Cloud Manufacturing for a Service-oriented Paradigm Shift

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Abstract – **Manufacturing industry is undergoing a major transformation from production-oriented business to service-oriented business, inspired by the advancement of smart technologies and sophisticated demand for product-service systems from the dynamic market. Cloud manufacturing is emerging as a key enabler for manufacturing companies to deliver highly customisable services over the Internet. This paper aims to investigate how cloud manufacturing systems is able to facilitate effective service-oriented business. Major challenges in developing a cloud-based manufacturing marketplace are discussed. A system framework for cloud-based service provision is proposed.**

Keywords – **service-oriented manufacturing, cloud manufacturing, manufacturing service, access control, semantic web**

I. INTRODUCTION

Industry revolution is becoming increasingly entrenched in, and driven by, sophisticated customer expectations of products and advancement of IT technologies. In recent years, the growing demand for integrated and customised solutions forces manufacturers of industrial goods to combine their products with service components, i.e. Product-Service Systems (PSS) [1]. PSS typically comprises tangible products and intangible add-on service. The advancement of smart technologies, such as Internet of Things and cloud computing, makes PSS readily and efficiently deliverable throughout different industry sectors. Tesla Motors [2] (an electric vehicle giant) embeds advanced upgradable software applications into their electric vehicles. IT vendors (e.g. Google, Amazon, and Microsoft) make computing resources as a service and then extend their product lines by including IaaS, PaaS and SaaS business models.

Clearly, manufacturing business is being transformed from physical product-based business to service-oriented business. Traditionally, manufacturing industry is featured as a type of heavy capital investment business because of the upfront investment on manufacturing assets (e.g. CAX software and CNC machines), which unfortunately does not provide the much needed agility for today's business.

In realising this, more and more companies have started adopting a service-oriented approach - packaging traditional manufacturing resources as consumable services on a pay-as-you-go basis. Autodesk (a world leader in computer-aided design software) has introduced a set of cloud-based tools for simulation and engineering processes - Autodesk 360 Cloud Services [3]. It brings mechanical, fluid flow and thermal simulations all to the cloud, and is typically based on a pay-as-you-go model that allows users to access the software without the need to make heavy investments in licensing fees, installation, or software updates and upgrades. NetSuite Inc. [4], a leading provider of ERP (Enterprise Resource Planning) solutions, unveiled its next-generation ERP solution as budget cloud services. Customers can choose the right software package based on their personalised needs and financial plans.

The above endeavours signal a trend of transforming business operating infrastructure to the cloud, which gives manufacturing companies business agility and financial flexibility. This paradigm shift gives rise to a novel manufacturing business model - cloud manufacturing. Cloud manufacturing is a customer-centric manufacturing model enabling ubiquitous, convenient, on-demand access to a shared pool of diversified and distributed manufacturing resources that can be rapidly provisioned as consumable services [5]. These services can range from conception of a product all the way up till its disposal.

The intention of this paper is to investigate how cloud manufacturing is able to facilitate service-oriented business in manufacturing industry and propose an execution system to deliver cloud-based manufacturing services.

II. CLOUD MANUFACTURING

Cloud manufacturing represents a new-generation service-oriented manufacturing paradigm that provides organisations with the ability to virtualise their resources and offer them as scalable cloud-based services. In this business model, there are two fundamental business roles, namely service consumers and service providers (Fig. 1). Service consumers request manufacturing services from the cloud, whereas service providers receive orders or sub-orders from the cloud by outsourcing resources [6].

In cloud manufacturing, the key concept is to carry out business transactions on manufacturing services that are typically composed of distributed manufacturing resources owned by service providers. A number of system frameworks have been proposed for various application scenarios [7-9]. The most notable generic architecture is a four-layer framework proposed by Xu [5]:

Fig. 1: High-level business interactions in cloud manufacturing

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- Manufacturing resource layer, such as manufacturing equipment, software and knowledge.
- Manufacturing virtual service layer, in which manufacturing resources are identified, virtualised and packaged as services.
- Global service layer, which relies on a suite of smart technologies responsible for service provision for various service requests.
- Application layer, which is the interface for users to invoke services for applications.

