An Interoperable Solution for Cloud Manufacturing

Xi Vincent Wang, Xun W Xu*

Department of Mechanical Engineering

Faculty of Engineering, University of Auckland, Auckland 1142, New Zealand

*xun.xu@auckland.ac.nz

Cloud Manufacturing is a new concept extending and adopting the concept of Cloud Computing for manufacturing. The aim is to transform manufacturing businesses to a new paradigm in that manufacturing capabilities and resources are componentized, integrated and optimized globally. This study presents an interoperable manufacturing perspective based on Cloud Manufacturing. A literature search has been undertaken regarding Cloud architecture and technologies that can assist Cloud Manufacturing. Manufacturing resources and capabilities are discussed in terms of Cloud service. A service-oriented, interoperable Cloud Manufacturing system is proposed. Service methodologies are developed to support two types of Cloud users, i.e. customer user and enterprise user, along with standardized data models describing Cloud service and relevant features. Two case studies are undertaken to evaluate the proposed system. Cloud technology brings into manufacturing industry with a number of benefits such as openness, cost-efficiency, resource sharing and production scalability.

KEYWORDS

Cloud, Cloud Computing, Cloud Manufacturing, Service-Oriented Architecture, STEP

AI	Artificial Intelligence
API	Application Protocol Interface
BA	Broker Agent
BiA	Billing Agent
CAx	Computer-Aided applications
CComputing	Cloud Computing
CDA	Change Detection Agent
CIA	Customer Interface Agent
CManufacturing	Cloud Manufacturing
CMService	Cloud Manufacturing Service
CNC	Computer Numerical Control
CService	Cloud Service
CU	Customer User
CUser	Cloud User
EIA	Enterprise Interface Agent
ERP	Enterprise Resource Planning
EU	Enterprise User
GUI	Graphical User Interface
MCapability	Manufacturing Capability

MCloud	Manufacturing Cloud
MResource	Manufacturing Resource
RRA	Resource Recognition Agent
SA	Supervision Agent
SCloud	Storage Cloud
SCM	Smart Cloud Manager
SME	Small and Medium-sized Enterprise
SOA	Service-Oriented Architecture
SProvider	Service Provider
ST	Service Template
STEP	STandard for Exchange of Product data

1. Introduction

Cloud Computing (CComputing) is a model for enabling ubiquitous, convenient and 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 interactions [1, 2]. It provides resources to a user on the "pay-as-you-go" basis. There are three common types of CComputing structure, i.e. Infrastructure as a Service (IaaS), Platform as a Service (PaaS), and Software as a Service (SaaS). IaaS provides a bunch of physical and virtual machines, based on which users are able to install and deploy their own operation systems and working environments. A PaaS model packages a computing platform including operating system, programming language execution environment, database, and web server. A PaaS client is able to develop and run its applications at the software layer. Finally, SaaS simplifies the utilization of a large amount of software applications remotely, elastically and seamlessly.

During the past few years, many successful CComputing business cases are found world-widely [3-7]. Among various types of models, the key characteristic of CComputing is that of pay-as-you-go. In the increasingly globalized manufacturing context, customer-oriented manufacturing is a promising approach to improving the service quality and competitiveness, in particular for the Small and Medium-sized Enterprises (SMEs). Thus, a new concept of advanced manufacturing model is proposed in this research, namely Cloud Manufacturing (CManufacturing).

2. CManufacturing - the Next Generation Manufacturing Model

CManufacturing is a model for enabling ubiquitous, convenient and 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 interactions [8]. Like CComputing concept, manufacturing infrastructure, platform and software application in CManufacturing can be offered as a service to a CUser. By extending the concept to a broader scope, all the production objects and features can be treated as a service, hence Everything-as-a-Service (XaaS). The rest of this section discusses the CManufacturing structure and related technologies.

2.1. State-of-art Cloud Manufacturing Approaches

Cloud concept presents a promising future for computing business and the same can be said for manufacturing business. Tao et al. [9] proposed a framework of CManufacturing with discussions of key advantages and challenges for future CManufacturing systems. It is predicted that a CManufacturing system would reduce the cost and increase the utilization rate of resources. Li et al. [10] proposed a service-oriented networked manufacturing model. The paper also discussed a number of methods to support the model. Intelligent agent, Product Lifecycle Management (PLM), resource modelling and evaluating technologies are considered as the supporting technologies for Cloud architecture.

A Cloud-based manufacturing research project [11] was launched in Europe in 2010, sponsored by the European Commission. The goal of this project is to provide users with the ability to utilize the manufacturing capabilities of configurable and virtualized production networks. A set of software-as-a-service applications have been developed. In the proposed system, customized production of technologically complex products is enabled by dynamically configuring a manufacturing supply chain [12, 13]. It is believed that the development of a front-end system with a next level of integration to a

Cloud-based manufacturing infrastructure is able to better support on-demand manufacture of customized products.

To facilitate a CManufacturing environment, existing resources need to be scaled, modelled and adapted into the Cloud. Wu and Yang [14] proposed a method to describe and scale manufacturing resources in a Cloud. Hu et al. [15] analysed the factors that affect the classification of virtual resources in CManufacturing. Examples are introduced to validate the effect of these factors to task assignment. Luo et al. [16] discussed a CManufacturing system from the viewpoint of network, function and running. A multi-dimensional information model was proposed to describe manufacturing abilities [17]. This knowledge-based data model helps provide a user with manufacturing services via network.

To control and manage the flexibility of the resource service composition in CManufacturing, Zhang et al. [18] proposed architecture considering major uncertain dynamic changing factors in the life-cycle of a resource service. Multi-agent is proved to be an effective tool in solving problems through sharing knowledge during the implementation of CManufacturing [19]. An Agent-based Mechanism provides flexible and effective sharing and utilizing of elastic resources.

After resource modelling, the next challenge is resource integration. Fan et al. [20] proposed integrated architecture of CManufacturing based on a federation principle. Federation integration rules are applied before resources are connected to the system. Thus, joining or exiting of a resource would not affect operation of the whole Cloud environment. To maintain the CManufacturing resources, an Optimal Allocation of Computing Resources (OACR) system was proposed [21]. In OACR, improved Niche immune algorithm is introduced to solve the resource scheduling problem in a grid system or CComputing system, associated with the Niche strategy.

2.2. Supporting Technologies for Cloud Manufacturing

Although CManufacturing is still a relatively new concept, it draws upon technologies such as virtual enterprise, distributed and collaborative manufacturing systems. Xu [8] reviewed the systematic requirements of CManufacturing systems. Advanced manufacturing technologies are discussed to fulfil these specifications and support a CManufacturing environment. Research contributions are reviewed regarding collaborative manufacturing and interoperable systems [22]. Manufacturing systems are re-evaluated from the Cloud perspective, e.g. IaaS and SaaS. In addition, ERP (Enterprise Resource Planning), SOA (Service-Oriented Architecture), and modelling systems are also relevant to the concept of CManufacturing.

After the manufacturing activities are properly modelled, the next step is to integrate their operational processes. To represent a business in a Manufacturing Cloud (MCloud), the first step is to understand and model an enterprise. ERP systems have been studied extensively [23-27], including the inter-organization performance [28] and the behaviour throughout the supply chain with multiple stakeholders [29]. With the help of ERPs, inter-organization behaviours/reactions can be modelled and mapped in a standardized manner as neutral APIs (Application Protocol Interfaces). Based on these APIs, MCloud can be established via integrating these reactions in standardized semantics, without changing the organizational structure of an enterprise.

Papazoglou and van den Heuvel [30] proposed a framework named Enterprise Service Bus. It is an integration platform that utilizes web services standards to support SOA applications within an enterprise. The extended SOA system can be further adopted by CManufacturing to enable capabilities such as service orchestration, "intelligent" routing, provisioning, integrity and security of message as well as service management. In an SOA system, business procedures can be modelled and componentized to support seamless business integration [31]. Schmidt et al. [32] proposed architecture declaring clear definitions of service capability and requirements in a service-oriented context. Models have been proposed to evaluate the quality/feedback in the business-to-business context [33].

It has been suggested that a commonly used data model/schema should be utilized for a wide range of products [34]. Data management should be encapsulated by schema and manipulation rules in a data model. In the perspective of CManufacturing, international standards, e.g. STEP/STEP-NC have a role to play in ensuring product data interoperability. STEP (the Standard for Exchange of Product data [35]) is one of such standards, providing mechanisms for describing product information throughout the lifecycle. Different Application Protocols have been developed for different applications/domains. As an extension of STEP, STEP-NC [36] is developed to support CNC (Computer Numerical Control) manufacturing. Compared with previous standards, these data models offer a set of effective tools for interoperability solutions in the computer-aided manufacturing context [37].

2.3. Recap

CManufacturing is not just an implementation of CComputing in manufacturing. Manufacturing enterprises and related resource/capability need to be described, componentized, virtualized and integrated in a MCloud. Some existing research work provides some enabling tools to the CManufacturing concept. This said, there is still a lack of Cloud solution for the entire manufacturing supply chain. The next section describes a proposed service-oriented CManufacturing system named Interoperable Cloud Manufacturing System (ICMS).

3. Interoperable Cloud Manufacturing System

Nowadays, a manufacturing enterprise would not survive without Computer Aided applications (CAx) technologies. Deploying CAx software on the Cloud improves the performance in terms of flexibility, extendibility, integrity and easy/unlimited data storage. With a Cloud structure, software is easily maintained and utilized on a Cloud server. Version updating, maintaining and integrating is remotely done by the Cloud provider, which replaces periodic services by on-site maintenance specialists. Thus, the cost of IT infrastructure is cut down via reduced management and maintenance effort. Additionally, thanks to the pay-as-you-go basis of a Cloud Service (CService), the cost of expensive applications is spread over multiple CUsers. Costly but rarely used software can be priced by the amount of usage.

CManufacturing faces a tougher challenge than implementing manufacturing-related software in CComputing. Unlike software programme and IT infrastructure, physical machines, monitors, and facilities cannot be readily deployed on the Cloud. There is also a need to understand the intermediate processes from raw material to finished products.

3.1. Manufacturing Capability and Manufacturing Resource

Zhang et al. [38] identified manufacturing ability as a kind of resource. In practice, the main reason for acquiring a manufacturing facility is the functionality of the equipment but not the equipment itself. It is therefore necessary to recognize a Cloud resource, capability, and service at different levels. In the Cloud background, the definitions of a resource, capability and service are given below,

- Manufacturing Resource (MResource): material and nonmaterial manufacturing supplies including equipment, machine, device and intelligent properties.
- Manufacturing Capability (MCapability): ability of transforming one form into another in manufacturing domain. It is realized via related MResources.
- Cloud Manufacturing Service (CMService): Self-contained, configurable and on-demand manufacturing service package to fulfil user's original needs. A CMService can be random, short-term, long-term, or strategic.

The containment relationships of MResource, MCapability and CMService can be summarized as shown in Figure 1. MResources are contained within MCapability as one of the essential requirements, since MCapability is realized and implemented via MResource. MCapabilities are re-packaged and deployed in the MCloud as CMService as a convenient feature that can be rapidly provisioned and released by a CUser.

