise information technologies under the support of cloud computing, IoT, virtualization and service-oriented technologies, and advanced computing technologies. It aims to realize the full sharing and circulation, high utilization, and on-demand use of various manufacturing resources and capabilities by providing safe and reliable, high quality, cheap and on-demand used manufacturing services for the whole lifecycle of manufacturing. The abstract running principle for CMfg is shown in Fig. 1.

In a CMfg system, various manufacturing resources and abilities can be intelligently sensed and connected into the wider internet, and automatically managed and controlled using IoT technologies (e.g. radio frequency identification (RFID), wired and wireless sensor network, embedded system). Then the manufacturing resources and abilities are virtualized and encapsulated into different manufacturing



**Fig. 1** Abstract running principle for CMfg system

cloud services (MCSs) that can be accessed, invoked, deployed, and on-demand used based on knowledge by using virtualization technologies, service-oriented technologies, and cloud computing technologies. The MCSs are classified and aggregated according to specific rules and algorithms, and different kinds of manufacturing clouds are constructed. Different users can search and invoke the qualified MCSs from a related manufacturing cloud according to their needs, and assemble them to be a virtual manufacturing environment or solution to complete their manufacturing task involved in the whole life cycle of manufacturing processes under the support of cloud computing, service-oriented technologies, and advanced computing technologies. As illustrated in Fig. 1, there are primarily three category users in a CMfg system, which can be described briefly as follows.

1. Provider: the providers own and provide the manufacturing resources and abilities involved in the whole life cycle of manufacturing process, where consumers were in charge. They can take the form of a person, an organization, an enterprise, or a third party.
2. Operator: the operators operate the CMfg platform to deliver services and functions to

providers, consumers, and third parties. They deal with the organization, sale, licensing, and consulting of the MCSs, and provide, update, and maintain the technologies and services involved in the operations to MCSs and the platform.

3. Consumer: the consumers are the subscribers of the MCSs available in a CMfg service platform. They purchase the use of the MCSs from the operator on an operational expense basis according to their needs.

## 2.2 Architecture of cloud manufacturing

The proposed architecture of the CMfg system is a hierarchical structure as illustrated in Fig. 2. It consists of the following ten layers.

1. Resource layer: provides the manufacturing resource and ability involved in the whole life cycle of manufacturing, which can be encapsulated into a service that can be invoked by user or consumer.
2. Perception layer: is responsible for sensing the physical manufacturing resources and abilities, enabling them to be connected into the wider