A typical cloud manufacturing system includes the following functions [6]:

- Manufacturing resource-related functionalities, including resource virtualisation, resource monitoring, resource schedule, etc.
- Service-related functionalities, including service request processing, QoS management, billing mechanism, and trust insurance.

III. TECHNICAL CHALLENGES

Provision of manufacturing services in the cloud brings a number of challenges to the traditional manufacturing model. In a service-oriented business environment, end users would prefer to purchase PSS with personalised add-on services or even one-of-a-kind product. Connected enterprise is another basic requirement in service-oriented manufacturing business. In the global market, it is unlikely that one enterprise by itself can produce competitive products. A concentrated and dynamic enterprise service network is required to connect geographically isolated enterprises, allowing effective collaborative product development activities.

However, today's networked manufacturing mainly refers to integration of distributed resources for undertaking a single manufacturing task [10]. What is lacking in this type of manufacturing regime is the synchronous management of project progress, choice of different operation modes and embedded access of manufacturing resources, without which a seamless, stable and high quality transaction of manufacturing services cannot be guaranteed. There are a number of challenges in implementing cloud manufacturing, e.g. exchange of service specifications, business document exchange, alignment of schedules, and tracking of services throughout the supply chain.

Firstly, a description framework for manufacturing services is needed. There are a couple of approaches and concepts that describe how to manage service related information in a manufacturing network. Some of the work is centred around extending Web service technologies such as WSDL (Web Service Description Language), DAML (DARPA Agent Markup Language), and OWL-S (Ontology language for Web Services) to implement management of manufacturing services [11, 12]. However, the above work is not sufficient to explicitly represent manufacturing services as production process, costs, and logistics are not taken into account.

There are also a surge of research work focusing on using more generic service descriptions, such as UML (Unified Modelling Language) to integrate e-commerce related information, technical information, and operational information into a unified model [13]. However, system integration remains a problem. The above generic modelling language is mainly for manual representation, which could not be well integrated with downstream manufacturing execution systems.

Additionally, there are standards that focus on exchange of product data. The most significant of the kind is STEP (Standard for the Exchange of Product Model Data) [14], which can be used to exchange data between CAD/CAM systems. Different APs (Application Protocols) are proposed to represent and exchange digital product information in different application domains. Continuous efforts have been made to extend the STEP standards to cloud manufacturing application by integrating other no-technical information (e.g., business entities, costs, and logistics) [15]. However, STEP cannot tackle heterogeneous data generated from multiple sources over the Internet as STEP files require a reasonably closed interpretation environment built upon relevant APIs (Application Programming Interface). This limitation restricts a broader scale of data sharing in the Web environment.

Based on the nature of service-oriented business in the cloud and discussions in [16], the following requirements on the description of manufacturing services could be extracted:

- Manufacturing services should be extendable to allow customised modelling of manufacturing services.
- Manufacturing services have to represent various aspects in the data structure which includes product characteristics (e.g. geometrics, materials, and functionalities), quality constraints, manufacturing process specifications (e.g., nominated manufacturing resources and manufacturing technologies), organisational information, cost expectations, logistics requirements, etc.
- The service description should only include a minimum amount of data that is just enough for system processing requirements.
- The service description model should be open, which can be processed in various programming environments, such as JRE (Java Runtime Environment), CLR (Common Language Runtime), and DOM (Document Object Model) environment.
- The service description should be able to support portable data exchange and archiving.
- The service description should be able to support distributed data environment, allowing different sets of data fragments to be integrated and reused.

In terms of developing service specifications in a cloud environment, an iterative approach is proposed to iterate each of the important aspects of manufacturing services in the cloud environment [16]. Within each step of iteration, the detailed needs for an appropriate description of the respective aspects were analysed.

