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From cloud computing to cloud manufacturing

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A B S T R A C T

Cloud computing is changing the way industries and enterprises do their businesses in that dynamically scalable and virtualized resources are provided as a service over the Internet. This model creates a brand new opportunity for enterprises. In this paper, some of the essential features of cloud computing are briefly discussed with regard to the end-users, enterprises that use the cloud as a platform, and cloud providers themselves. Cloud computing is emerging as one of the major enablers for the manufacturing industry; it can transform the traditional manufacturing business model, help it to align product innovation with business strategy, and create intelligent factory networks that encourage effective collaboration. Two types of cloud computing adoptions in the manufacturing sector have been suggested, manufacturing with direct adoption of cloud computing technologies and cloud manufacturing—the manufacturing version of cloud computing. Cloud computing has been in some of key areas of manufacturing such as IT, pay-as-you-go business models, production scaling up and down per demand, and flexibility in deploying and customizing solutions. In cloud manufacturing, distributed resources are encapsulated into cloud services and managed in a centralized way. Clients can use cloud services according to their requirements. Cloud users can request services ranging from product design, manufacturing, testing, management, and all other stages of a product life cycle.

1. Introduction

Collaboration, Internet of things and cloud have been identified as key business technology trends that will reshape enterprises worldwide [1]. The manufacturing industry is undergoing a major transformation enabled by IT and related smart technologies. Cloud computing is one of such smart technologies. The main thrust of Cloud computing is to provide on-demand computing services with high reliability, scalability and availability in a distributed environment. The National Institute of Standards and Technology (NIST) [2] defined cloud computing as "*a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable computing resources (e.g., networks, servers, storage, applications, and services) that can be rapidly provisioned and released with minimal management effort or service provider interaction.*"

In Cloud computing, everything is treated as a service (i.e. XaaS), e.g. SaaS (Software as a Service), PaaS (Platform as a Service) and IaaS (Infrastructure as a Service). These services define a layered system structure for cloud computing (Fig. 1). At the Infrastructure layer, processing, storage, networks, and other fundamental computing resources are defined as standardized services over the network. Cloud providers' clients can deploy and run operating systems and software for their underlying infrastructures. The middle layer, i.e. PaaS provides abstractions and services for developing, testing, deploying, hosting, and maintaining applications in the integrated development environment. The application layer provides a complete application set of SaaS. The user interface layer at the top enables seamless interaction with all the underlying XaaS layers [3].

Sometimes, cloud computing is considered as a multidisciplinary research field as a result of evolution and convergence of several computing trends such as Internet delivery, "pay-as-you-go/use" utility computing, elasticity, virtualization, distributed computing, storage, content outsourcing, Web 2.0 and grid computing. In fact, cloud computing can be considered the business-oriented evolution of grid computing [4]. Implementing cloud computing means a paradigm shift of business and IT infrastructure, where computing power, data storage and services are outsourced to third-parties and made available as commodities to enterprises and customers.

More and more businesses are taking advantage of cloud computing, one of which is NEC. Its Cloud-oriented Service Platform Solutions play an important role in transforming enterprise systems, contributing to cost reduction, agile deployment of services, expanded flexibility and improved productivity [5]. Cloud computing is also being used in other business and science sectors, e.g. inline commerce [6], conference origination [7], and

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Nomenclature

AaaS	Application as a Service
AP	Application Protocol
API	Application Programming Interface
ASP	Application Service Provider
B2B	Business-to-business
BOL	Beginning-Of-Life
BPM	Business Process Management
CAD	Computer-Aided Design
CAE	Computer-Aided Engineering
CAM	Computer-Aided Manufacturing
CAPP	Computer-Aided Process Planning
CIO	Chief Information Officer
CMM	Coordinate-Measuring Machine
CNC	Computer Numerical Control
CRM	Customer Relationship Management
CRM	Customer Relationships Management
DAMA	Design Anywhere, Manufacture Anywhere
DAML	DARPA Agent Markup Language
DARPA	Defense Advanced Research Projects Agency, USA
DIMP	Distributed Interoperable Manufacturing Platform
EDM	Electrical Discharge Machining
EOL	End-Of-Life
ERP	Enterprise Resource Planning
GPS	Global Positioning System
HaaS	Hardware as a Service
IaaS	Infrastructure as a Service
IT	Information Technology
LAN	Local Area Network
MGrid	Manufacturing Grid
MOL	Middle-Of-Life
NIST	National Institute of Standards and Technology, USA
openCBM	open Computer-Based Manufacturing
OWL	Web Ontology Language
PaaS	Platform as a Service
QoS	Quality of Service
REST	REpresentational State Transfer
RFID	Radio-Frequency IDentification
SaaS	Software as a Service
SHOE	Simple HTML Ontology Extension
SLA	Service Level Agreement
SOA	Service-Oriented Architecture
STEP	Standard for Exchange of Product data
STEP-NC	STEP for Numerical Control
STRL	STEP Resource Locator
UbiDM	Ubiquitous Design and Manufacture
UPLS	Ubiquitous Product Life cycle Support
URL	Universal Resource Locator
UX	User Experience
VMM	Virtual Machine Manager
WPM	Workforce Performance Management
WSN	Wireless Sensor Networks
XaaS	everything is treated as a Service

biomedical information sharing [8]. There are valid reasons and perhaps requirement for manufacturing businesses to embrace cloud computing and to “borrow” the concept of cloud computing to give rise to “cloud manufacturing”, i.e. the manufacturing version of cloud computing. Such a lateral thinking is considered logical and natural as manufacturing businesses in the new millennium become increasingly IT-reliant, globalized, distributed and agile-demanding.

In the first-half of this paper, the essential requirements of a cloud computing system are briefly discussed. These considerations are useful for software architects and developers to design cloud-based applications. They also preface the main focus of this paper, i.e. cloud manufacturing, which forms the second-half of the paper. The rest of this paper is organized as follows. Section 2 describes the key requirements of cloud computing systems. Section 3 discusses cloud computing in the context of manufacturing businesses. In particular, Section 3.1 discusses utilization of cloud computing in manufacturing businesses and Section 3.2 presents the “manufacturing version” of cloud computing—cloud manufacturing. Section 4 concludes the paper.