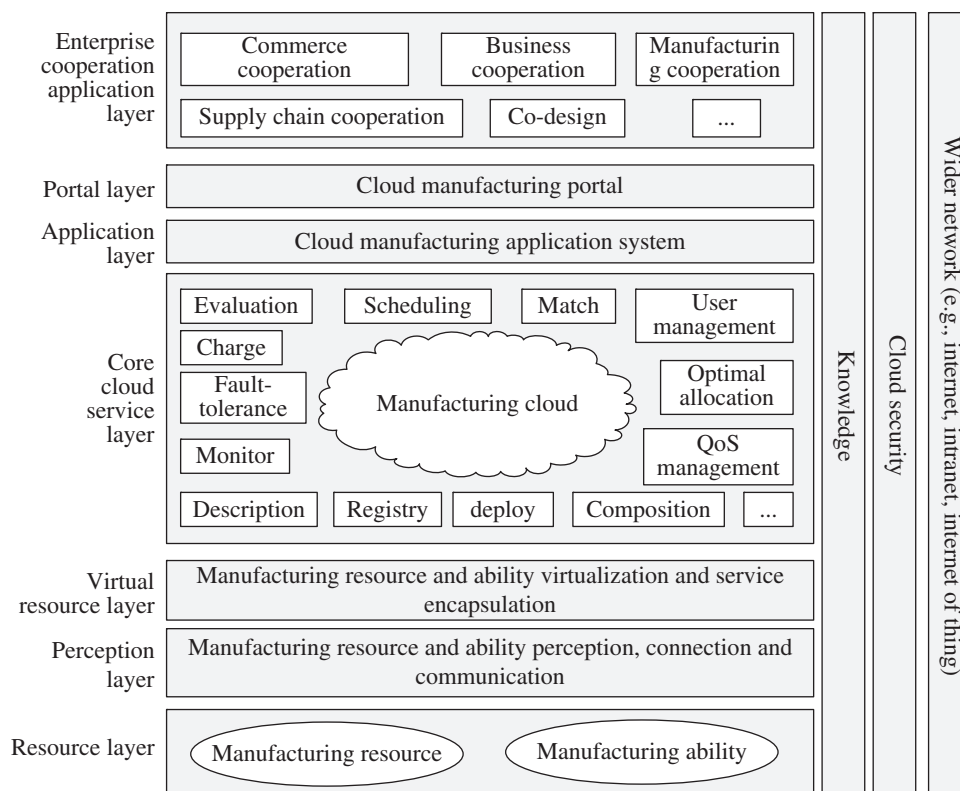


Fig. 2 Architecture of CMfg system

network, and processing the related data and information.

3. Resource virtualization layer: is responsible for the virtualization of manufacturing resources and abilities, and encapsulating them into the manufacturing cloud service.
4. Cloud service layer: primarily provides two categories of service, the manufacturing cloud service (MCS) and the CMfg core service. MCS is the result of service encapsulation of manufacturing resources and ability, which can be invoked by end users. CMfg core services are the main services provided by the CMfg platform for the three category users (i.e. the provider, operator, and consumer) to manage, access and invoke MCSs, including description, registry, publication, match and search, scheduling, charge, evaluation, and so forth.
5. Application layer: based on the integration of the existing manufacturing system in an enterprise with CMfg, the application layer develops a special manufacturing application system according to specific demands, such as cooperative supply chain management system, CMfg-based ERP, and so forth.
6. Portal layer: provides various man-machine interaction interfaces for users accessing and invoking MCSs in CMfg.
7. Enterprise cooperation application layer: supported by the MCSs and CMfg core services, different kinds of cooperation application can be realized, including commerce cooperation, business cooperation, collaborative design, and manufacturing cooperation.
8. Knowledge layer: provides various knowledge needed in the other layers such as manufacturing domain knowledge, process knowledge, model knowledge, etc.
9. Cloud security layer: provides different security architecture, mechanisms, and strategies for the CMfg system.
10. Wider internet layer: provides the base communication environment to all resources, service, users, and operations in the CMfg system.

### 3 CORE ENABLING TECHNOLOGIES FOR CLOUD MANUFACTURING

While the evolution of CMfg will take several years or even longer to unfold fully, the six core technologies that will enable it are rapidly taking shape. They are:

- (a) existing manufacturing informationization technologies – the foundation of CMfg;
- (b) cloud computing – the enabling technologies for intelligent information processing and decisions in manufacturing activities;
- (c) IoT technologies, which can provide enabling technologies for the realization of intelligent perception and effective connection among different things (including man-to-man, machine-to-machine, and man-to-machine);
- (d) virtualization – the technology that hides the physical characteristics of the manufacturing resource and ability of a CMfg platform from users;
- (e) service-oriented technologies, such as SOA, web service, and semantic web, which can provide enabling technologies for intelligently constructing a virtual manufacturing and service environment;
- (f) advanced computing technologies, which provide enabling technologies for solving large-scale and complex manufacturing problems and carrying out large-scale cooperative manufacturing and work, such as HPC technology.

### 4 TYPICAL CHARACTERISTICS OF CLOUD MANUFACTURING

Compared with existing manufacturing models, CMfg has the following typical characteristics.

1. *Service-and requirement-oriented.* Most manufacturing models are resource- or order-oriented, while CMfg is a service-and requirement-oriented manufacturing model. In CMfg, both manufacturing resource and ability are virtualized and encapsulated into manufacturing cloud service, and can be used by all users according to their requirements via the wide internet. The core thought of CMfg is manufacturing as a service. Its aim is to realize the free currency and sharing of manufacturing resource and ability, and to enable manufacturing resource and ability to be used according to requirements.
2. *Dynamic with uncertainty.* The resources and services in CMfg are various and dynamic, and the solutions for addressing a manufacturing task are dynamic too.
3. *Knowledge-based.* The whole life cycle of CMfg needs knowledge support, including knowledge-based:
  - (a) manufacturing resource and ability perception, connection, and virtualization;
  - (b) cloud service description, match and search, aggregation, and composition;
  - (c) optimal allocation and scheduling;
  - (d) business workflow management, and so on.