Secondly, a unified description for manufacturing resources is required. Manufacturing resources are the most fundamental elements that collaboratively undertake a given service request. It consists of manufacturing physical resources and manufacturing capabilities as illustrated in Fig. 2. Description of manufacturing resource includes the technical properties and functional capabilities of a resource. Take CNC milling machine as an example. Technical properties include its manufacturer, manufacturer instructions, machining envelope, control system, maximum spindle speed, mass, foot-print, etc., whereas functional capabilities include planar face milling, 3D free-form surface milling, drilling, boring, pocketing, etc. Traditionally, product manuals from product manufacturers only provide explicit descriptions on physical properties and technical details of a product. Instructions on how to use the product properly and best practice in different application scenarios are often not well-documented for systematic reference. In a service-oriented business, resource capabilities need to be explicated documented and this information should be in a form that allows easy reuse in the cloud environment.

Besides the technical properties and functional capabilities of a resource, the cost model and availability information should also be integrated into the description. In a service-oriented business, usage-based billing could be an effective approach, which has already been proven successful in service-oriented computing business. On the financial side, each product must include the costs of direct material, direct labour cost, and overheads. Direct material and direct labour costs are directly traceable to the products being manufactured. Overheads, however, consist of indirect factory-related costs which must be divided up and allocated to each unit product. Some of the costs that would typically be included in manufacturing overhead include: (1) Material handlers (forklift operators who transport materials and units); (2) People who inspect products; (3) Factory management team; (4) Utility costs (e.g., electricity, gas and water); (5) Computer and communication systems; and (6) Safety and environment costs. To enable accurate usage-based metering, qualitative analysis for converting costs of direct material, direct labour, and overheads to activity-based cost model needs to be carried out strategically before a company starts to migrate to the service-oriented business.

Resource availability information is also critical to intelligent service-oriented business transactions. Timely delivery of a manufacturing service in the cloud is subject to the dynamic nature of anticipated resources. The dynamic changes in manufacturing shop floors, such as production change, job delay, unavailable machines, and even temporary leave of an operator, lead to uncertainty in service delivery. The absence of up-to-date information on machine availability may cause a generated service plan un-executable. Such a lack of information also prevents consumers from keeping track of their service progress. Therefore, a resource availability module is required to be embedded in the cloud environment. In this module, availability information is streamed to the cloud through embedded sensors on machines or integrated resource scheduling systems.

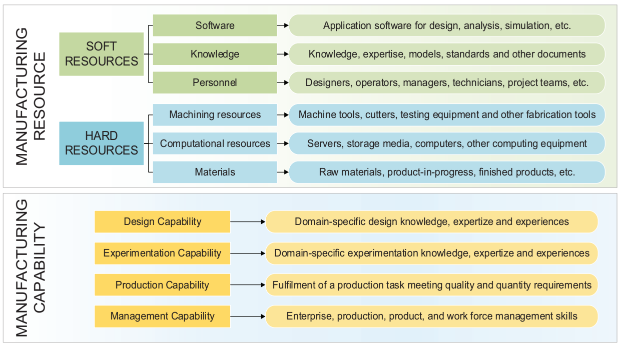

Fig. 2 Classification of manufacturing resources [6]

Thirdly, intelligent mapping between service requests and anticipated resources is one of the cornerstones in service-oriented business. Selection of the most appropriate resources for a given application scenario is among the most knowledge-intensive activities in manufacturing. In this activity, a service request is mapped to the available information of the various existing manufacturing resources to determine an executable plan. This process involves knowledge-based decision-making and is often undertaken by experienced production engineers in a workshop. In a cloud environment, a knowledge-based decision support system is to be developed, in which explicated knowledge on manufacturing resources selection is represented.

Privacy is a common concern that may drive enterprises away from migrating to a service-oriented business in the cloud. Indeed, manufacturing resources and know-how on operation are of the core competencies in a manufacturing enterprise. It is desirable to mandate resource owners (service providers) full control of their resources in the cloud, which means entities in the cloud can define access rules for each resource. The access rules specify who, when, where and what can be done to a connected resource.

Access policies change dynamically over time in terms of the resource involved, the nature of the access permitted, and the participants to whom access is available. Developing a unified access control mechanism is challenging for it requires a unified ontology, a lightweight description framework for access rules and a standardised programming interface [6].