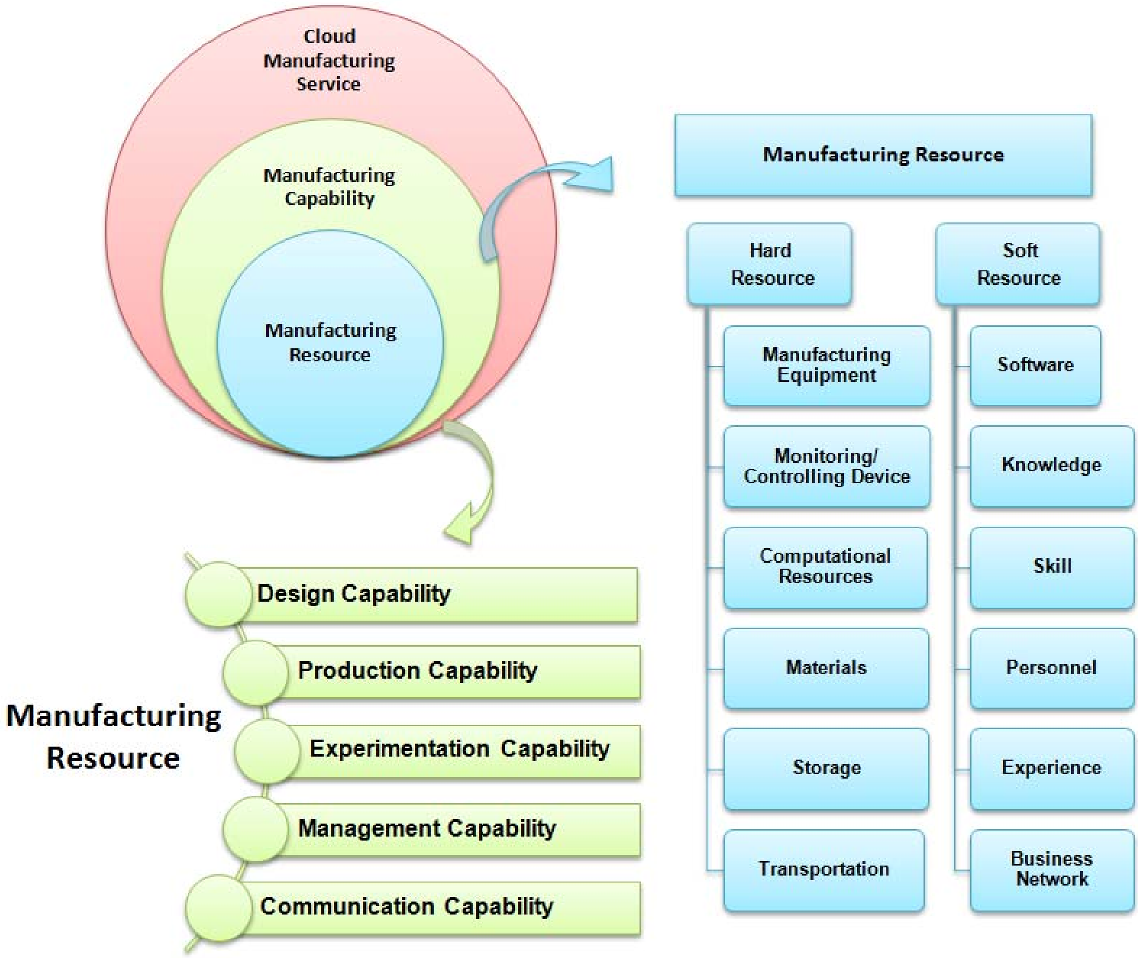

Figure 1 MCapability and MResource

A CManufacturing system encapsulates and implements MCapability in the Cloud as CMService packages. Manufacturing Capability is composed of Design, Production, Experimentation, Management, and Communication Capability.

- Design Capability (DC) refers to domain-specific design knowledge, expertise of the organization and past experience from previous design activities.
- Production Capability (PC) relies on the speed and quality of creating an output, i.e. product or service, to fulfil a production order.
- Experimentation Capability (EC) entails the experimentation knowledge and specialists.
- Management Capability (MC) includes planning, organizing, staffing, leading and controlling of an organization. It relies on the ability of the operational business and organizational activities.

- Communication Capability (CC) refers to the data exchangeability between applications/devices. It includes data transportation, speed, storage, conversion and QoS.

From the resource's perspective, each kind of manufacturing capability requires support from the related MResource(s). For each type of MCapability, its related MResource(s) comes in two forms, soft resources and hard resources. The soft resources include:

- Software: software applications throughout the product lifecycle including design, analysis, simulation, process planning, and etc.
- Knowledge: experience and know-how needed to complete a production task, i.e. engineering knowledge, product models, standards, evaluation procedures and results, customer feedback, and etc.
- Skill: expertise in performing a specific manufacturing task.
- Personnel: human resource engaged in the manufacturing process, i.e. designers, operators, managers, technicians, project teams, customer service, and etc.
- Experience: performance, quality, client evaluation and etc.
- Business Network: business relationships and business opportunity networks that exist in an enterprise.

Hard resources contain:

- Manufacturing Equipment: facilities needed for completing a manufacturing task, e.g. machine tools, cutters, test and monitoring equipment and other fabrication tools.
- Monitoring/Control Resource: devices used to identify and control other manufacturing resource, for instance, RFID (Radio-Frequency IDentification), WSN (Wireless Sensor Network), virtual managers and remote controllers.
- Computational Resource: computing devices to support production process, e.g. servers, computers, storage media, control devices, and etc.

- Materials: inputs and outputs in a production system, e.g. raw material, product-in-progress, finished product, power, water, lubricants, and etc.
- Storage: automated storage and retrieval systems, logic controllers, location of warehouses, volume capacity and schedule/optimization methods.
- Transportation: movement of manufacturing inputs/outputs from one location to another. It includes the modes of transport, e.g. air, rail, road, water, cable, pipeline and space, and the related price, and time taken.

To formulate MCapability, a MCapability Description Model (MCDM) as a 4-Tuple is proposed,

$$MCapability = \{DC(R_{SoftDC}, R_{HardDC}), EC(R_{SoftEC}, R_{HardEC}), PC(R_{SoftPC,}R_{HardPC}), MC(R_{SoftMC}, R_{HardMC}), CC(R_{SoftCC}, R_{HardCC})\} \quad (1)$$

where,

R – MResource, all the resources required to carry out the Task, including hard resource R_{Hard} and soft resourceR_{Soft}.

High-performance service needs sufficient resource and suitable methodology to exploit it. Hence, an effective MCapability is contributed by the domain-specific ability and its related resource. MCDM includes the capability of both an individual enterprise and an alliance made up of multiple participants. This means a MCapability meeting a CUser's need could be provided by a single Service Provider (SProvider) or a union of them. A comprehensive Cloud solution is required to take care of all the capabilities and resources mentioned above and provide an optimal solution. Eventually, identified MCapabilities are packaged as CMServices and deployed in the MCloud. During the conversion from current manufacturing status into CManufacturing, existing capabilities and resources should be integrated and utilized in the CManufacturing environment. Thus, an interoperable, service-oriented CManufacturing system can be realized.

3.2. *ICMS architecture*

As mentioned above, Cloud technology provides an opportunity to re-shape manufacturing business, in particular SMEs. Combined with SOA, it is capable of creating new economic growth for customized production or One-of-a-Kind Production (OKP) businesses. Specialized and customized demands can be better served due to the flexible and fast-reaction nature of a CManufacturing system. Compared with the Business-to-Business (B2B), Business-to-Consumer (B2C) models, an X2C (Everything-to-Cloud) model is proposed. The preliminary concept of ICMS has been reported in [22]. As public Cloud infrastructure, ICMS consists of three layers, i.e. Smart Cloud Manager (SCM), User Cloud (UCloud), and MCloud (Figure 2).

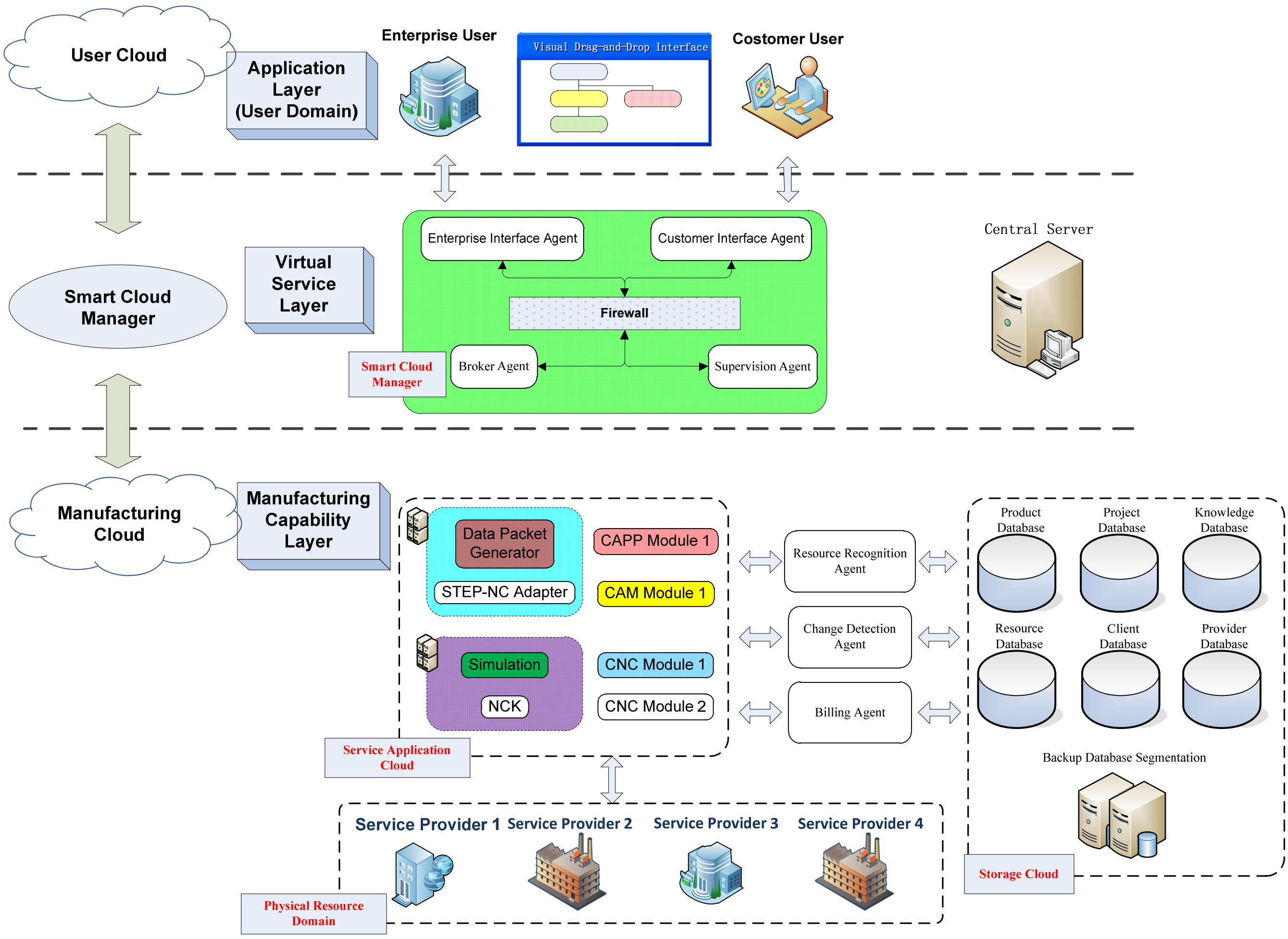

Figure 2. ICMS Architecture

3.2.1. *Customer & Enterprise User*

At the UC layer, the CMService consumer is divided into two categories: Customer User (CU) and Enterprise User (EU). ICMS takes care of traditional manufacturing tasks for CUs as well as collaborative production requests from multiple organizations (Figure 3). By combining the Consumer-to-Cloud and Business-to-Cloud model, ICMS provides an X2C structure from the industrial context.