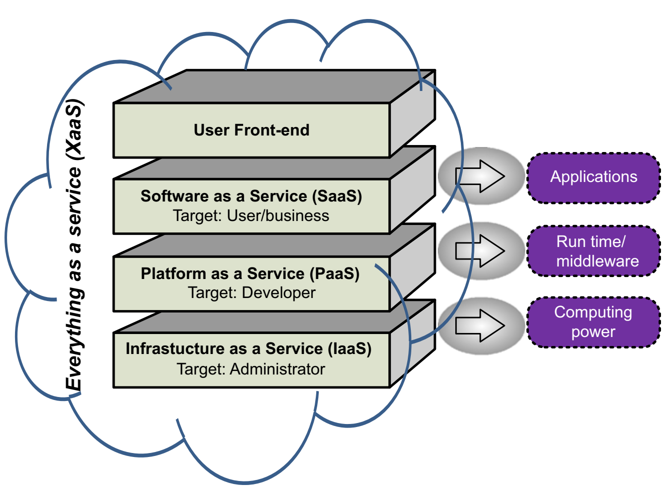

Fig. 1. Cloud computing: everything is a service.

2. Cloud computing systems

This section provides an abridged version of general architectural requirements for cloud computing as presented in [9]. Rimal et al. [9] classified architectural requirements into cloud *providers*, the *enterprises* that use the cloud, and cloud *users*.

2.1. Provider requirements

From the service provider’s perspective, highly efficient service architecture to support infrastructure and services is needed in order to provide virtualized and dynamic services. This section explains the requirements of a provider service delivery model and other key requirements.

2.1.1. Service delivery models

Software as a Service, Platform as a Service, and Infrastructure as a Service are three common types of service delivery models. These services are usually delivered through industry standard interfaces, such as Web services, service-oriented architecture (SOA) [10] or REpresentational State Transfer (REST) [11] services.

Software-as-a-Service is sometimes referred to as Application as a Service (AaaS). It offers a multi-tenant platform whereby common resources and a single instance of both the object code of an application and the underlying database are used to support multiple customers simultaneously. To this end, SaaS is also referred to as the Application Service Provider (ASP) model. Examples of the key providers are the Salesforce Customer

Relationships Management (CRM) system, NetSuite, and Google Office Productivity application. A major consideration in SaaS is effective integration with other applications. At the application level, the important aspects of scalability, performance, multi-tenancy, configurability, and fault-tolerance are primary considerations.

As the name implies, *Platform-as-a-Service* provides developers with a platform including all the systems and environments comprising the life cycle of development, testing, deployment and hosting of sophisticated web applications as a service delivered by a cloud-based platform. Commonly found *PaaS* includes Facebook F8, Salesforge App Exchange, Google App Engine, Bunzee connect and Amazon EC2. PaaS may offer a number of readily available services, which means that PaaS can support multiple applications on the same platform.

Infrastructure-as-a-Service is sometimes called Hardware as a Service (HaaS). IaaS promotes a usage-based payment scheme, meaning that customers pay as they use. This service is extremely useful for enterprise users as it eliminates the need for investing in building and managing their own IT systems. Another important advantage is the ability of having access to, or using, the latest technology as it emerges. On-demand, self-sustaining or self-healing, multi-tenant, customer segregation are the key requirements of IaaS [9]. GoGrid, Mosso/Rackspace, MSP On-Demand, and masterIT are some of the pioneer IaaS providers.

2.1.2. Other essential requirements

Other essential requirements are to do with service-centric issues, quality of service, interoperability, fault-tolerance, load balancing and virtualization management [9].

- Service-centric issues
  Cloud architecture needs to have a unified service-centric approach. The cloud services should have the ability to dynamically adapt to changes with minimum human assistance. Services need to be self-describing so that they can notify the client exactly how they should be called and what type of data they will return.
- Quality of Service (QoS)
  Like many services on offer, QoS provides a guarantee of performance, availability, security, reliability and dependability. QoS requirements are associated with service providers and end-users. Service Level Agreements (SLAs) are an effective means for assuring QoS between service providers and end-users. QoS may entail systematic monitoring of resources, storage, network, virtual machine, service migration and fault-tolerance. In the context of a Cloud service provider, QoS should emphasize the performance of virtualization and monitoring tools.
- Interoperability
  Interoperability is about creation of an agreed-upon framework/ontology, open data format or open protocols/APIs that enable easy migration and integration of applications and data between different cloud service providers. It is an essential requirement for both service providers and enterprises. Services with interoperability allow applications to be ported between clouds, or to use multiple cloud infrastructures before business applications are delivered from the cloud.
- Fault-tolerance
  Fault-tolerance presents the ability of a system to continue to operate in the event of the failure of some of its components. Application-specific, self-healing, and self-diagnosis mechanisms are for example enabling tools for cloud providers to detect failure. Once detected, fault is isolated and revision mode is activated.
- Load balancing
  Load balancing represents the mechanism of self-regulating the workloads within the cloud's entities (e.g. servers, hard drives, network and IT resources). Load balancing is often used to implement failover in that the service components are monitored continually and when one becomes non-responsive, the load balancer stops sending traffic, de-provisions it and provisions a new service component. A load balancer is another key requirement to build dynamic and stable cloud architecture.
- Virtualization management
  Virtualization refers to abstraction of logical resources from their underlying physical characteristics in order to improve agility, enhance flexibility and reduce cost [12]. Virtualization in the cloud may concern servers, client/desktop/applications, storage (e.g. Storage Area Network), network, and service/application infrastructure. Quality of virtualization determines the robustness of a cloud infrastructure. Good virtualization can effectively assist sharing of cloud facilities, managing of complex systems, and isolation of data/application.

2.2. Enterprise requirements

Enterprises are being constantly reminded about the services they are paying in terms of the service quality, service levels, privacy matters, compliances, data ownership, and data mobility. This section describes some of the cloud deployment requirements for enterprises.

2.2.1. Cloud deployment for enterprises

There are four types of cloud deployment models, public, private, community and hybrid clouds. These cloud services are ubiquitous as a single point of access. Different types of deployment models suit different situations. Public cloud realizes the key concept of sharing the services and infrastructure provided by an off-site, third-party service provider in a multi-tenant environment [13]. Private cloud entails sharing services and infrastructure provided by an organization or its specified service provider in a single-tenant environment. Enterprises' mission-critical and core-business applications are often kept in a private cloud. Community cloud is shared by several organizations and is supported by a specific community that has shared interests and concerns [2]. Hybrid cloud consists of multiple internal (private) or external (public) clouds. Added complexity of determining how to distribute applications across both private and public clouds can be challenging. Clearly, enterprises need to strategically leverage all four cloud deployment models.

2.2.2. Security

The notion of entrusting data to information systems that are managed by external entities on remote servers "in the cloud" causes varying levels of anxiety [7]. This is because corporate information often contains data of customers, consumers and employees, business know-how and intellectual properties. Popović and Hocenski [14] discussed security issues and challenges in detail. The above discussed service models (i.e. SaaS, PaaS and IasS) place different levels of security requirements in the Cloud environment. IaaS is the foundation of all cloud services, with PaaS built upon it and SaaS in turn built upon PaaS. Just as capabilities are inherited, so are the information security issues and risks [15].