4. *Initiative*. In a CMfg system, both manufacturing cloud services and manufacturing tasks (or requirements) are active; they can automatically find and match with each other with the support of semantic reasoning based on knowledge.
5. *Physically distributed and logically centralized*. The physical manufacturing resource and ability in CMfg locate in different places and are controlled by different persons or organizations. However, they are all virtualized and encapsulated into MCSs that are managed, controlled, and used centrally in logic.
6. *Wikipedia style and group innovation-based manufacturing*. Any person, institute or enterprise can participate in and contribute their manufacturing resources, abilities, and knowledge to a CMfg service platform. Meanwhile, any enterprise can carry out its manufacturing actions based on these manufacturing resources, abilities, and knowledge. Similar to Wikipedia, CMfg is a group innovation-based manufacturing model.
7. *Lower threshold and outsourcing*. Within a CMfg environment, an enterprise does not need to possess all the hardware manufacturing environment (such as workshop, equipment, IT infrastructures, and personnel) or the software manufacturing ability (such as design, manufacturing, management, and sales ability). It can rent or invoke the resources and abilities, and services in CMfg platform according to its requirements after payment. This reduces the entry threshold for a new enterprise to carry out manufacturing actions.

## 5 DIFFERENCE AND RELATIONSHIP BETWEEN CLOUD COMPUTING AND CLOUD MANUFACTURING

CMfg is proposed after cloud computing, and cloud computing is a core enabling technology for CMfg as described in section 3. However, the resources involved in cloud computing primarily are computational resources (e.g. server, storage, network, software), and they are primarily provided as services for the user in the following three models.

1. *Infrastructure as a service* (IaaS). The storage and compute capabilities are provided as a service; examples are Amazon's S3 storage service, Rackspace Cloud Servers, and EC2 computing platform.
2. *Platform as a service* (PaaS). The platform is provided as a service, which can enable the development and deployment of applications without

the cost and complexity of buying and managing the underlying hardware and software layers; examples are Microsoft's Azure Services Platform, Google App Engine, Amazon's Relational Database Services.

3. *Software as a service* (SaaS). The application and software are offered as a service, in which the application runs on the cloud, the need to install and run the application on the client computer are eliminated; examples are Salesforce, Gmail, Facebook, and Twitter [16].

In CMfg, in addition to the information technology (IT) resources, all manufacturing resources and abilities involved in the whole life cycle of manufacturing are aimed to be provided for the user in different service models based on IaaS, PaaS, and SaaS, including the following models:

- (a) *design as a service* (DaaS) – the design resource and ability are provided as a service;
- (b) *manufacturing as a service* (MFGaaS) – the manufacturing resource and ability are offered as a service;
- (c) *experimentation as a service* (EaaS) – the experimentation resource and ability are provided as a service;
- (d) *simulation as a service* (SIMaaS) – the simulation resource and ability are provided as a service;
- (e) *management as a service* (MaaS) – the management resource and ability are provided as service;
- (f) *maintain as a service* (MAaaS) – the maintenance resource and ability are provided as a service;
- (g) *integration as a service* (INTaaS) – the integrated resource and ability, information system, and platform are provided as a service.

The difference and relationships between cloud computing and CMfg are illustrated in Fig. 3.

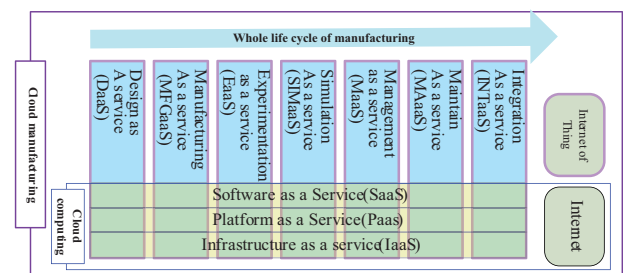


Fig. 3 Relationship between cloud computing and CMfg

## 6 CLASSIFICATION OF CLOUD MANUFACTURING SERVICE PLATFORM

For the consideration of security and safety, and utilization scope, there are primarily four kinds of CMfg service platform, namely:

- (a) a public CMfg service platform;
- (b) a private CMfg service platform;
- (c) a community CMfg service platform;
- (d) an hybrid CMfg service platform.

A public CMfg service platform is characterized as being available from a third-party service provider and demander, and is used to realize the sharing and optimal allocation of the entire manufacturing resources and abilities distributed in and owned by different enterprises and organizations, especially for small and medium-sized enterprises (SMEs).