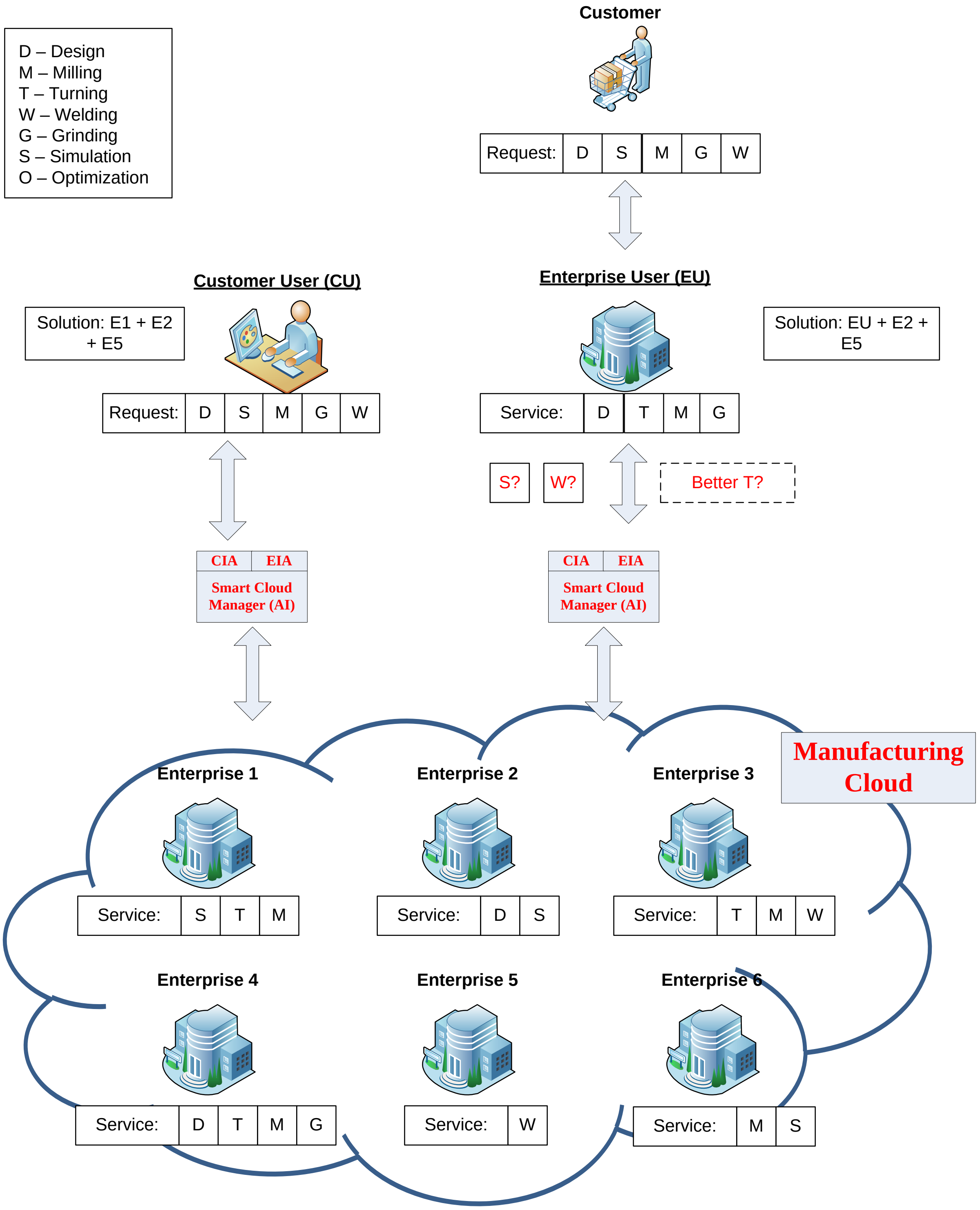

Figure 3. Customer User and Enterprise User

CU is defined as a customer or organization with the request of a self-contained production task. Assisted by the Customer Interface Agent (CIA) of SCM, the manufacturing request of a CU is analysed and located by SCM, and provided by the MCloud. Thus, it forms a Request-Find-Provide service chain. Original user's requests are taken care of by SCM. SCM searches for potential solutions and feeds back the results to the user. The user is able to optimize the solution based on his/her original needs and finalize the service request. ICMS provides a user with a big range of flexible manufacturing capabilities. Customized and original requirements can be realized easily, compared with the traditional manufacturing practice. For industry, it offers new opportunities especially for the OKP enterprises and SMEs. The enterprises are loosely integrated in MCloud as ICMS SProviders. MCapabilities and business opportunities are integrated and broadcasted in a larger resource pool, which enhances the competiveness of the entire consortium. Thus, more manufacturing objects can be achieved with minimum additional investment and effort.

Besides CUs, ICMS also takes care of organizations/enterprises (EU) who are seeking additional MCapabilities and supports. In practice, customers occasionally come to a manufacturing enterprise requiring products or capability that the enterprise by itself cannot fulfil. With the help of the Enterprise Interface Agent (EIA), an EU can search for qualified SProviders who are able to "fill in the gap". The EU is able to recognize related MResources and allocate the temporary partner(s) for the task. In this case, the original EU plays a role of the "leading company" in this virtual organization. The leading company is in charge of interacting with the customer, and collaborating with other participants as a coordinator. From the ICMS perspective, the leading company is considered as the EU, who will be assisted by the SCM module. This way, the CUsers are able to accomplish bigger and more demanding production tasks that are otherwise not possible by a single enterprise. As a matter of fact, the partner network of a company is made boundaryless.

3.2.2. Smart Cloud Manager

Intelligent agent technology is capable of supporting manufacturing procedures/decisions [39-41]. The SCM module is constructed by intelligent agents. In an ideal system, user should have full confidence of the system's intelligence. The interaction between a human being and system intelligence should be minimized as long as the service request is well-defined by the user. Intelligence kernel is capable of optimizing and executing the task with the preference variables from the user. However, manufacturing decisions are difficult to make due to complexity of manufacturing processes, variety of machines/devices, and uncertainty of resources status. When multiple resources and variables are involved, it is even harder to predict a reliable and optimum service solution for the user. Thus, to fully utilize AI and human expertise/knowledge, a decision-making model is proposed. SCM works in a neutral manner and consists of EIA, CIA, Broker Agent (BA), Supervision Agent (SA), and Firewall Module (Figure 4). EIA works with EUs, and CIA handles requests from CUs. Although the GUIs (Graphical User Interface) and algorithms of EIA and CIA are different, the service procedures are almost the same (from the SCM perspective). After the user's request is collected by the Interface Agent (IA), BA communicates with the Provider Database and maps the requirement to the available CMServices. As long as the user modifies and confirms the service package, an ICMS Service Template (ST) is generated and delivered to the SCM. Based on ST, Supervision Agent starts up and works with the Service Application Cloud (SACloud). Specific CMServices are organized and launched to meet the users' expects. The final service output, which can be product, computing data or technical document, is sent to the user. After the feedback/evaluation document is finished by the user, the CMService is terminated.

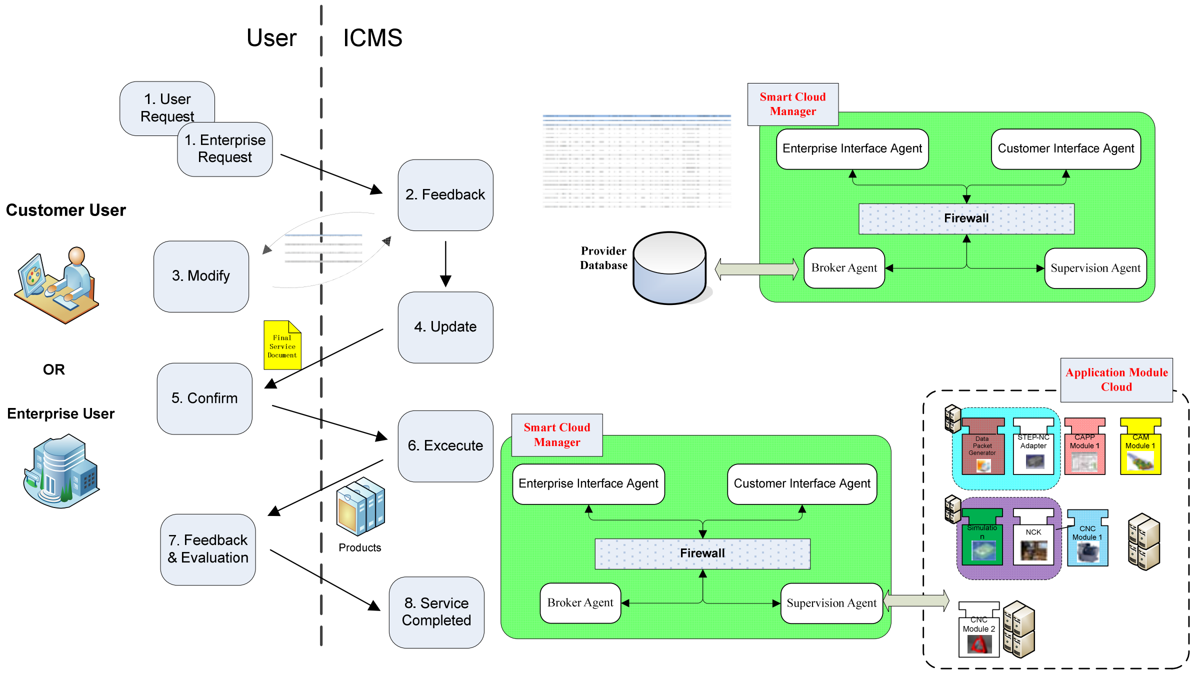

Figure 4. Cloud Service Procedure

As the supervisor or brain of ICMS, SCM analyses and controls the CMServices to fulfil the user's demand. Inside SCM, the interactions among IA, BA, and SA are summarized in Figure 5. After a user's request is collected by the IA, the details are converted into a standard format. Based on these details an internal request document is generated and sent to BA. According to the request document, BA searches in the MRsource database for potential solutions. Afterward an initial ST file is created and sent back to the user. Cloud consumer is able to view all these solutions along with the suggestions from SCM. Based on factors such as cost, quality, functionality and etc., SCM recommendation is visible to the user in different levels of details. If the Cloud customer is not satisfied with any of the suggestions provided, he/she is able to modify the ST.