IV. A SYSTEM FRAMEWORK

The preceding section discusses key challenges in facilitating a service-oriented manufacturing business in the cloud. This section discusses a system framework that addresses the challenges in a holistic view as depicted in Fig. 3. As the system span across multiple tiers from application layer to shop-floor environment, the system needs to deal with APIs in different programming languages, which may cause integration problem. To overcome the communication barrier between different programming languages, the system is built upon Service-oriented architecture (SOA). The aim is to enable a loose coupling between interacting software agents, which are often constructed as services [17]. The proposed system was designed to isolate independent software modules as separable Web services. The fundamental modules include: service parser module, monitoring module, access control module, service composition module, and knowledge building module.

The presentation layer resembles the application layer in Xu's four-layer structure [5], which contains the components that construct user interface and manage user interactions. In order to facilitate business interactions on the fly with great user experience (UI), the responsive Web design pattern [18] is adopted to provide optimal viewing experience across a wide range of devices (from mobile phones to desktop computers).

The UI components consist of controls and buttons that generate different events. If an event is triggered from the client-side, the controller can impose the event handler to retrieve and invoke a set of remote services. Once the service responses are handled by the client-side, the view components can display the information to the end user.

The service parser module takes the responsibility of reading/writing service requests from service consumers. These service requests are represented in the XML data format, which enables data exchange on different software platforms as there are various parsing tools developed for different programming environments. Take the service request (Fig. 4) as an example. It is a schematic representation of a machining request with all the essential parameters specified, including consumer information, service requirements, and machining feature and its design model.

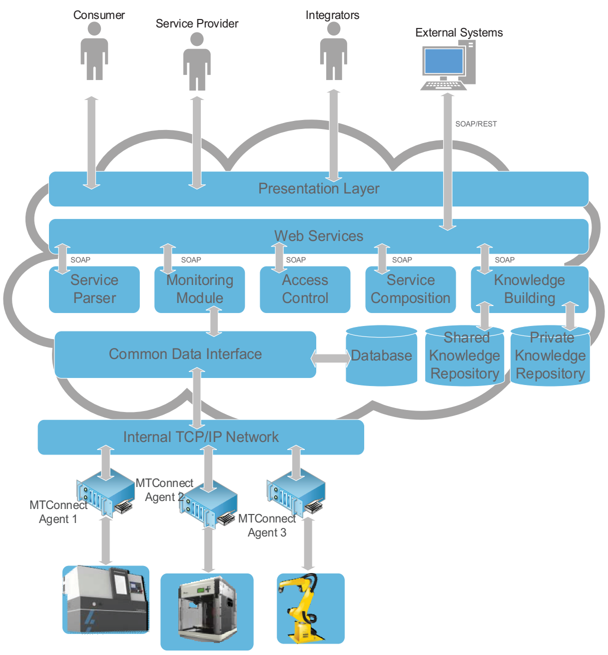

Fig. 3 Layered architecture of a cloud manufacturing system


```xml
<?xml version="1.0" encoding="utf-8"?>
<job name="Job 122612" description="manufacturing job request" material="P" owner="Michael Lu" id="122612">
  <serviceRequirements>
    <deliveryTime>none</deliveryTime>
    <costExpectation>none</costExpectation>
  </serviceRequriements>
  <machiningFeatures>
    <machiningFeature featureType="General Open Pocket" externalId="" unit="Metric" name="General Open Pocket">
      <parameters>
          <parameter name="Dp" description="Depth of pocket">20</parameter>
          <parameter name="Rm" description="Minimum radius in concave corner">3</parameter>
          <parameter name="Wo" description="Width of open area">12</parameter>
          <parameter name="Cs" description="Corner style">Corner Break</parameter>
          <parameter name="Cb" description="Corner break">1.6</parameter>
          <parameter name="Rg" description="Floor radius">0</parameter>
          <parameter name="Wc" description="Width of 45° chamfer">0</parameter>
          <parameter name="Aw" description="Angle of wall">90</parameter>
          <parameter name="Wi" description="Smallest width of the gap">0</parameter>
          <parameter name="Vp" description="Volume of the pocket">0</parameter>
          <parameter name="Qw" description="Quality of wall surface">N10</parameter>
          <parameter name="Unit" description="Unit of Tool">None</parameter>
          <parameter name="FType" description="Solid/Indexable Tool">None</parameter>
          <parameter name="SBType" description="Shank/Bore Type">None</parameter>
      </parameters>
      <toolAssemblies>
          <toolAssembly referenceId="" />
      </toolAssemblies>
      <designModels>
          <model format="STEP">.\Models\PocketModel.stp</model>
      <designModels>
    </machiningFeature>
  </machiningFeatures>
</job>
```