2.2.3. Business Process Management (BPM)

Typically, a business process management system provides a business structure, security and consistent rules across business processes, users, organization and territory. Some of the examples of BPM applications include customer relationship management (CRM), workforce performance management (WPM), enterprise resource planning (ERP) and e-commerce portals. Cloud-based BPM (e.g. combining SaaS with a BPM application) enhances flexibility, deploy-ability and affordability for complex enterprise applications [9].

2.3. User requirements

Users' requirements are the third key factor for a willing and successful adoption of any cloud system in an enterprise. For users, trust is often a major concern. Trust-based cloud is therefore an essential and must-have feature [7]. This section describes user consumption-based billing and metering requirements, user-centric privacy requirements, service level agreements and user experience requirements.

2.3.1. User consumption-based billing and metering

When it comes to individual end-users and consumption-based billing and metering in a cloud system, an analogy can be drawn with the consumption measurement and allocation of water, gas or electricity on a consumption unit basis. Cost management is important for making planning and controlling decisions. Cost breakdown analysis, tracing the utilized activity, adaptive cost management, transparency of consumption and billings are also important considerations.

2.3.2. User-centric privacy

In cloud computing, some of the users' data (regarded as his/her personal intellectual property) are stored at mega-data centers located in the cyber space. In such an environment, privacy becomes a major issue [7,16]. There is strong resistance and reluctance of an enterprise storing any sensitive data on the cloud. Thankfully, there are various technologies that can enhance data integrity, confidentiality, and security in the clouds, e.g. data compressing and encrypting at the storage level, virtual LANs and network middle-boxes (e.g., firewalls and packet filters).

2.3.3. Service Level Agreements (SLAs)

Service level agreements are mutual contracts between providers and users for the assurance of a cloud provider to deliver the services that are agreed-upon. Currently, many cloud providers offer SLAs, but they are rather weak on user compensations on outages. Some of the important architectural issues are measurement of service delivery, method of monitoring performance, and amendment of SLA over time.

2.3.4. User Experience (UX)

The notion of UX is to provide an insight into the needs and behaviors of an end-user so as to maximize the usability, desirability and productivity of the applications. UX-driven design and deployment is the next logical step in the evolution of Cloud Computing. Cloud-based application/systems should be easy to use, capable of providing faster and reliable services, easily scalable, and customizable to meet the goal of localization and standardization. Human-Computer Interaction, ergonomics and usability engineering are some of the key technologies that can be used for designing UX-based Cloud applications [9].

3. Cloud computing in the context of manufacturing

In recent years, the philosophy of "Design Anywhere, Manufacture Anywhere (DAMA)" has emerged [17–19]. The DAMA approach demands the ability to exchange design and manufacturing data across multiple sites. DAMA also helps establish links between manufacturing resource planning, enterprise resource planning, engineering resource planning and customer relationship management. It is believed that cloud computing may play a critical role in the realization of DAMA. In general, there are two types of cloud computing adoptions in the manufacturing sector, manufacturing with direct adoption of some cloud computing technologies and cloud manufacturing—the manufacturing version of cloud computing.

3.1. Smart manufacturing with cloud computing

Cloud computing is rapidly moving from early adopters to mainstream organizations. It has become one of the top priorities of many CIOs in terms of strategic business considerations. Some manufacturing industry starts reaping the benefits of cloud adoption today, moving into an era of smart manufacturing with the new agile, scalable and efficient business practices, replacing traditional manufacturing business models.

In terms of cloud computing adoption in the manufacturing sector, the key areas are around IT and new business models that the cloud computing can readily support, such as pay-as-you-go, the convenience of scaling up and down per demand, and flexibility in deploying and customizing solutions. The adoption is typically centered on the BPM applications such as HR, CRM, and ERP functions with Salesforce and Model Metrics being two of the popular PaaS providers (refer to Section 2.2.3).

The cost benefit of adopting clouds in a typical manufacturing enterprise can be multiple. The savings obtained from the elimination of some of the functions that were essential in traditional IT can be significant. With cloud-based solutions, some application customizations and tweaks that the company needs at the process level may be dealt with by the company's IT sector along with some of the smart cloud computing technologies. When a different way of executing a process is initiated, the IT staff can make the change happen seamlessly and in less time [20]. Elkay Manufacturing Company, a world leader in stainless steel sinks, water coolers and kitchen cabinets, is one of the manufacturing companies that have successfully adopted and benefited from cloud computing technologies [20].

When it comes to supporting smart business processes, cloud computing can be effective in offering Business-to-business (B2B) solutions for commerce transactions between businesses, such as between a manufacturer and a wholesaler, or between a wholesaler and a retailer. Cloud-based solutions enable better-integrated and more efficient processes.

Cloud computing can also be used to enhance many other aspects of manufacturing businesses by moving a traditional process to the cloud for improved operational efficiency. For example, cloud computing can assist the development of an application for customer on-boarding process that is more efficient than the traditional process of company on-boarding customers. The procedure for a company to on-board customers may involve a salesperson visiting a prospective customer, the customer filling in a form, company credit checking etc. A Cloud-based customer on-boarding process may do all of these automatically via cloud resources on the Internet.

Collaboration at scale using cloud technology is an emerging business trend according to McKinsey [1]. Adopting cloud technologies, enterprise collaboration can happen at a much broader scale. Within the organization, demand planning and supply chain organization can be tied into a cloud-based system, allowing different parts of the organization to take a peek into the opportunities that their sales teams are working on. In a more traditional environment, that would involve a few sit-down meetings, several face-to-face discussions, or phone conversations.

The cloud in this case provides a collaborative environment that can give people agility, more transparency, and empowerment through more effective collaborations.

Typically, there are some parts of the manufacturing firm that can quickly and easily adopt cloud-based solutions, whereas other areas are better to remain traditional. Hence, what a cloud-adopting manufacturing enterprise also requires is a smart mechanism to deal with integration. Solutions such as Cast Iron are addressing some aspects of such integration; vendors such as Model Metrics are pitching in as well.

3.2. Cloud manufacturing

With cloud manufacturing, what comes into one's mind first is the existing networked manufacturing concept, or sometimes called Internet-based manufacturing or distributed manufacturing. However, today's networked manufacturing mainly refers to integration of distributed resources for undertaking a single manufacturing task [21,22]. What is lacking in this type of manufacturing regime are the centralized operation management of the services, choice of different operation modes and embedded access of manufacturing equipment and resources, without which a seamless, stable and high quality transaction of manufacturing resource services cannot be guaranteed. In a typical distributed manufacturing environment, the resource service provider and resource service demander have little coordination. Thus, adoption of the networked manufacturing concept has been slow and less effective.