A private CMfg service platform offers many of the benefits and services of a public CMfg service platform environment, but is managed within an organization or enterprise. It provides greater control over its resource and service, and is usually established and used to realize the sharing and optimal allocation of a group enterprise's in-house manufacturing resources and abilities distributed in its branch companies or subsidiary companies, research centres, different departments, etc., so as to promote utilization and reduce the cost.

A community CMfg service platform is controlled and used by a group of organizations that have shared interests, such as specific security requirements or a common mission.

An hybrid CMfg service platform is a combination of a public and a private CMfg service platform. Non-critical services or information are outsourced to the public CMfg service platform, whereas business-critical services and data are kept within the control of the organization.

## 7 KEY TECHNOLOGIES AND MAIN RESEARCH CONTENTS OF CLOUD MANUFACTURING

The key technologies and main research contents that need to be researched for implementing CMfg are as follows:

- (a) architecture, models, standards, and criteria for CMfg;
- (b) intelligent perception, connection technologies, and equipment for various physical manufacturing resource and ability, including hardware and software resource;
- (c) knowledge-based resource virtualization and virtual resource management technologies;

- (d) cloud service encapsulation technologies of manufacturing resource and ability, including cloud service modelling, description, deployment, and so forth;
- (e) cloud service comprehensive management technologies, such as aggregation and classification, cost management, QoS (quality of service) management, integrated evaluation, composition, trust and reliability management, scheduling and optimal allocation of cloud service;
- (f) CMfg task management, such as task definition, description, decomposition, evaluation, and scheduling;
- (g) manufacturing ability and cloud service transaction process management;
- (h) CMfg user business management and ubiquitous interface development;
- (i) CMfg service platform development and management;
- (j) CMfg safety and security technologies, and so forth.

## 8 KEY ADVANTAGES AND CHALLENGES OF CLOUD MANUFACTURING

Specifically, CMfg can offer the following key advantages.

1. It can reduce resource idle capacity and increase utilization. In conventional manufacturing models, manufacturing resource utilization is low, e.g. estimated at 15–20 per cent for IT resources, while the estimates for other manufacturing resources are lower. In contrast, a CMfg platform can increase the utilization across many customers, e.g. the IT resource utilization attains at least 40 per cent [17].
2. It can reduce the up-front investments and lower the cost of entry for SMEs trying to benefit from high-value manufacturing resources (e.g. high-end equipment, expensive application systems) and specific manufacturing abilities that were hitherto available only to the larger corporations. These manufacturing resources or abilities involve large amounts of investment for a relatively short period of time. CMfg makes such dynamic provisioning of resources possible, and provides an almost immediate access to these resources and abilities without up-front capital investments [1].
3. It can lead to reduced infrastructure and administrative cost, energy saving, and reduced upgrades and maintenance cost according to the advantage mentioned in list point 2 above [16].

4. CMfg makes it easier for manufacturing enterprises (both smaller and larger) to scale their production and business according to client demand. As the resources and services can be easily obtained, so they can be invoked and assembled very quickly as new requirements arise for an enterprise. The successful application of cloud computing in IT enterprise is a very convincing example [16, 17].
5. CMfg also can generate new types and classes of manufacturing/business model or process and deliver manufacturing services that were not previously possible, such as mfg.com (see www.mfg.com) and Local-Motors.com (www.local-motors.com)
6. It can optimize industrial distribution and speed up the transformation from a distributed and high-energy-consumption manufacturing model to a centralized, resource-and environment-friendly manufacturing model, and from production-oriented manufacturing to service-oriented manufacturing. Furthermore, it can promote the specialization division of manufacturing, because under a CMfg environment, an enterprise does not need to carry out all activities involved in the whole life cycle of manufacturing, they only need to emphasize their core business and service, even if it is a very small part.

Meanwhile, there are many challenges that need to be addressed before CMfg can be accepted as a viable choice in manufacturing, such as:

- (a) the possibility of backlash from entrenched ideas, manufacturing processes, and models;
- (b) lack of standards and criteria;
- (c) regulation at the personal, enterprise, local, national, and international level;
- (d) safety and security problems.

## 9 CONCLUSIONS

A computing and service-oriented manufacturing model called CMfg has been proposed using the support of cloud computing, IoT, advanced computing, virtualization and service-oriented technologies. The model has been proposed in order to enhance resource utilization and reduce resource and energy consumption; realize free transactions and currency, and the sharing and cooperation, and on-demand use of manufacturing resource and ability; to speed up the transformation from production-oriented manufacturing to service-oriented manufacturing; and to promote the services of competitive power and innovation based on knowledge of

manufacturing enterprise. The concept, architecture, core enabling technologies, typical characteristics, and four types of service platforms for CMfg have been discussed, as well as the key technologies, advantages, and challenges for implementing CMfg.