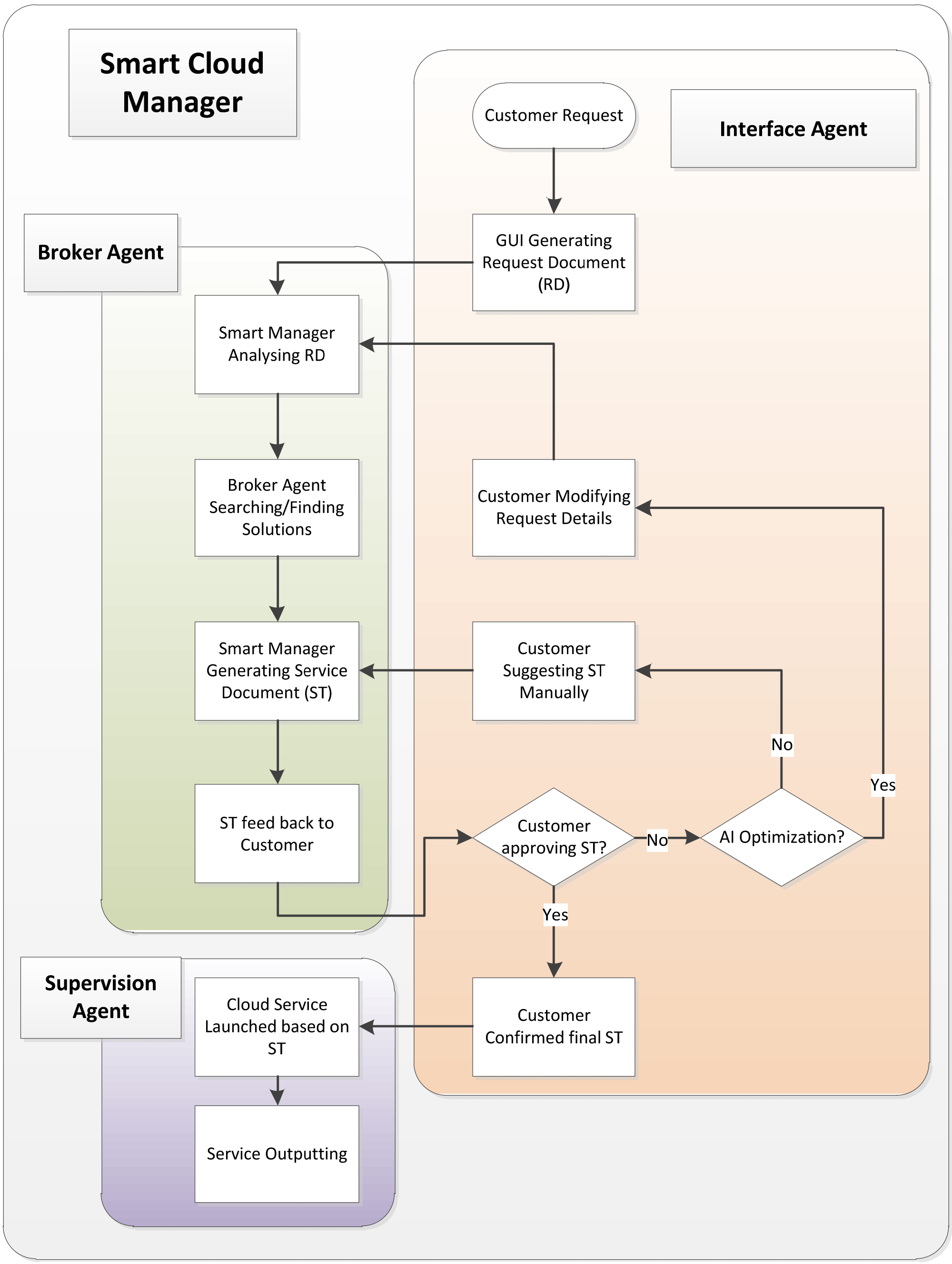

Figure 5. Logic Flow within Smart Cloud Manager

At this stage, the Cloud customer is able to either optimize the ST via BA intelligence or do it manually. If the customer prefers to utilize AI continuously, CUser is requested to modify his/her original searching request by providing more details or to modify technical variables. Then, the altered request condition is sent back to BA, who will process one more round of analysis and service detection. On the other hand, if the Cloud customer chooses to improve the ST manually, he/she can work on it via GUI and allocate a preferred provider. This way, both of expert knowledge and optimization are utilized in SCM.

As long as the user confirms ST, the specific Cloud Services are launched by the SA. SA is responsible for monitoring and controlling all the activities of the Cloud service modules. By marking and manipulating the event/data flow of all the application modules, the ST is executed accurately as it is defined.

3.2.3. Manufacturing Cloud: Provider & Service database

At the Manufacturing Capability Layer, MCapabilities are integrated as self-contained service modules in the SACloud. The operational processes throughout the supply chain stay in form of CMService applications at this layer. By controlling the service input and output, CMServices are shared and published in the high-performance resource pool. The plug-and-play ability of service applications enables flexibility and adaptability to cope with uncertain and changing manufacturing market.

In Storage Cloud (SCloud), database maintains the product/project data as well as the information of the MResources meshed in SACloud. To model and recognize these application modules, three smart agents are developed, i.e. Resource Recognition Agent (RRA), Change Detection Agent (CDA) and Billing Agent (BiA). RRA is responsible for identifying newly-published capability and termination of existing ones. Since MCapabilities are loosely merged in the SACloud, the performance of the entire MCloud is not affected by binding or detaching an individual CMService. CDA is in charge of detecting and updating resource changes, such as its availability, price adjustment, facility maintaining, and etc. Thus, the up-to-date data of resource can be supplied while SCM is searching for applications for the CUser. BiA works with Storage Cloud and SCM directly. When ST is generated, BA provides the service quote based on the pre-defined service description in SC. Thus, real-time information exchanging between MCapabilities and MCloud is enabled.

To clearly describe and present CMService, CProvider and CUser’s requests, efficient data models are needed. A number of modelling languages can be used, e.g. Web Services Description Language (WSDL) for web-service description, Web Ontology Language (OWL) for knowledge representations, Web Services Business Process Execution Language (WS-BPEL) for executable business processes with web-services, and EXPRESS. Among them, EXPRESS is chosen since it provides more robust modelling methods. EXPRESS is a standardized data modelling language for product data which is formalized in an ISO standard [42]. As the graphical notation of EXPRESS, Provider & Service models in EXPRESS-G provide the portability with standard data models such as STEP and STEP-NC.

As shown in Figure 6, the enterprise which provides CMServices is defined as a SProvider. Therefore, a manufacturing enterprise can be described in Cloud terminology, as provider profile and service properties. The provider specifications describe the information of the organization, while service specifications present the MCapability in terms of service that it provides. Note that one company has a unique Enterprise Entity, while its Service entities can be multiple. Hence, the organization consistency and service variety are maintained concurrently. Entity Enterprise outlines the properties of a CManufacturing via entities Provider_ID, Company_Name, Provider_Size, Provider_Capability, Provider_Location, Provider_Contact, Prior_Experience, Provider_Evaluation and Provider_Description.

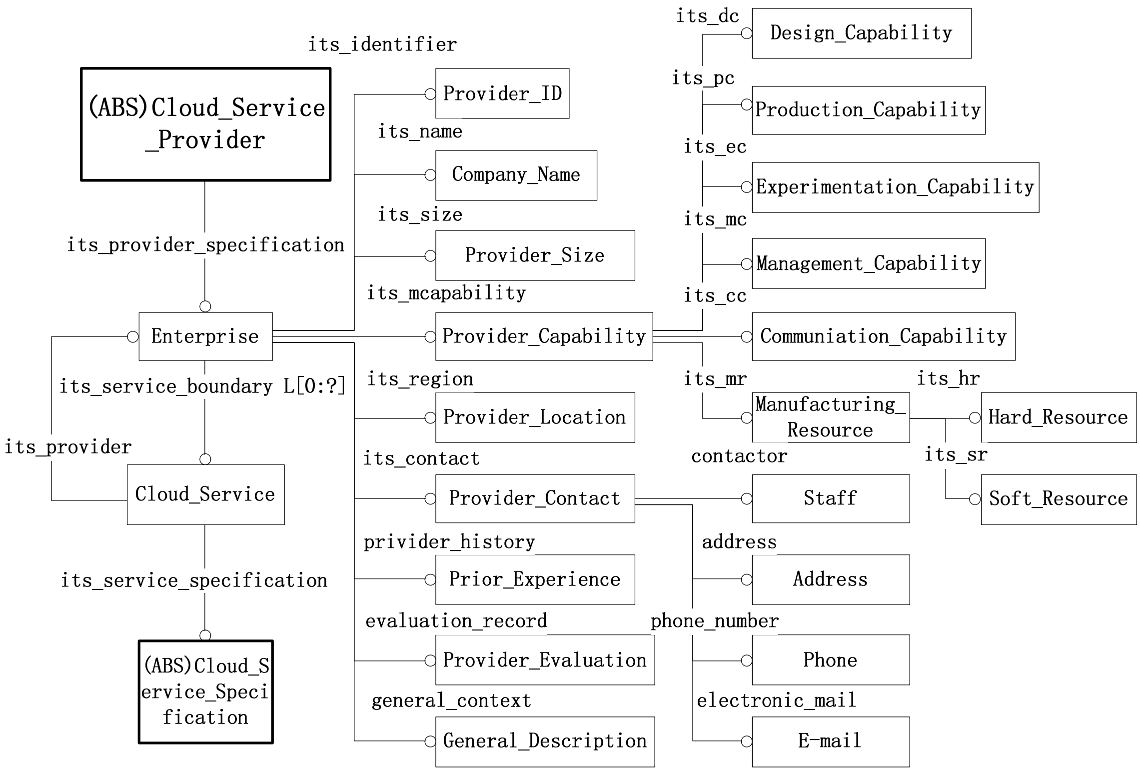

Figure 6. Cloud Service Provider model in EXPRESS-G

Entity Provider_ID provides a unique identifier in the MCloud for a SProvider. Based on its Provider_ID, all the CMServices from a provider and its related service history can easily be traced.

Entity Provider_Capabilities describes the MCapability of a SProvider via sub-entities Design_Capability, Experimentation_Capability, Production_Capability, Management_Capability, and Manufacturing_Resource, which are compliant with the aforementioned MCDM model. Entity Hard_Resource and Entity Soft_Resource describe the MResources that support a specific MCapability. These entities can be connected to a standardized data model directly, for example ISO14949-201 for machine tools, and ISO10303-45 for material and engineering properties. Hence, the MCapability of a SProvider is described in an explicit and scalable data model.