Moving from production-oriented manufacturing to service-oriented manufacturing and inspired by cloud computing, cloud manufacturing seems to offer an attractive and natural solution. cloud computing is viewed as the evolution and convergence of several independent computing trends such as Internet delivery, "pay-as-you-go" utility computing, elasticity, virtualization, grid computing, distributed computing, content outsourcing and Web 2.0 [3]. Likewise, cloud manufacturing is also considered as a new multidisciplinary domain that encompasses technologies such as networked manufacturing, manufacturing grid (MGrid), virtual manufacturing, agile manufacturing, Internet of things, and of course cloud computing. Cloud manufacturing reflects both the concept of "integration of distributed resources" and the concept of "distribution of integrated resources". Mirroring NIST's definition of cloud computing, cloud manufacturing may be defined as "*a model for enabling ubiquitous, convenient, on-demand network access to a shared pool of configurable manufacturing resources (e.g., manufacturing software tools, manufacturing equipment, and manufacturing capabilities) that can be rapidly provisioned and released with minimal management effort or service provider interaction.*"

In Cloud manufacturing, distributed resources are encapsulated into cloud services and managed in a centralized way. Clients can use the cloud services according to their requirements. Cloud users can request services ranging from product design, manufacturing, testing, management and all other stages of a product life cycle. A cloud manufacturing service platform performs search, intelligent mapping, recommendation and execution of a service. Fig. 2 illustrates a cloud manufacturing system framework, which consists of four layers, manufacturing resource layer, virtual service layer, global service layer and application layer.

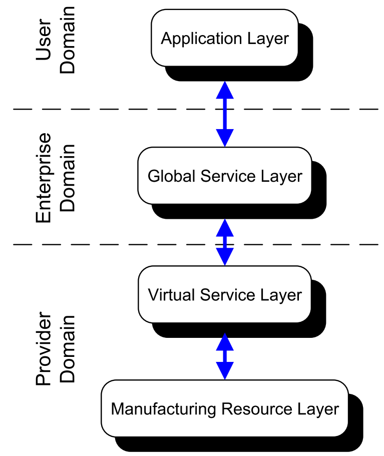

Fig. 2. Layered architecture of a cloud manufacturing system.

3.2.1. Manufacturing resource layer

The manufacturing resource layer encompasses the resources that are required during the product development life cycle. These manufacturing resources may take two forms, manufacturing physical resources and manufacturing capabilities. Manufacturing physical resources can exist in the hardware or software form. The former includes equipment, computers, servers, raw materials, etc. The latter includes for example simulation software, analysis tools, "know-hows", data, standards, employees, etc. Manufacturing capabilities are intangible and dynamic recourses representing the capability of an organization undertaking a particular task with competence. These may include product design capability, simulation capability, experimentation, production capability, management capability, and maintenance capability. The types of service delivery models that may exist at this layer are IaaSs and SaaSs.

3.2.2. Manufacturing virtual service layer

The key functions of this layer are to (a) identify manufacturing resources, (b) virtualized them, and (c) package them as cloud manufacturing services. Comparing with a typical cloud computing environment, it is much more challenging to realize these functions for a cloud manufacturing application.

A number of technologies can be used for identifying (or tagging) manufacturing resources [23–25], e.g. RFID, computational RFID, wireless sensor networks (WSN), Internet of things, Cyber Physical Systems, GPS, sensor data classification, clustering and analysis, and adapter technologies.

Manufacturing resource virtualization refers to abstraction of logical resources from their underlying physical resources. Quality of virtualization determines the robustness of a cloud infrastructure. Different manufacturing resources are virtualized in different ways. Computational resources and manufacturing knowledge can be virtualized in similar ways as are the general Cloud computing resources. Manufacturing hardware is usually mapped to become virtual machines that are system-independent. Virtualization managers (e.g. Virtual Machine Monitor and Virtual Machine Manager (VMM)) are responsible for communicating with the lower level devices, and coordinating and allocating virtual machines.

Agent can be an effective tool for virtualization. Take MTConnect [26–28] as an example. MTConnect is a standard based on an open protocol for data integration. Although it is for enhancing data acquisition capabilities of machine tools, the use of agent technology provides a plug-and-play environment for manufacturing facilities, which has the potential to support cloud manufacturing. Fig. 3 shows a schematic of a factory system with three machine tools that are virtualized and integrated via MTConnect agents. It needs to be pointed out though that MTConnect mainly supports monitoring processes.

The next step is to package the virtualized manufacturing resources to become cloud manufacturing services. To do this, resource description protocols and service description languages can be used. The latter may include different kinds of ontology languages,

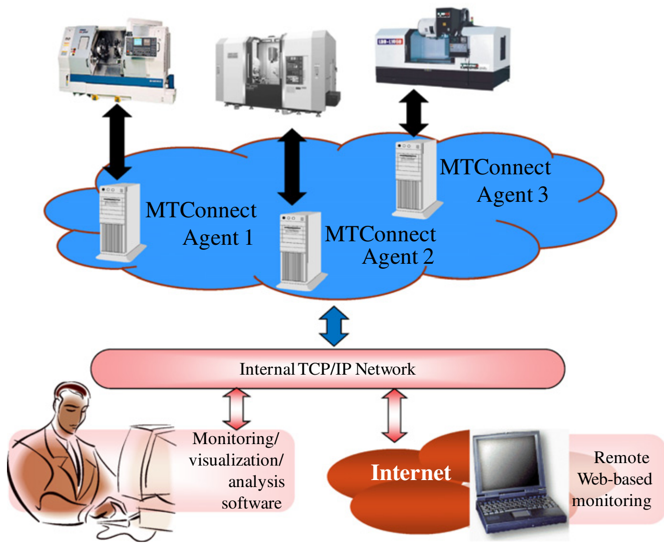

Fig. 3. Cloud manufacturing resources enabled by MTConnect.