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## REFERENCES

- 1 **Tao, F., Hu, Y. F., and Zhang, L.** *Theory and practice: Optimal resource service allocation in manufacturing grid*, ed.1st 2010, pp. 1–18 (China Machine Press, Beijing).
- 2 **Sharifi, H., Colquhoun, G., Barclay, I., and Dann, Z.** Agile manufacturing: a management and operational framework. *Proc. IMechE, Part B: J. Engineering Manufacture*, 2001, **215**(6), 857–869.
- 3 **Mitsubishi, M. and Nagao, T.** Networked manufacturing with reality sensation for technology transfer. *CIRP Ann., Mfg Technol.*, 1999, **48**(1), 409–412.
- 4 **Bremer, C. F. and Eversheim, W.** From an opportunity identification to its manufacturing: a references model for virtual manufacturing. *CIRP Ann., Mfg Technol.*, 2000, **49**(1), 325–329.
- 5 **Chen, L., Bender, P., Renton, P., and El-Wardany, T.** Integrated virtual manufacturing systems for process optimization and monitoring. *CIRP Ann., Mfg Technol.*, 2002, **51**(1), 409–412.
- 6 **Kara, S., Manmek, S., and Herrmann, C.** Global manufacturing and the embodied energy of products. *CIRP Ann., Mfg Technol.*, 2010, **59**(1), 29–32.
- 7 **Shah, R. and Ward, P. T.** *Lean manufacturing: context, practice bundles, and performance.*, 2003, 129–149.
- 8 **Chrysosouris, G., Mavrikios, D., Papakostas, N., Mourtzis, D., Michalos, G., and Georgoulas, K.** Digital manufacturing: history, perspectives, and outlook. *Proc. IMechE, Part B: J. Engineering Manufacture*, 2009, **223**(5), 451–462.
- 9 **Meier, H., Roy, R., and Seliger, G.** *Industrial Product-Service Systems – IPS<sup>2</sup>*. *CIRP Ann., Mfg Technol.*, 2010, **59**(2), 607–627.
- 10 **Tao, F., Zhang, L., and Nee, A. Y. C.** A review of the application of grid technology in manufacturing. *Int. J. Production Research*, 2011, **49**(13), 4119–4155.
- 11 **Tao, F., Zhao, D., Hu, Y. F., and Zhou, Z. D.** Resource service composition and its optimal-selection based on particle swarm optimization in manufacturing grid system. *IEEE Transactions on Industrial Informatics*, 2008, **4**(4), 315–327.

- 12 **Tao, F., Hu, Y. F., and Zhou, Z. D.** Study on manufacturing grid & its resource service optimal-selection system. *Int. J. Adv. Manuf. Tech*, 2008, **37**(9–10), 1022–1041.
- 13 **Tao, F., Hu, Y. F., and Zhou, Z. D.** Application and modeling of resource service trust – QoS evaluation in manufacturing grid system. *Int. J. Prod. Res*, 2009, 1521–1550.
- 14 **Howe, J.** *Why the power of the crowd is driving the future of business*, ed.1st, 2009 (China CITIC Press, Beijing).
- 15 **Venkatesh, V. C. and Izman, S.** *Precision Engineering*, ed.1st, 2008 (McGraw Hill, USA).
- 16 **Marston, S., Li, Z., Bandyopadhyay, S., Zhang, J., and Ghalsasi, A.** Cloud computing – the business perspective. *Decision Support Systems*, 2011, **51**(1), 176–189.
- 17 **Rosenthal, M., Mork, P., Li, M. H., Stanford, J., Koester, D., and Reynolds, P.** Cloud computing: a new business paradigm for biomedical information sharing. *J. Biomed. Informatics*, 2009, **43**(2), 342–353.
- 18 **Bosin, A., Dessì, N., and Pes, B.** *Future Generation Computer Systems. Extending the SOA paradigm to e-Science environments*, 2011, **27**(1), 20–31.
- 19 **Atzori, L., Iera, A., and Morabito, G.** *The Internet of Things: A survey*. *Computer Networks*, 2010, **54**(5), 2787–2805.