Entity Prior_Experience records the service history of one SProvider which is visible to the Cloud administrator and provider itself, but not entirely to the users. Entity Provider_Evaluation documents the feedback from these service consumers. Based on these two entities, the performance of the service experiences are modelled explicitly.

As the second category of enterprise attributes, the recognition of the specific CMService is modelled via Entity Cloud_Service_Specification and its entities, i.e. Service_ID, Service_Cost, Price, Time, Shipping_Price, Shipping_Time, Service_Status, Service_Document, Data_Object, Pre_Condition, Availability, Resource, Quality_Evaluation, Technical_Support_Capability, Warranties and Service_Description (Figure 7).

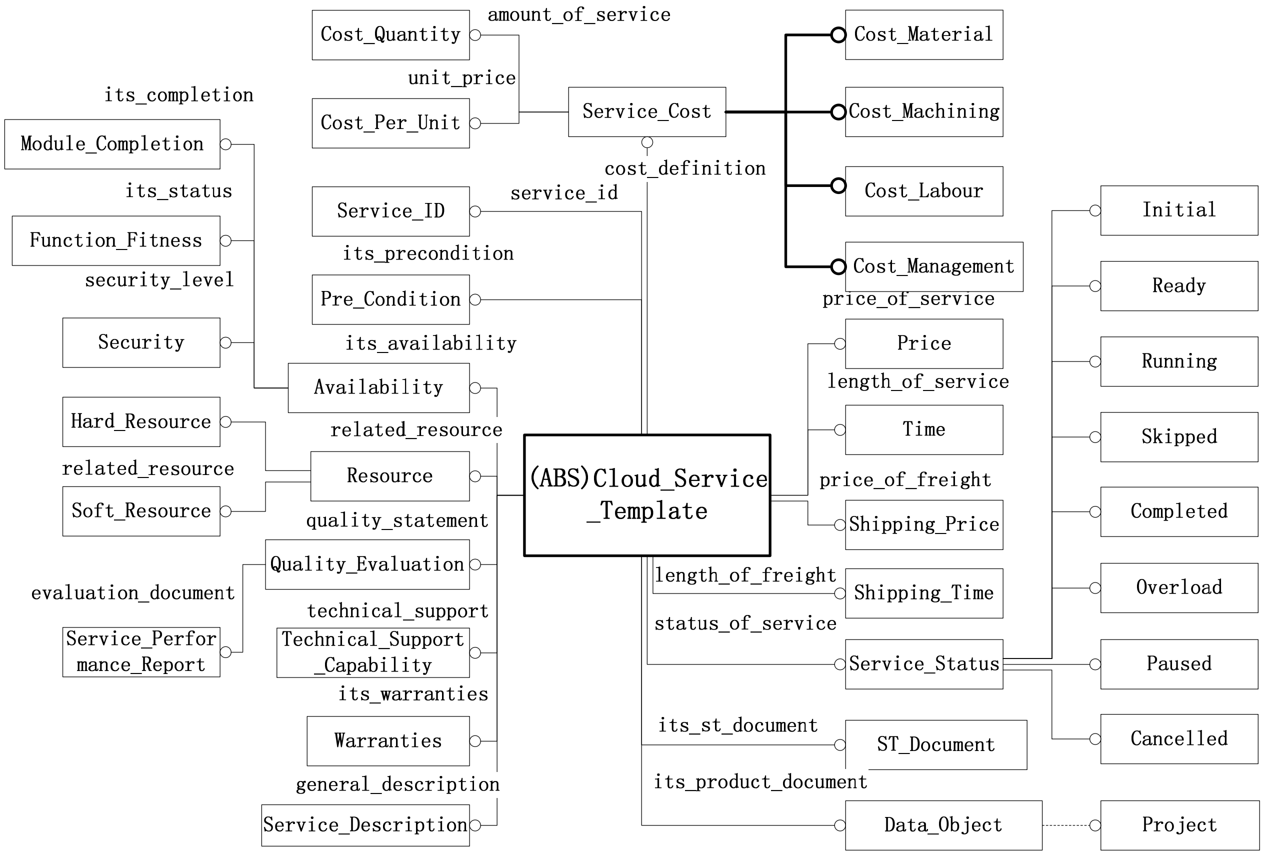

Figure 7. Cloud Service Model

Entity Service_Cost documents the value of CMService in the monetary form. This entity provides an explicit model of the value that has been used to accomplish a service object. Service_Cost is only visible for SProviders to understand their MCapability internally, and to make reasonable price for external CUsers. Service_Cost is described with the help of entities Cost_Per_Unit and Cost_Quantity. The Service_Cost model structure is inherited by four subtypes, which divides the service cost into four categories, Cost_Material, Cost_Machining, Cost_Labour, and Cost_Management.

Entity Service_Status contains the information about the running stages after a CMService is launched. Stages of implementation are described via entities Initial, Ready, Running, Skipped, Completed, Overload, Paused, and Cancelled.

Entity ST_Document keeps the path and version of a ST file as above-mentioned. When a CUser is working on a ST, all versions of the ST are recorded by this entity. Thus, the service/modification history is maintained.

Entity Data_Object records the technical document(s) related to the CMService. The optional attribute of this entity is Entity Project, which is compliant with the top level of a neutral data format defined in ISO10303 [43].

Entity Pre_Condition defines the requirements prior to the start of CMService. Limitations or preparations of the service input are recorded and published, e.g. limits of size, material preparation, heat treatment and so forth.

Entity Availability represents the availability and working condition of a CMService. This entity is dynamically updated by CDA. With the help of CDA, CUser is informed by the trust-worthy situation of availability without major delays. CUsers are able to select the available CMService only, or queue in the list waiting for the preferred package till it is ready-to-be-used. The availability information is further described by its attributes, i.e. Module_Completion, Function_Fitness and Security.

Entity Resource defines the manufacturing resource that is required for a specific service. Its structural attributes (Hard_Resouce and Soft_Resource) are compliant with the resource representation of Entity Enterprise. Thus, the resource specifications, from both service point of view and enterprise point of view, are shaped and integrated in SCloud.

To describe the user's query of a CMService, Cloud_Service_Request model is used (Figure 8). Cloud_Service_Request is compliant with the SProvider and Cloud_Service_Template data structure. As a bridge between user's original demand and CMService in the MCloud, it provides a neutral and standardized methodology to document the query. Via GUI, the service description is arranged in the structured statement and transmitted to the SCM. Based on this piece of data, SCM is able to suggest the solution from the resource pool based on the terms and mapping preference. The request data is shaped via entities such as Request_ID, CUser, Request_Status, Service_Type, Data_Object, Service_Time, Service_Price, Preference, Request_Description, Service_Document, and optional entities Preferred_Resource, Preferred_Provider, Preferred_Region, Quantity_Of_Service_Output, and Keywords.

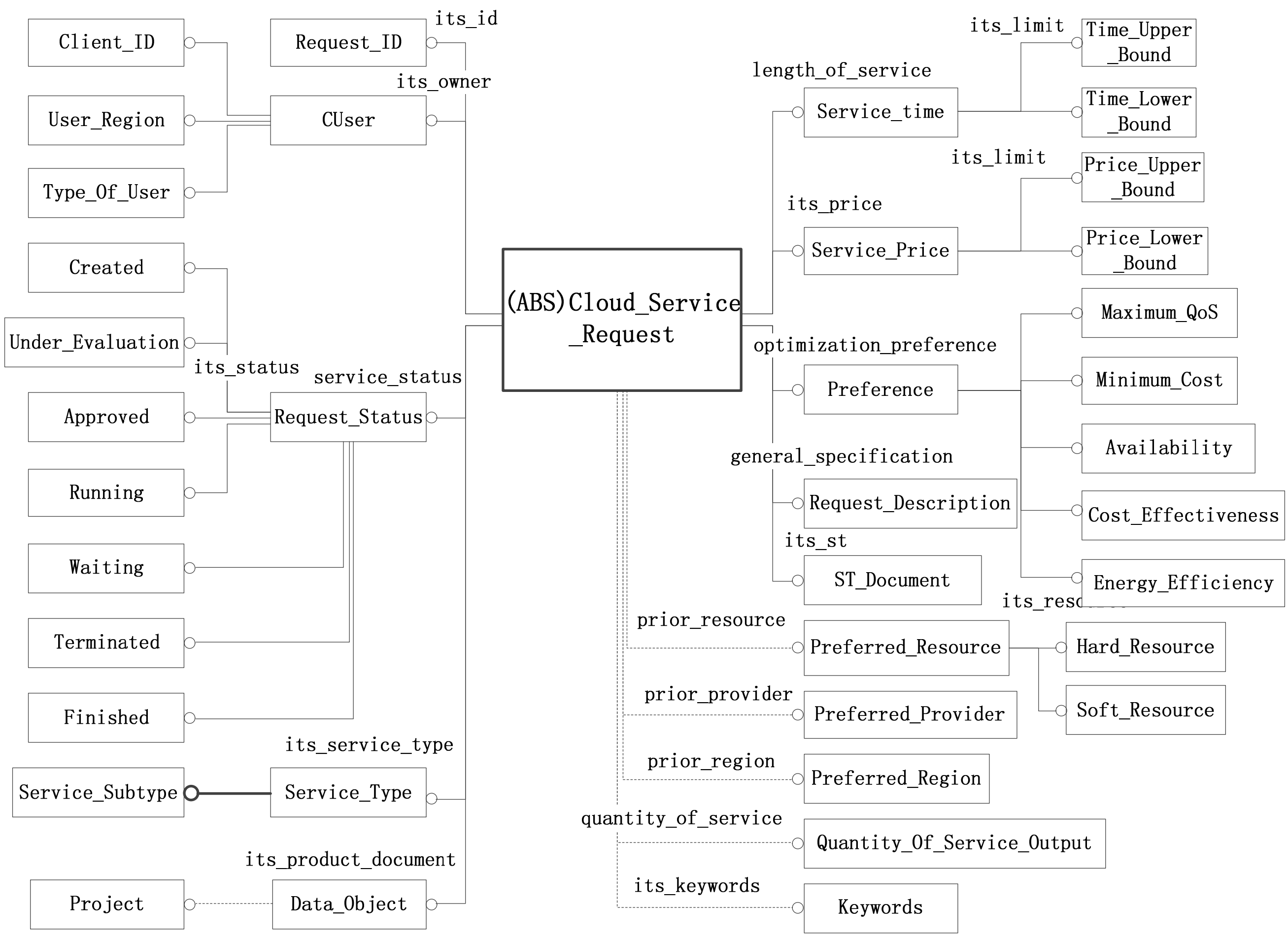

Figure 8. Service Request Model

Entity Request_ID gives a unique serial number for a CUser's request. When a new query case is created, a permanent Request_ID is assigned. Users are able to resume, modify, and review the request case. Additionally, all the related Cloud behaviour and history are traceable based on a Request_ID.