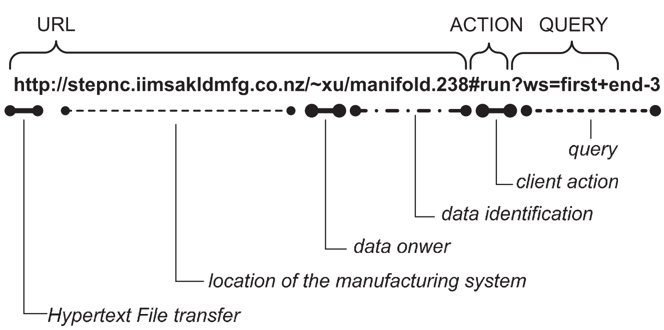

Fig. 4. A STEP resource locator for STEP-enabled manufacturing.

e.g. Simple HTML Ontology Extension (SHOE), DARPA Agent Markup Language (DAML), and Web Ontology Language (OWL).

In a STEP-enabled, networked manufacturing process planning environment [29–32], a STEP resource locator (STRL for short) represents a simplest form of cloud manufacturing service. STRL consists of a URL, an Action and a Query (Fig. 4). STRL is similar to the concept of giving a URL address through the Web. The URL gives the name (location) of the system and data identification. It can therefore be used as a link to a particular manufacturing resource, e.g. a data file, workingstep (machining step), program, etc. For example, if an STRL as shown in Fig. 4 is activated, we will know that the client has requested the job (as described by file manifold.238) to be machined (run) from the first line until the end for all the three workingsteps.[1]

To describe manufacturing capability, Zhang et al. [34] used a four-dimension array: (Task, Resource, Participator, Knowledge). Task denotes a manufacturing job; Resource denotes the manufacturing resources that are needed to do the task; Participator represents human resources needed for the job; and Knowledge represents all the knowledge required to do the job.

3.2.3. Encapsulating manufacturing resources with mapping

The process of virtualizing a manufacturing resource can also be viewed as an encapsulating process, which can be carried out using three different mapping methods, one-to-one, many-to-one, and one-to-many.

One-to-one mapping is the simplest situation, which applies to manufacturing resources that can only provide a single function and can therefore directly be encapsulated into one service. The CAD and CAE data format exchange service is one of the common types of such resource. For example, Creo Elements/Pro can save a *.iv file that is to, and can only, be read by Autodesk's Inventor. Vice versa, Inventor can save a *.prt file only for Creo Elements/Pro to read in. An EDM tool is another example that can only carry out the EDM process.

In a many-to-one mapping, multiple resources (each providing a specific function) may be combined to create a more powerful or functional resource form. For example, the ADINA software can provide mesh function, and SOLIDCast software can simulate a casting process. When combined, these two resources can provide a generic simulation service. At the user end, such combination of multiple resources is invisible. In cloud manufacturing, when multiple manufacturing resources are combined, more comprehensive manufacturing resource services called resource service composition can be provided to users to enable value-added services. Zhang et al. [34] and Guo et al. [35] discussed the flexibility issues of resource service compositions. For example, use of a particular machine tool for a manufacturing job may lead to generation of a specific CAM program for machining and a specific CMM program for inspection. All of these will only appear to the client as one manufacturing service. It is up to the resource provider to seek a way of delivering the service and guarantee the quality. Manufacturing of complex mechanical components, e.g. car engine block and alloy wheel, may call upon multiple resources, e.g. casting equipment, machine tools and heat treatment facilities.

The one-to-many mapping concerns with a single resource that appears to a client as a multiple resource. The client interfaces with the virtualized resources as though he/she is the only consumer. In fact, the client is sharing the resource with other users. For example, ANSYS software can provide structure analysis, thermal analysis, magnetic analysis, and computational fluid dynamics analysis. Therefore, ANSYS software can be encapsulated by many different services.

3.2.4. Enterprise requirements—Global Service Layer

The Global Service Layer relies on a suite of cloud deployment technologies (i.e. PaaS). Internet of things has advanced to a new level with RFID, intelligent sensors, and nano-technology as the supporting technologies. Interconnections between physical devices or products are made easier because of Internet of things. Having said this, a centralized and effective management regime needs to be in place to provide manufacturing enterprises with agile and dynamic cloud services. Based on the nature of the provided cloud resources and the user's specific requirements, two types of cloud manufacturing operation modes can take place at the Global Service Layer, complete service mode and partial service mode.

In a complete service mode, the Global Service Layer takes full responsibility of the entire cloud operational activities. The type of cloud service that suits this mode is virtualized computing resources, e.g. CPU, RAM, and network. These cloud services can be dynamically monitored, managed and load-balanced with ease. Application software is also suitable for the complete service mode in that running and execution of software can take place in a distributed computing environment taking advantage of grid computing and parallel computing. Knowledge, human resources, and manufacturing capabilities may also be managed at the Global Service Layer in a complete service mode.

It is possible and sometimes necessary to partially hand over an activity to the cloud manufacturing service—hence a partial service mode. In such a mode, the service provider provides

[1] The workingsteps represent technology-independent actions in STEP-NC such as rapid movements or probing operations, and machining workingsteps that relate to the different technologies like milling, drilling, turning, etc.

additional input and operational activities. Typically, manufacturing hardware (e.g. machine tools and experiment devices) is this type of cloud services. The Global Service Layer is mainly responsible for locating, allocating, fee-calculating and remote monitoring the manufacturing resources. The hardware providers are still responsible for executing the manufacturing tasks and ensuring the quality of the manufacturing job.

In order to meet the above enterprise requirements, some critical technologies are needed. For example, optimal resource selection and allocation methods are needed to guarantee an effective cloud manufacturing service. Theories such as Intuitionistic Fuzzy Set, Partial Swarm Optimization, and Quantum Multi-agent Evolutionary Algorithm can be handy when developing an enabling technology. Evaluation and management of QoS is another important exercise at this layer [22,33].

3.2.5. *User requirements–Application Layer*

The Application Layer serves as an interface between the user and manufacturing cloud resources. This layer provides client terminals and computer terminals. Some examples of interfaces are complex system modeling tools, generic simulation terminals, and new product development utilities. The user can define and construct a manufacturing application through the virtualized resources. Such a manufacturing application often involves more comprehensive manufacturing resource services that provide users with a value-added service [34,35].

Similar to cloud computing, end-user consumption-based billing and metering in cloud manufacturing resembles the consumption measurement and allocation of costs of water, gas, and electricity. Users often have a demand for transparency of consumption and billings. Activity-Based Costing [36] can be a useful profiler that the user can use to understand how much their implementation will cost in terms of cloud manufacturing charges, hence enhance cost transparency.

The issue of user-centric privacy is a thorny one. The main concern with cloud manufacturing for end-users is related to the storage of personal/enterprise sensitive data. This data includes not only product information but also information of some of the high-end manufacturing resources. There are some technologies that can enhance data integrity, confidentiality and security over cloud Manufacturing [9]. They are

- data compressing and encrypting at the storage level,
- virtual LANs, that can offer secure remote communications, and
- network middle-boxes (e.g., firewalls, packet filters), for fail-safe communications.