Fig. 4 Service request in XML format

The service composition module disassembles a service request into elementary, indivisible service units and maps a set of resources to single service units. This process is carried out through a sequential process: (1) retrieval of a list of feasible resources for a given service unit by deductive reasoning using the general engineering knowledge stored in the knowledge repository, and (2) multi-constraints optimisation taking cycle time, process efficiency, cost and other metrics into consideration.

The above process relies on up-to-date availability information of manufacturing resources. MTConnect [19], an open standard that is intended to foster greater interoperability between devices and software applications, is adopted to stream machine status from a geographically distributed shop-floor environment to the Internet. This information is stored as common data objects to facilitate data sharing among different software platforms.

The access control module manages resource access rules set by different service providers. Authorising access to resources in the cloud involves establishing the identity of a consumer (authentication), and determining if an operation is consistent with applicable access policies defined by corresponding resource owners.

Lu et al. [6] introduces a semantic Web-based approach to managing dynamic resource-sharing policies (Fig. 5). Service providers are allowed to create various sharing requirements for every single resource base on their periodical business situations. The access control module is able to make intelligent decisions on authorising satisfied users for each resource using the built-in inference engine.

The knowledge building module stores general engineering knowledge into the shared knowledge repository and allocates a dedicated knowledge repository for each service provider to host private knowledge used in business processes, including resource sharing rules, manufacturing know-hows, etc. This intention creates explicit boundaries between general engineering knowledge and knowledge with intellectual property rights and thus protects the core competences of a manufacturing enterprise.

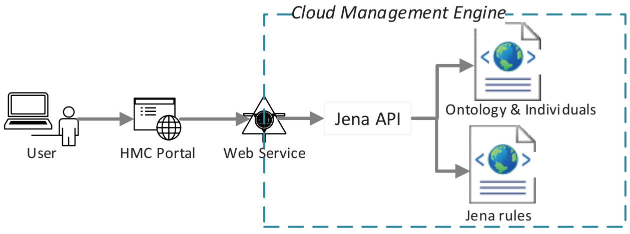

Fig. 5 Architecture of the access control module [6]

The layered architecture can leverage service-oriented business interactions and can be integrated with existing systems such as ERP systems using service-oriented integration mechanisms. The main role of service-oriented integration mechanism is to invoke encapsulated web services through SOAP (Simple Object Access Protocol) and REST (Representational State Transfer).

V. DISCUSSIONS AND CONCLUSIONS

For manufacturing companies to stay competitive, producing new PSS utilising distributed resources based on a pay-as-you-go model is an effective approach. There are still a number of technical challenges in transforming today's manufacturing systems into service-oriented manufacturing models under a cloud manufacturing environment. The proposed cloud-based system can facilitate service-oriented manufacturing business in a decentralised and dynamic manufacturing environment. The challenges in delivering consumable manufacturing services over the Internet include but not limited to:

- Development of a description framework for manufacturing services.
- Development of a unified description for manufacturing resources - ontology.
- An intelligent mapping mechanism between service requests and anticipated resources.
- An efficient privacy mechanism to enable resource access configuration and protect intellectual property.

The proposed system is built upon SOA architecture, which enables different technologies to be dynamically integrated, independently of the system's platform in use. Additional novelty of this work includes, (1) using XML data format to explicitly represent service requests, (2) proposing a two-stage process of mapping service requests to available resources; and (3) bringing in a semantic Web-based approach to facilitate user-centric privacy requirements.

It is envisioned that dynamic market needs and advancement of IT technologies will re-organise manufacturing businesses by means of cloud services, where manufacturing resources can be shared autonomously and optimally.

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