Entity Request_Status maintains the operational condition of a request. The variables of a process status are Created, Under_Evaluation, Approved, Running, Waiting, Terminated, and Finished.

Optional Entity Preferred_Resource keeps the user's predilection of resource and facility, for example specific machine tools, testing method or design software. The structure of this entity is compliant with the Hard_Resource and Soft_Resource entities of SProvider model aforementioned. Thus, the user's request can be directly connected to the MCapabilities in the Cloud.

Thanks to the service request, CMService and SProvider models, the data is modelled from the initialization to implementation stage in the SCloud. Information packages can be submitted, retrieved, and maintained over the Internet regardless the locations of the central database and server. For data storage queries, customer's private data is not maintained in the SCloud directly. In the background, data centers are hosted by third parties that are integrated as SProviders in the MCloud. Thus, the storage task is integrated as one of the CMServices in the virtualized service pools.

3.3. Recap

To recap, ICMS provides a flexible and distributed environment for shared MCapabilities. In particular, it offers a number of benefits:

- Data Interoperability: manufacturing business is commonly troubled by data interoperability issues. CAx applications are widely utilized throughout the production stages. However, these applications are provided by multiple providers using different programme languages and document formats, leading to a heterogeneous data environment. Software tools using different kernels are difficult to communicate with each other. Data loss and errors often occur during format conversions. By using ICMS, the explicit specifications of software tools are represented as soft resource in the MCloud. Detailed descriptions, e.g. input and output format requirements, are visible to all the CUsers. Interoperable problems can be easily identified and avoided. Users are able to choose the SPs that can smoothly communicate with each other, or alternately allocate reliable data conversion service before-hand as one of the CMServices. Therefore, interoperability is achieved even before a CMService is launched.

- Globalization/Sub-Contracting: with the help of Internet of Things, manufacturing services/capabilities are virtualized in the MCloud. Compared with web-based manufacturing, ICMS provides a more distributed and flexible environment which knocks down the boundaries between organizations/enterprises. It is easier to find business partners/sub-contractors based on their performance of service, regardless of who and where they are.
- Customized Service & Specialized Demand: customization is becoming more and more important in modern manufacturing, especially for SMEs. In a machine shop, specific cutter/machine tools are required for a particular job. With SCM, it is easy to locate required facilities in the resource pool. Therefore, specialized objects are achieved without additional investment on costly facilities and expertise.
- Facility Utilization: resource can be shared in a Cloud. Technical details and availability can be dynamically updated and published in the SCloud. Thus, manufacturing resources/capabilities can be better utilized. Production tasks can be easily balanced between high-usage facilities and the low-usage ones. From the user's perspective, CUsers are able to choose the available qualified providers for urgent jobs, or to wait for the preferred facility in the queue. Therefore, the facility utilization is improved by widely shared environment and reasonable schedule.
- Global Optimization: since services are broadcasted in the Cloud, service solution can be improved and optimized based on the virtualized service modules implemented in the Cloud. SCM predicts the service performance features beforehand, e.g. cost/time caused by preparing, machining, transporting and packing stages. So much so, the global solution is optimized based on particular factors or user's preferences.
- Cost-Saving: by adopting the CManufacturing concept, the manufacturing cost can be reduced. With the shared MCapabilities available in the Cloud, optimized business solution is easily found according to optimized results. Since the features of SProviders are virtualized in the SC, it is more likely to find supplier with better performance, cheaper labour, higher productivity, and better geographical location. As a consequence of time-critical or cost-critical optimization

strategies, the performance of the service solution is predicted and improved from a higher level and in a bigger scope of Cloud. Besides the cost of the service itself, the cost of strategic decision is reduced as well. With the technical specifications highly integrated in the SCloud, the cost of management, analysis, and comparison decreases, too.

- Better Enterprise Performance: when it comes to cost/time management, ICMS improves not only the experience of the CUsers but also the enterprise's performance as a CMService provider. The MCapabilities are accessible in the Cloud, bringing more business opportunities. With the help of SCM, a SProvider is able to increase its production volume and react rapidly to market changes.

4. Case Studies

To evaluate the concept of ICMS, two case studies have been carried out. MCapabilities are virtualized in the CManufacturing environment. The first case study shows the ability of integrating CMServices, and the second demonstrates how a CManufacturing environment can provide user with multiple options and improve enterprise performance at the same time.

4.1. Cloud Service Segmentation

In the first case study, a customer launches customer interface remotely, and requires a serial of services such as product design, simulation, CNC milling, precision welding and grinding. The service query descriptions and specifications are input via a GUI. CIA collects these data and transmits the data into a XML format to enable Internet communications (Figure 9). Note that the XML document which is transmitted from the client side is compliant with the EXPRESS-G schemas but in a flat data structure. This means that the meta-model only keeps the information of entity instance and temporarily suspends attributes and inheritance logics. The flat meta-model is utilized to enhance the data portability. CUsers are able to view and process these data via general software tools, e.g. web browser, Microsoft Excel, Access and so on. When the data comes back to the MCloud, it is mapped back to the structured model tree. Then, SCM continues to process the service process and searches for all the possible solutions.


```
<?xml version="1.0" encoding="UTF-8" ?>
- <dataroot xmlns:od="urn:schemas-microsoft-com:officedata" xmlns:xsi="http://www.w3.org/2001/XMLSchema-instance" xsi:noNan
  20study%201%20v%202.0.xsd" generated="2012-08-31T14:10:13">
  - <case_x0020_study_x0020_1>
      <ID>1</ID>
      <Cloud_x0020_Service_x0020_Request>null</Cloud_x0020_Service_x0020_Request>
      <Request_x0020_ID>Req0001</Request_x0020_ID>
      <User_x0020_ID>Use0003</User_x0020_ID>
      <User_x0020_Region>Auckland, NZL</User_x0020_Region>
      <Request_x0020_Status>New</Request_x0020_Status>
      <Service_x0020_Type>Production</Service_x0020_Type>
      <Service_x0020_Subtype>product design,</Service_x0020_Subtype>
      <Ammount_x0020_of_x0020_Service>1</Ammount_x0020_of_x0020_Service>
      <Request_x0020_Description>stanless grinder *30</Request_x0020_Description>
      <Service_x0020_Document>http://130.216.83.89/Req0001/Req0001.sd</Service_x0020_Document>
      <Data_x0020_Object>http://130.216.83.89/Req0001/grind.prt.6</Data_x0020_Object>
      <Time_x0020_Upper_x0020_Bound_x0020__x0028_week_x0029_>2</Time_x0020_Upper_x0020_Bound_x0020__x0028_week_x0029_>
      <Time_x0020_Lower_x0020_Bound_x0020__x0028_week_x0029_>0</Time_x0020_Lower_x0020_Bound_x0020__x0028_week_x0029_>
      <Price_x0020_Upper_x0020_Bound_x0020__x0028_NZD_x0029_>1000</Price_x0020_Upper_x0020_Bound_x0020__x0028_NZD_x0029_>
      <Price_x0020_Lower_x0020_Bound_x0020__x0028_NZD_x0029_>0</Price_x0020_Lower_x0020_Bound_x0020__x0028_NZD_x0029_>
      <Preference>null</Preference>
      <Keywords>CNC, Milling, Machining</Keywords>
      <Prefererred_x0020_Region>USA, NZL, AUS, CHN</Prefererred_x0020_Region>
      <Preferred_x0020_Provider>null</Preferred_x0020_Provider>
    </case_x0020_study_x0020_1>
  - <case_x0020_study_x0020_1>
      <ID>2</ID>
      <User_x0020_Region>Auckland, NZL</User_x0020_Region>
      <Request_x0020_Status>New</Request_x0020_Status>
      <Service_x0020_Type>Production</Service_x0020_Type>
      <Service_x0020_Subtype>simulation,</Service_x0020_Subtype>
      <Ammount_x0020_of_x0020_Service>1</Ammount_x0020_of_x0020_Service>
      <Request_x0020_Description>stanless grinder *30</Request_x0020_Description>
      <Service_x0020_Document>http://130.216.83.89/Req0001/Req0001.sd</Service_x0020_Document>
      <Data_x0020_Object>http://130.216.83.89/Req0001/grind.prt.6</Data_x0020_Object>
      <Time_x0020_Upper_x0020_Bound_x0020__x0028_week_x0029_>3</Time_x0020_Upper_x0020_Bound_x0020__x0028_week_x0029_>
      <Time_x0020_Lower_x0020_Bound_x0020__x0028_week_x0029_>0</Time_x0020_Lower_x0020_Bound_x0020__x0028_week_x0029_>
      <Price_x0020_Upper_x0020_Bound_x0020__x0028_NZD_x0029_>1000</Price_x0020_Upper_x0020_Bound_x0020__x0028_NZD_x0029_>
      <Price_x0020_Lower_x0020_Bound_x0020__x0028_NZD_x0029_>0</Price_x0020_Lower_x0020_Bound_x0020__x0028_NZD_x0029_>
      <Preference>null</Preference>
```


Figure 9. XML Representation of a Service Request

As a result, the SProviders which are able to meet the user's requirements are summarized in Figure 10. The service is constructed by five service phases that are mapped to the five stages of production. Multiple service providers are matched and stated by the SCM. Due to the sequence of different routes, the service procedure is presented in the flowchart. The service is illustrated as nodes and the transmitting methods as edges.