A rigorous Service Level Agreements for cloud manufacturing is a must to win any end-user's trust and confidence over the services. When manufacturing hardware is involved, SLAs are particularly important as hardware failure is more difficult to recover from.

Data portability at the Application Layer is another important matter. Open data format and open APIs have been suggested [9]. Industry vendors and users have been seeking a common language to be used for the entire product development life cycle that can describe design, manufacturing, and other data pertaining to a product. Many solutions were proposed, the most successful being the Standard for Exchange of Product data (STEP) [32,37]. STEP provides a mechanism that is capable of describing product data, independent of any particular system. The nature of this description makes it suitable not only for neutral file exchange, but also as a basis for implementing, sharing and archiving product data over a cloud manufacturing system. ISO 10303-AP203 [38] is the first and perhaps the most successful AP (Application Protocol) developed to exchange design data between different CAD systems. Going from geometric data (as in AP203) to features (as in AP224) represents an important step towards having the right type of data in a STEP-based CAD/CAM system. Of particular significance is the publication of STEP-NC [39–41], as an extension of STEP to NC, utilizing feature-based concepts for CNC machining purposes. STEP and STEP-NC can therefore provide a common information ground for cloud manufacturing at the Application Layer.

4. Research contributions to the concept of cloud manufacturing

Although the concept of cloud manufacturing is new, virtual enterprise and distributed manufacturing concepts have been around for awhile and some of the proposed systems and frameworks bear visible traces of cloud manufacturing or make contributions to a cloud manufacturing system. This section discusses some of these research outcomes.

4.1. *Service-oriented manufacturing environment*

Brecher, et al. [42] recognized that applications in an information-intensive manufacturing environment can be organized in a service-oriented manner. They proposed a module-based, configurable platform for interoperable CAD-CAM-CNC planning. The goal is to combat the problems of software inhomogeneity along the CAD-CAM-NC chain. The approach is called open Computer-Based Manufacturing (openCBM) in support of co-operative process planning (Fig. 5). To implement the architecture and integrate inspection tasks into a sequence of machining operations, STEP standard is utilized to preserve the results of manufacturing processes that are fed back to the process planning stage [43]. The openCBM platform is organized through a service-orient architecture providing the abstractions and tools to model the information and connect the models [45]. It is much like the Platform as a Service concept and resembles an Application Layer, where applications are not realised as monolithic programs, but as a set of services that are loosely connected to each other, guaranteeing the modularity and reusability of a system. The module providers as shown in the figure form the Manufacturing Virtual Service Layer and the module database forms a Global Service Layer.

4.2. *SaaS for engineering simulations*

To achieve a run-time configuration integration environment for engineering simulations, van der Velde [45] reported a plug-and-play framework for the construction of modular simulation software. In this framework (Fig. 6), the user (at the Application Layer as in a cloud manufacturing system) is allowed to select a target of simulation and assign the performer of the simulation called "component" before running the selected components. These components are effectively software entities (or otherwise known as SaaS as in cloud computing/manufacturing). They are modulised, self-contained, mobile and pluggable. After the simulation, the output is post-processed through the components. In such architecture, software modules are detected, loaded and used at run-time with the framework (i.e. the Global Service Layer) needing no prior knowledge of the type and availability of components, thus providing true plug-and-play capabilities.

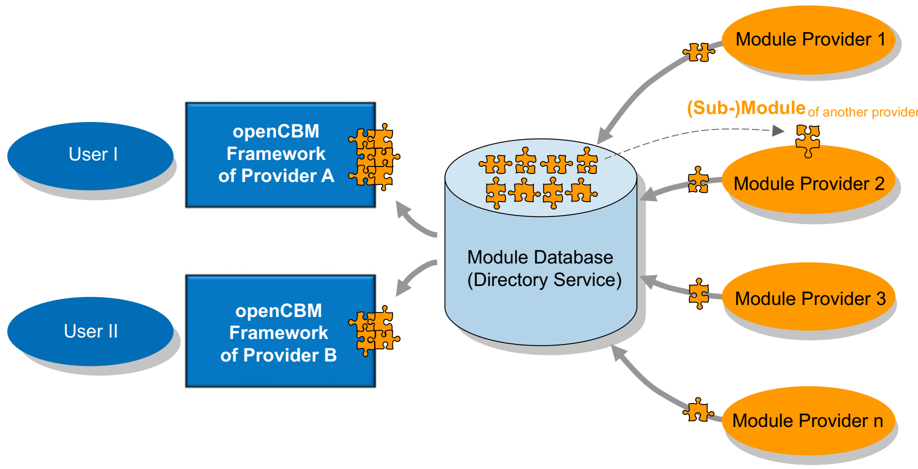

Fig. 5. Module users and providers of the openCBM approach [42].

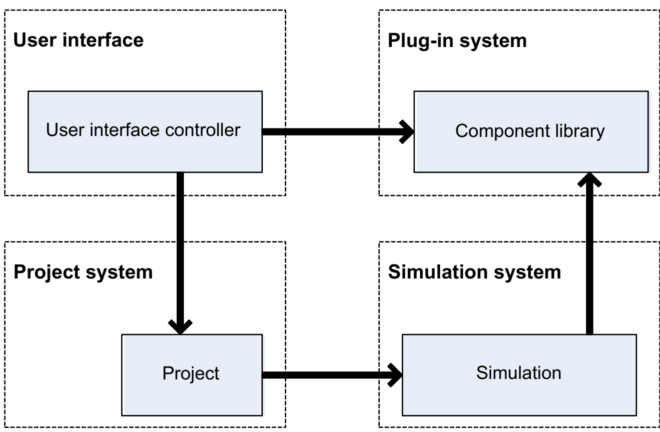

Fig. 6. Main elements of the plug-and-play framework.

4.3. *Some embryonic cloud manufacturing systems*

This section presents a few embryonic or quasi-cloud manufacturing systems that are developed in the recent years. Although these systems vary in their structures and application domains, the philosophy and underpinning concepts are converging toward those of cloud manufacturing.

Nessehi et al. proposed a framework to comeback the incompatibility problem among CAx systems [46]. Much like an IaaS, the platform provides individual interfaces for different CAD/CAM/CNC systems. A comprehensive data warehouse is utilized to store CNC manufacturing information with STEP-NC data model utilized as the basis for representing manufacturing knowledge that is augmented with XML schema. Such knowledge information is categorized into product information, process information and resource information. The platform is further explained in [46], where the system consists of manufacturing data warehouse, manufacturing knowledgebase, intercommunication bus, and various CAx interfaces as the main structure (Fig. 7). Mobile agent technology is used to support the intercommunication bus and CAx interfaces. In the system, different components of the CAD/CAM/CNC chain can exchange information with one another regardless of their native standards.

More recently, Mokhtar and Houshmand [48] studied a similar manufacturing platform, using the axiomatic design theory to realize interoperability among the CAx chain. The methodology of axiomatic design is proposed to generate a systematic roadmap of an optimum combination of data exchange via direct (using STEP neutral format) or indirect (using bidirectional interfaces) solution in the CAx environment (Fig. 8). This approach provided some insight into how a design and manufacturing resource may be encapsulated and how Global Service Layer may be developed for cloud manufacturing.

UbiDM, a concept of design and manufacture via ubiquitous computing technology, is proposed by the researchers in POSTECH, Korea [49]. The key aspect of UbiDM is the utilization of the entire product life cycle information obtained via ubiquitous computing technology for product design and manufacture (Fig. 9). To support the concept, a Ubiquitous Product Life Cycle Support (UPLS) system is presented as well [50]. Module and agent concepts are mentioned in the function of the request-find-provide chain. A unified product life cycle data model, which is compliant with international standards, is utilized for data exchanges. The model represents the input and output information used in the life cycle activity, in the stages of Beginning-Of-Life (BOL), Middle-Of-Life (MOL), and End-Of-Life (EOL).

Wang and Xu [51,52] proposed a Distributed Interoperable Manufacturing Platform (DIMP) as an integrative environment among existing and future CAD/CAM/CNC applications. It is a module-based structure. In order to integrate the software suites based on the requests and tasks from a user, service-oriented architecture is used. In DIMP, user's requests are collected and organized as a serial of software services. From the service point of view, heterogeneous software tools are integrated as "Virtual Service Combinations" and provided to the user. In this way, software suites are embedded into operational processes.

Both STEP and STEP-NC data models are utilized as the central data schema. With "coupling" technologies, STEP and STEP-NC data models can be connected to commercial CAD/CAM software suites, giving the system much needed portability. DIMP aims to integrate software applications (i.e. SaaS) based on the request from users. The platform is capable of handling requests from users such as task objects, software functionality and input/output requirements, and then organizing a serial of software services, which forms a "request-find-combine-provide" loop. As depicted in Fig. 10, DIMP has a User Domain and a Platform Domain. The User Domain is effectively the Application Layer as in Cloud Manufacturing. The Platform Domain contains the Resource Layer and Provider Layer. An important feature of the system is its service-oriented supervision mechanism. Consisting of an interface agent, broker agent and supervision agent, the Supervisory Module is connected with the other modules directly, e.g. Database Module and Application Warehouse Module. The latter represents the cloud manufacturing resources.

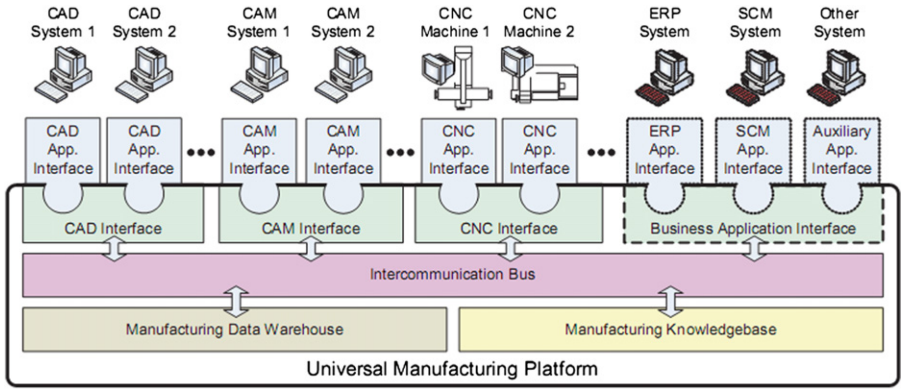

Fig. 7. Universal manufacturing architecture [47].

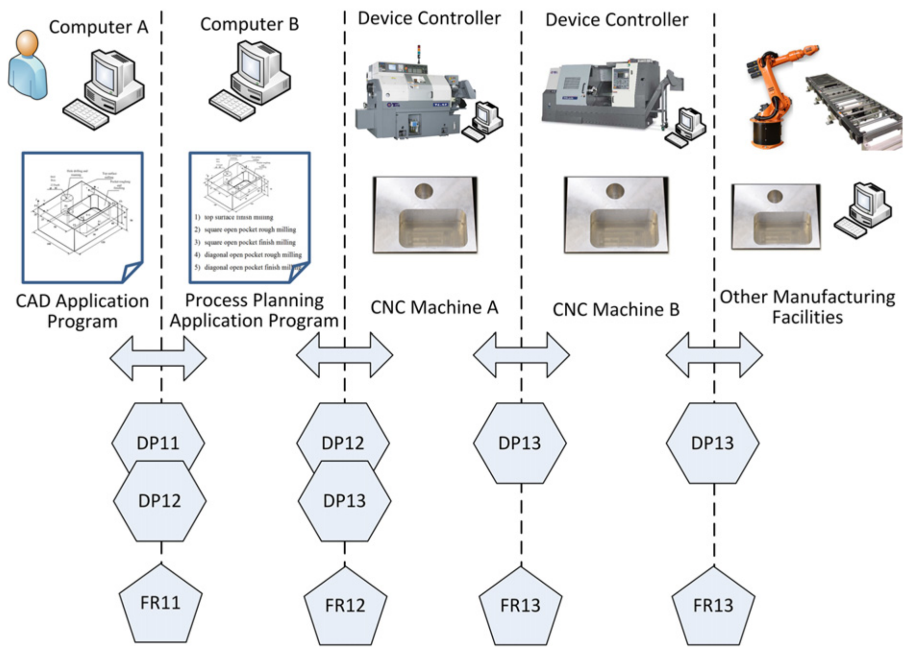

Fig. 8. Data exchange in a typical production echelon, the shop floor level [48].

The Supervision Module is a decision maker and core supervisor for the platform. The Interface agent collects requirements from a user. After proposing a set of tasks to the user, the Interface agent gives the user access to a list of available application modules and translates the result into a service description in a predefined format before passing it to the Broker agent. The Broker agent searches for available modules in the Application Warehouse and chooses the best composition of the Cloud Manufacturing resources. As an approach to scenario generation, an optimized list of tasks and events is generated and passed to the Supervision agent. Based on this list, selected software tools will be packaged and provided to the user.

So far, there has been no report on a developed cloud manufacturing system. However, the above-mentioned systems and concepts echo the spirit of cloud manufacturing and provide some essential technological support.