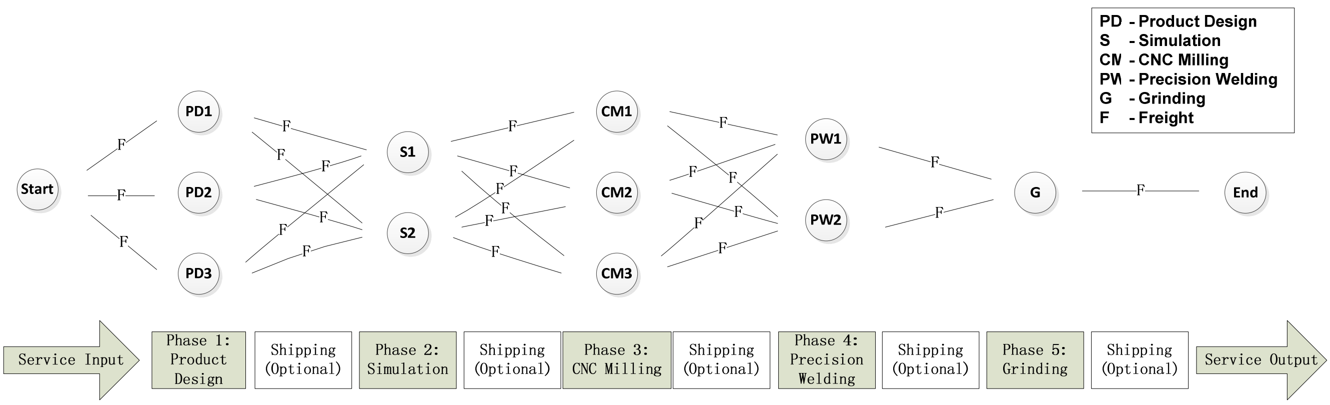

Figure 10. Cloud Service Results Pool

To optimize the solutions and provide a customized result, SCM analyses the feedback from the SCloud and evaluates the selections based on the user's preference (e.g. cost-critical and time-critical rules). The total cost includes the cost and the expenses of freight between different providers. After SProviders are found, all the possible transmitting services are detected as attachment services. The actual cost includes the Cost of service phase *i* (Cost(*i*)), and Shipping Cost that follows phase *i* (SC(*i*)) in total.

$$\mathrm{Cost} = \mathrm{Cost}(i) + \mathrm{SC}(i) = \sum_{\mathrm{i}=0}^{\mathrm{n}} \mathrm{C}_{(i+1)} + \sum_{i=0}^{\mathrm{n}+1} \mathrm{SC}_{i,(i+1)} \quad (2)$$

In this case study, the SCM computes all of the possible paths through service nodes and their edges. The sequential relationships between nodes can be represented as shown in Table 1. Value "1" indicates there is an operational sequence from node X to node Y. The lowest cost combination is found and suggested to the user. Since there are 36 combinations in this case, iterative algorithm is deployed. For more complex business matters, neural network and genetic algorithm can used to improve the computing efficiency.

$$\mathrm{Cost}_{\mathrm{opt}} = \mathrm{Minimize}\left[\mathrm{Cost}\left(\mathrm{PD_j}, \mathrm{S_k}, \mathrm{CM_l}, \mathrm{PW_m}, \mathrm{G_p}\right) + \mathrm{Cost}\left(\mathrm{SC_{jk}}, \mathrm{SC_{kl}}, \mathrm{SC_{lm}}, \mathrm{SC_{mp}}\right)\right] \quad (3)$$

where,

PD – Product Design;

S – Simulation;

CM – CNC Milling;

PW – Precision Welding;

G – Grinding.

Table 1. Sequence Matrix of Cloud Service Phases

From Node X

To Node Y

	Start	PD1	PD2	PD3	S1	S2	CM1	CM2	CM3	PW1	PW2	G	End
Start													
PD1	1												
PD2	1												
PD3	1												
S1		1	1	1									
S2		1	1	1									
CM1					1	1							
CM2					1	1							
CM3					1	1							
PW1							1	1	1				
PW2							1	1	1				
G										1	1		
End												1	

Computation under the time-critical rule is similar. Besides the period of service, results of transitions between SProviders cannot be ignored. SCM traverses all the possible paths and finds the most sufficient solution in terms of time.

$$\mathrm{Time} = \sum_{i=0}^{n} (\mathrm{T}_{(i+1)} + \mathrm{ST}_{i(i+1)}) \quad (4)$$

where,

T – Time of Service;

ST – Time of Shipping.

$$\mathrm{Time_{opt}} = \mathrm{Minimize}\left[\mathrm{T}\left(\mathrm{PD_j}, \mathrm{S_k}, \mathrm{CM_l}, \mathrm{PW_m}, \mathrm{G_p}\right) + \mathrm{T}\left(SC_{\mathrm{jk}}, SC_{\mathrm{kl}}, SC_{\mathrm{lm}}, SC_{\mathrm{mp}}\right)\right] \quad (5)$$

Eventually, the entire solution pool is detected and provided to the user. The results are mapped into a general chart visible to the user via the User Interface (Table 2). The optimized solution is marked for the user. At this stage, the user is able to follow the SCM recommendation or customize the selection.

Table 2. Cloud Service Mapping Results from SCM

Suggestion (Cost)	Suggestion (Time)	Service (Activity)	Provider	Service Serial No.	Activity ID	Price /each	Quantity	Time (week)	Capability /Quality	Price (total)	Time (total)	Location
	●	Product Design	CAMEX	S002	C001	1100	1	2	***	1100	2	North Shore, NZ
		Product Design	EagleBurgmann	S001	E006	900	1	3	***	900	3	North Shore, NZ
●		Product Design	UoA Workshop	S003	U001	800	1	2	***	800	2	Auckland, NZ
		Freight		NULL						0	0	Data Trans
		Simulation	PTC Creo	S009	P001	1000	1	2	***	1000	2	PTC, US
●	●	Simulation	UoA Workshop	S008	U003	700	1	1	**	700	1	Auckland, NZ
		Freight		NULL						0	0	Data Trans
	●	CNC Milling	CAMEX	S019	C008	200	100	1	***	20000	1	North Shore, NZ
●		CNC Milling	BENZ	S017	E004	160	100	1	**	16000	1	North Shore, NZ
		CNC Milling	UoA Workshop	S018	U004	200	100	2	**	20000	2	Auckland, NZ
		Freight		NULL						0	0	CAMEX ->CAMEX
	●	Freight	NZPOST	S101	N101	500	1	0.5	***	500	0.5	CAMEX ->BENZ
		Freight	NZPOST	S102	N102	500	1	0.5	***	500	0.5	BENZ ->CAMEX
●		Freight		NULL						0	0	BENZ ->BENZ
		Freight	NZPOST	S103	N103	600	1	0.5	***	600	0.5	UoA->CAMEX
		Freight	NZPOST	S104	N104	600	1	0.5	***	600	0.5	UoA ->BENZ
		Precision Welding	CAMEX	S012	C004	60	100	2	**	6000	2	North Shore, NZ
●	●	Precision Welding	BENZ	S013	E003	40	100	1	***	4000	1	North Shore, NZ
		Freight	NZPOST	S101	N101	500	1	0.5	***	500	0.5	CAMEX ->BENZ
		Freight		NULL							0	BENZ->BENZ
●	●	Grinding	BENZ	S010	E001	70	100	2	**	7000	2	North Shore, NZ

To recap, manufacturing services, from design to production, are virtualized and integrated within public CManufacturing architecture, without changing the existing organizational structures of a manufacturing enterprise or company. The CMService participants are able to improve their enterprise performances while maintaining their autonomy and competiveness. The participants are part of the integrated environment via contributing their valuable resources and services for mutual benefits.

4.2. Manufacturing Service Identification

When manufacturing enterprises are brought into the MCloud, the first step is to understand the MCapability of the enterprise which is then offered as a CMService. The second case study concerns a manufacturing service provider named BE, who has factories around the world. An example product is selected to demonstrate how industrial service is virtualized and implemented in the MCloud.

The example product, ID T14859 Driver, is a ring-shape part with multiple holes at different angles. An order of thirty parts are processed at BE Australia branch. BE has sites in Australia (BEAU) and New Zealand (BENZ), both of which are SProviders and capable of machining this part. The MCapabilities of the two sites are identified (Figure 11).

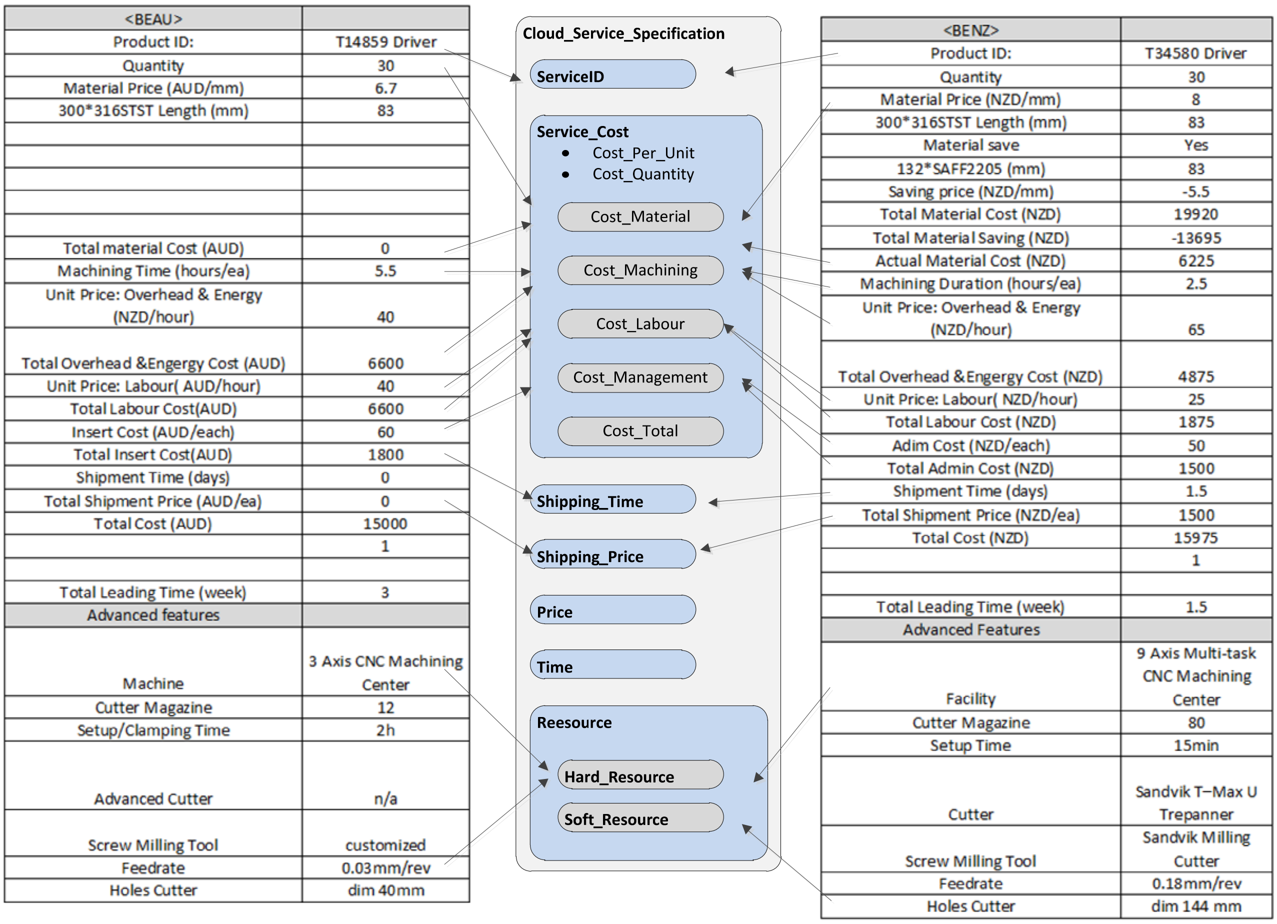

Figure 11. Integrated CMService Data

Historically, the product data and process plans are documented in different data semantics. Due to the geographical and currency differences, it is hard to evaluate machining tasks in the two sites. With the help of ICMS, the technical details are mapped from the flat chart to the modularized Cloud_Service_Specification model aforementioned. Compared with BEAU, there are stronger Hard Resources in BENZ, i.e. 9-axis multi-tasking CNC machining centre, Sandvik T–Max® U Trepanner cutters and Sandvik saw blade cutters. The parameters and features are described by the Entity Hard_Resource.