5. Conclusions

Cloud computing is changing the way industries and enterprises do their businesses. With wider cloud adoption, access to business-critical data and analytics will not just help enterprises stay ahead, it will also be crucial to their existence. There are three architectural features of cloud computing in terms of the requirements of end-users, enterprises that use the cloud as a platform, and cloud providers themselves. These architectural features play a major role in the adoption of the cloud computing paradigm as a mainstream commodity in the enterprise world.

Cloud computing is emerging as one of the major enablers for the manufacturing industry, transforming its business models, helping it align product innovation with business strategy, and creating intelligent factory networks that encourage effective collaboration. This pay-by-use scenario will revolutionize manufacturing in the same way that the Internet has already revolutionized our everyday and business lives. Manufacturing shops are starting to take advantage of cloud computing because it simply makes good economic sense. Two types of cloud computing adoptions in the manufacturing sector have been suggested, manufacturing with direct adoption of cloud computing technologies and cloud manufacturing—the manufacturing version of cloud computing.

In terms of direct adoption of cloud computing in the manufacturing sector, the key areas are around IT and new business models, e.g. pay-as-you-go, production scaling up and down per demand, and flexibility in deploying and customizing solutions.

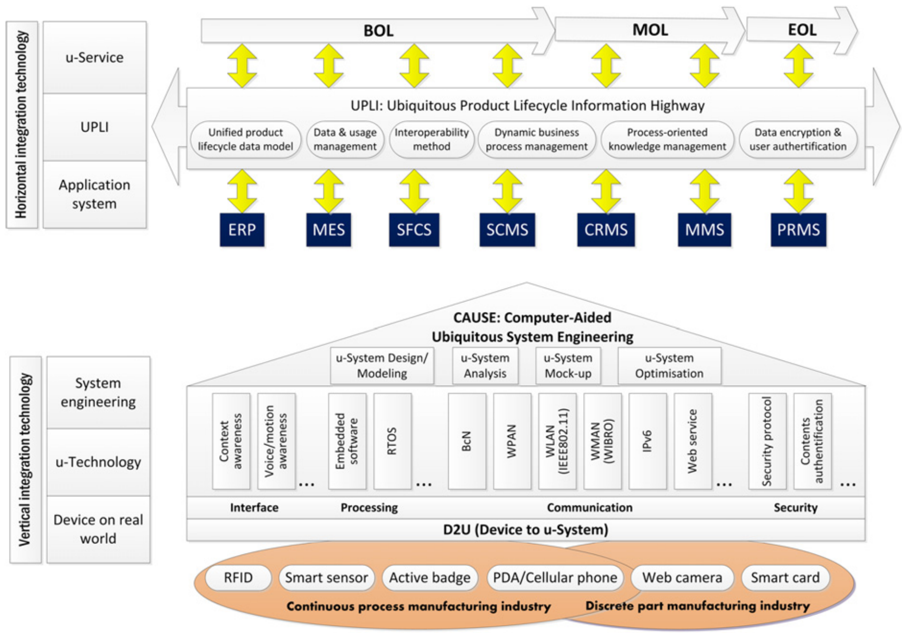

Fig. 9. System spectrum of the UbiDM [50].

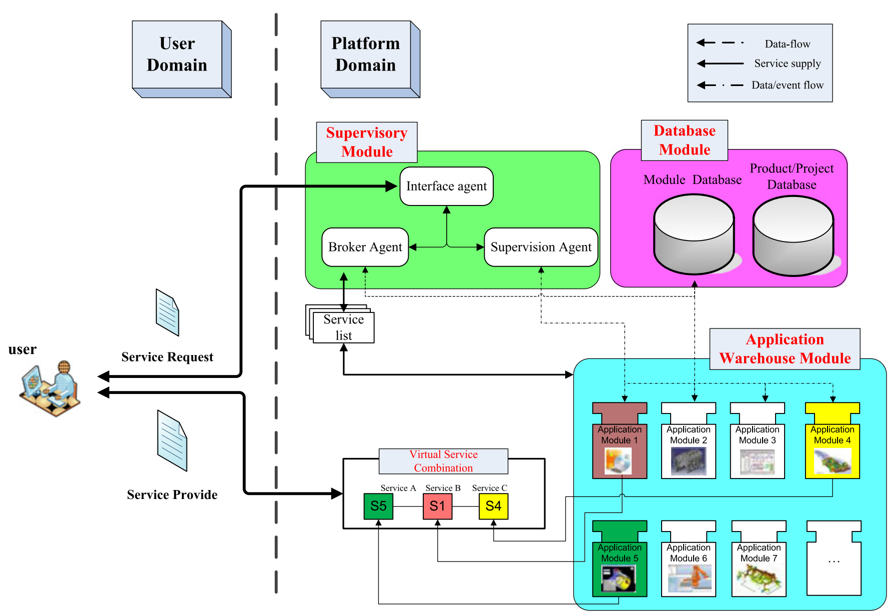

Fig. 10. Service-oriented DIMP architecture.

The HR, CRM, and ERP functions may benefit from using some emerging PaaS. Cloud computing can be effective in offering Business-to-Business solutions for commerce transactions between businesses, such as between a manufacturer and a wholesaler, or between a wholesaler and a retailer.

Moving from production-oriented manufacturing to service-oriented manufacturing, cloud manufacturing seems to offer an attractive and natural solution. In cloud manufacturing, distributed resources are encapsulated into cloud services and managed in a centralized way. Clients can use cloud services according to their requirements. Cloud users can request services ranging from product design, manufacturing, testing, management and all other stages of a product life cycle. The cloud manufacturing service platform performs search, mapping, recommendation, and execution of a service. Two main types of manufacturing resources can be considered at the manufacturing resource layer, manufacturing physical resources, and manufacturing capabilities.

Although the concept of cloud manufacturing is relatively new, virtual enterprise, and distributed manufacturing concepts have been around for a while and some of the proposed systems and frameworks bear the trace of cloud manufacturing, e.g. development of a service-oriented manufacturing environment and different SaaS for engineering applications. There are also some embryonic cloud manufacturing systems developed in the past 2–3 years. In response to concerns about cloud computing adoption for manufacturing businesses, enterprises need to address them in constructive and positive ways. The IT professionals as well as personnel from other manufacturing departments need to work hand in hand to look for solutions to the problems. It can be anticipated that cloud manufacturing will provide effective solutions to the manufacturing industry that is becoming increasingly globalized and distributed. Cloud manufacturing means a new way of conducting manufacturing businesses, that is everything is perceived as a service, be it a service you request or a service you provide.

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