With the help of the 9-axis machining centre and its bigger cutter magazine at BENZ, the clamping and setup time is drastically decreased. Additionally, the service input is 316 stainless steel round bar of diameter 300 millimetres. Originally, the removing materials are in forms of chips that can only be recycled. Thanks to the Trepanner cutter, the result of the machining process is a hollow product with a cylindrical bar (diameter 130 millimetres) that can be utilized directly at BENZ. Thus, the actual material cost is drastically reduced. The cost margins are mapped to the subtypes of Service_Cost. Based on the data in this section, the actual service cost is summarized and provided. Subsequently, BENZ is chosen to carry out the production task.

In this case study, ICMS serves as a community Cloud for the organization. BE plays a role of service provider and user at the same time. Cloud-based virtualization mechanism provides explicit integrating presentations of its service/products. It provides clear knowledge of the operational processes. From the provider’s perspective, BE is able to understand its services and review/optimize them as required. As a CUser, the enterprise is able to choose the suitable service provider, which can be a partner/contractor connected by the MCloud or the enterprise itself.

5. Conclusions

It is largely impossible to carry out some manufacturing tasks without the support of suppliers, contractors and business partners. There is a need to connect manufacturers together to share risks, benefits, competiveness and costly resources. More than just deploying manufacturing-related software applications in the Computing Cloud, CManufacturing is an integrated solution that provides a pool of MCapabilities provided by Cloud participants. Manufacturers are integrated by either long-term arrangements or short-term business objectives. In this paper, a Cloud-based manufacturing system, called ICMS is proposed to achieve a collaborative manufacturing environment. With the help of ICT technologies and MCapability identifications, it is possible to realize remote collaboration, coordination, and interaction among participants.

To implement the CManufacturing concept, the key is to identify existing manufacturing abilities and resources, to virtualize and implement them in the Cloud as trust-worthy manufacturing services. A three-layer CManufacturing structure is proposed with a virtualization methodology describing CMService, SProvider and CMService queries. Supervision mechanism is developed for remote interaction between MCloud and Cloud clients that are categorized as either CU or EU. The case studies evaluate the ICMS system. Operational processes are integrated as CMServices from design to manufacturing. Optimization and management can be further assisted by SCM in the future. Meanwhile, additional optimization tools can be possibly adopted in the Cloud to improve the global performance of ICMS.

Efforts are made world-widely to realize faster time-to-market and reduce the cycle time of a product. ICMS connects distributed companies by provisioning their MCapabilities as CMServices. With shared capacities, knowledge and competencies, it is possible to for a business to take on more substantial projects that are otherwise not possible for one business to do. In a long term, more advanced manufacturing technologies can be brought into the CManufacturing context to improve efficiency, interoperability, sustainability and flexibility of a manufacturing business.

References

[1] P. Mell, T. Grance, The NIST definition of cloud computing (draft), NIST special publication, 800 (2011).

[2] P. Mell, T. Grance, Perspectives on cloud computing and standards. National Institute of Standards and Technology (NIST), Information Technology Laboratory, (2009).

[3] Apple, iCloud, (2012),Available: https://www.icloud.com/.

[4] Amazon, Amazon Elastic Compute Cloud (EC2), (2012),Available: http://aws.amazon.com/ec2/.

[5] Google, Google App Engine - Google Code, (2012),Available: http://code.google.com/intl/en/appengine/.

[6] Microsoft, Windows Azure Platform _ Microsoft Cloud Services, (2012),Available: http://www.microsoft.com/windowsazure/.

[7] Oracle, Sun Cloud Developer Homepage, (2012),Available: http://developers.sun.com/cloud/.

[8] X. Xu, From cloud computing to cloud manufacturing, Robotics and Computer-Integrated Manufacturing, 28 (2012) 75-86.

[9] F. Tao, L. Zhang, V. Venkatesh, Y. Luo, Y. Cheng, Cloud manufacturing: a computing and service-oriented manufacturing model, Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture, 225 (2011) 1969-1976.

[10] B. Li, L. Zhang, S. Wang, F. Tao, J. Cao, X. Jiang, X. Song, X. Chai, Cloud manufacturing: a new service-oriented networked manufacturing model, Computer Integrated Manufacturing Systems, 16 (2010) 1-7.

[11] W. Terkaj, G. Pedrielli, M. Sacco, Virtual Factory Data Model, in: Proceedings of the Second International Workshop on Searching and Integrating New Web Data Sources (VLDS 2012), Istanbul, Turkey, 2012.

[12] O.E. Ruiz, S. Arroyave, J. Cardona, EGCL: An Extended G-Code Language with Flow Control, Functions and Mnemonic Variables, World Academy of Science, Engineering and Technology, 67 (2012) 455-462.

[13] A.L.K. Yip, A.P. Jagadeesan, J.R. Corney, Y. Qin, U. Rauschecker, I. Fraunhofer, A Front-End System to Support Cloud-Based Manfuacturing of Cutstomized Products, in: Proceedings of the 9th International Conference on Manufacturing Research ICMR 2011, 2011.

[14] L. Wu, C. Yang, A solution of manufacturing resources sharing in cloud computing environment, Cooperative Design, Visualization, and Engineering: Lecture Notes in Computer Science 6240 (2010) 247-252.

[15] C.S. Hu, C.D. Xu, X.B. Cao, J.C. Fu, Study of Classification and Modeling of Virtual Resources in Cloud Manufacturing, Applied Mechanics and Materials, 121-126 (2012) 2274-2280.

[16] Y.L. Luo, L. Zhang, D.J. He, L. Ren, F. Tao, Study on Multi-View Model for Cloud Manufacturing, Advanced Materials Research, 201 (2011) 685-688.

[17] Y.L. Luo, L. Zhang, K.P. Zhang, F. Tao, Research on the Knowledge-Based Multi-Dimensional Information Model of Manufacturing Capability in CMfg, Advanced Materials Research, 472 (2012) 2592-2595.

[18] L. Zhang, H. Guo, F. Tao, Y. Luo, N. Si, Flexible management of resource service composition in cloud manufacturing, in: Proceedings of the 2010 IEEE IEEM, IEEE, 2010, pp. 2278-2282.

[19] Q. Liu, L. Gao, P. Lou, Resource management based on multi-agent technology for cloud manufacturing, in: Electronics, Communications and Control (ICECC), 2011 International Conference, IEEE, Zhejiang, China, 2011, pp. 2821-2824.

[20] W.H. Fan, T.Y. Xiao, Integrated architecture of cloud manufacturing based on federation mode, Computer Integrated Manufacturing Systems, 17 (2011) 469-476.

[21] Y. Laili, F. Tao, L. Zhang, B.R. Sarker, A study of optimal allocation of computing resources in cloud manufacturing systems, The International Journal of Advanced Manufacturing Technology, 63 (2012) 1-20.

[22] X.V. Wang, X. Xu, ICMS: A Cloud-based Manufacturing System, in: Cloud Manufacturing: Distributed Computing Technologies for Global and Sustainable Manufacturing, Springer (In Press), 2012.

[23] G. Buonanno, P. Faverio, F. Pigni, A. Ravarini, D. Sciuto, M. Tagliavini, Factors affecting ERP system adoption: A comparative analysis between SMEs and large companies, Journal of Enterprise Information Management, 18 (2005) 384-426.

[24] T.F. Gattiker, D.L. Goodhue, What happens after ERP implementation: understanding the impact of interdependence and differentiation on plant-level outcomes, MIS quarterly, 29 (2005) 559-585.

[25] D.G. Ko, L.J. Kirsch, W.R. King, Antecedents of knowledge transfer from consultants to clients in enterprise system implementations, MIS quarterly, 29 (2005) 59-85.

[26] H. Liang, N. Saraf, Q. Hu, Y. Xue, Assimilation of enterprise systems: The effect of institutional pressures and the mediating role of top management, MIS quarterly, 31 (2007) 59-87.

[27] C.C. Wei, C.F. Chien, M.J.J. Wang, An AHP-based approach to ERP system selection, International Journal of Production Economics, 96 (2005) 47-62.

[28] A. Paulraj, A.A. Lado, I.J. Chen, Inter-organizational communication as a relational competency: antecedents and performance outcomes in collaborative buyer-supplier relationships, Journal of Operations Management, 26 (2008) 45-64.

[29] S.B. Modi, V.A. Mabert, Supplier development: Improving supplier performance through knowledge transfer, Journal of Operations Management, 25 (2007) 42-64.

[30] M.P. Papazoglou, W.J. Van Den Heuvel, Service oriented architectures: approaches, technologies and research issues, the VLDB Journal, 16 (2007) 389-415.

[31] L. Cherbakov, G. Galambos, R. Harishankar, S. Kalyana, G. Rackham, Impact of service orientation at the business level, IBM Systems Journal, 44 (2005) 653-668.

[32] M.T. Schmidt, B. Hutchison, P. Lambros, R. Phippen, The enterprise service bus: making service-oriented architecture real, IBM Systems Journal, 44 (2005) 781-797.

[33] P. Rauyruen, K.E. Miller, Relationship quality as a predictor of B2B customer loyalty, Journal of Business Research, 60 (2007) 21-31.

[34] P.A. Bernstein, S. Melnik, Model management 2.0: manipulating richer mappings, in: SIGMOD 2007, ACM, Beijing, China, 2007, pp. 1-12.

[35] ISO, ISO 10303 -1: Industrial automation systems and integration -- Product data representation and exchange -- Part 1: Overview and fundamental principles, International Organization for Standardization, Geneva, Switzerland, 1994.

[36] ISO, ISO 14649-1. Industrial automation systems and integration -- Physical device control -- Data model for computerized numerical controllers -- Part 1: Overview and fundamental principles, International Organization for Standardization, Geneva, Switzerland, 2003.

[37] W. Gielingh, An assessment of the current state of product data technologies, CAD Computer Aided Design, 40 (2008) 750-759.

[38] L. Zhang, Y.L. Luo, F. Tao, L. Ren, H. Guo, Key technologies for the construction of manufacturing cloud, Computer Integrated Manufacturing Systems, 16 (2010) 2510-2520.

[39] R.D. Allen, J.A. Harding, S.T. Newman, The application of STEP-NC using agent-based process planning, International Journal of Production Research, 43 (2005) 655-670.

[40] L. Monostori, J. Váncza, S.R.T. Kumara, Agent-Based Systems for Manufacturing Annals of the CIRP, 55 (2006) 697-720.

[41] A. Nassehi, S.T. Newman, R.D. Allen, The application of multi-agent systems for STEP-NC computer aided process planning of prismatic components, International Journal of Machine Tools and Manufacture, 46 (2006) 559-574.

[42] ISO, ISO 10303-11 Industrial automation systems and integration -- Product data representation and exchange -- Part 11: Description methods: The EXPRESS language reference manual, International Organization for Standardization, Geneva, Switzerland, 2004.

[43] ISO, ISO 10303-21. Industrial automation systems and integration -- Product data representation and exchange -- Part 21: Implementation methods: Clear text encoding of the exchange structure International Organization for Standardization, Geneva, Switzerland, 2002.